This Supplemental Material accompanies Gottlieb, E.S., Miller, E.L., Valley, J.W., Fisher, C.M., Vervoort, J.D., and Kitajima, K., 2022, Zircon petrochronology of Cretaceous Cordilleran interior granites of the Snake Range and Kern Mountains, Nevada, USA, *in* Craddock, J.P., Malone, D.H., Foreman, B.Z., and Konstantinou, A., eds., Tectonic Evolution of the Sevier-Laramide Hinterland, Thrust Belt, and Foreland, and Postorogenic Slab Rollback (180–20 Ma): GSA Special Paper 555, https://doi.org/10.1130/2022.2555(02).

SUPPLEMENTAL RESULTS DESCRIPTIONS

SHRIMP–RG Zircon U–Th–Pb Geochronology

All uncertainties in text and figures are shown at the 95% confidence level, with total uncertainty including propagated systematic error shown in square brackets. Figure numbers referred to in this supplemental section correspond to figures shown in the main body of the manuscript.

Northern Snake Range Tonalitic Orthogneiss

The oldest intrusions dated (samples NS2A, 20-210, and SCKG) were collected from a broadly exposed complex of biotite bearing tonalitic orthogneiss (Lee et al., 1999) (Fig. 3a). In upper Deadman Canyon, this unit contains a penetrative deformational fabric defined by foliated biotite that is subhorizontal and parallel to the foliation in the Neoproterozoic McCoy Creek Group strata this pluton intrudes (Fig. 3a). Cathodoluminescence images clearly show many zircons from these samples contain easily discernable inherited “cores” (Fig. 4). Most of the zircons are rimmed by oscillatory–zoned overgrowths of variable thicknesses that yielded reliable ages for determining the ages of intrusion (Fig. 4). An exposure of the orthogneiss in Horse Canyon (sample 20-210, Fig. 3a) that had been previously assigned a TIMS age of 100±8 Ma (Miller et al., 1988) is dated by SHRIMP–RG as 100.0 ± 1.3 [2.2] Ma (Fig. 5a–b). Two other parts of this intrusive complex overlap this age: An orthogneiss exposure in Smith Creek (sample SCKG, Fig. 3a) is 101.4 ± 1.2 [2.1] Ma (Fig. 5c-d) and a tonalitic orthogneiss in Deadman Canyon (sample NS2A, Fig. 3a) is 102.1±1.0 [2.0] Ma (Fig. 5e–f). A few zircons from these samples have cores that are distinct in CL from the oscillatory–zoned overgrowths and numerous fragmental cores, but yield similar ages to the oscillatory–zoned overgrowths (e.g., grain 20-210-14 and NS2A-5, Fig. 4). Fifty-eight zircons from these three samples had core domains that yielded Precambrian ages (Fig. 6). Each sample yields a primary age peak around 1.1 Ga and subsidiary peaks ca. 1.4–1.5 Ga and 1.6–1.8 Ga (Fig. 6). Samples SCKG and NS2A also yielded ages between ca. 2.5–3.0 Ga, and NS2A yielded one result ca. 0.7 Ga (Fig. 6).

Southern Snake Range Lexington Canyon Pluton

Sample SS1 was collected from the equigranular two-mica bearing Lexington Canyon pluton in the southern Snake Range (Fig. 3b) previously assigned an 86 Ma minimum age (K–Ar, muscovite; Lee and Christiansen, 1983). The pluton intrudes lower plate rocks (Late Neoproterozoic–Early Cambrian Prospect Mountain quartzite and Middle Cambrian Pole Canyon limestone) and is structurally overlain by Late Cambrian Lincoln Peak Formation and Late Cambrian–Early Ordovician Notch Peak Formation in the upper plate (Miller et al., 1999) (Fig. 3b). Forty-four zircons with diverse appearances in CL images were analyzed from this sample.

Many of the polished zircons have substantial inherited core domains and expose insufficient areas to reliably analyze magmatic overgrowths (e.g., grain SS1-9, Fig. 4). Analytical inaccuracy is suggested by highly discordant 251±16 Ma Pb/U and 854±32 Ma Pb/Pb results for spot SS1-7.1 suggest mixing of inherited and magmatic domains. Conversely, four grains (SS1-8, 10, 14, and 109) appear devoid of inherited material based on CL imagery (e.g., SS1-10, Fig. 4). Twenty-seven spots spread among these four grains plus twelve other grains that had inherited cores overgrown by magmatic rims yielded an intrusive age of 93.8 ± 1.0 [2.0] Ma (Fig. 5g-h).

Thirty-seven of the forty-four zircons analyzed from sample SS1 contained Precambrian inherited domains (Fig. 6). The Pb/Pb ages span ca. 0.85–2.7 Ga, but the youngest concordant ages are ca. 1.0 Ga. Inherited Precambrian core ages in sample SS1 exhibit a range of concordant ages from ca. 0.95–1.6 Ga, another population ca. 1.8 Ga, and a single result ca. 2.7 Ga (Fig. 6). Three variably discordant grains exhibit a $^{207}Pb/^{206}Pb$ age peak ca. 2.4 Ga (Fig. 6). Additionally, a single large oscillatory zoned zircon grain fragment yielded an Early Cretaceous age of 129.0±2.2 [3.1] Ma (2s, MSWD=1.8, n=3), indicating it crystallized ca. 30 Myr prior to its incorporation as a xenocryst in the Lexington Canyon pluton (Figs. 4 and 5g-h).

Northern Snake Range Leucogranite

Numerous deformed biotite + muscovite ± garnet bearing equigranular and pegmatitic leucogranite dikes intrude lower plate Neoproterozoic to Cambrian metasedimentary strata (schist, quartzite, and marble) in the northern Snake Range (Fig. 3a). Two samples of deformed equigranular two-mica bearing leucogranite (NS3A and ELM89DM) collected near the tonalitic orthogneiss sample NS2A in Deadman Canyon were dated in this study. Although numerous coarse-grained pegmatite dikes are also present in Deadman Canyon (Fig. 3a), zircons separated from pegmatite samples were uniformly metamict and thus not used in this geochronology study. Locally, the Deadman tonalitic orthogneiss is cut by pegmatitic leucogranite that is part of a west–northwest trending swarm of pegmatite and aplite dikes associated with an increase in metamorphic grade from S to N (Fig. 3a) (Lee et al., 1999). An age of 82.5±0.5 Ma (U–Pb, monazite) for a pegmatite at the junction of Smith and Deadman canyons (Fig. 3a) (Huggins, 1990) overlaps 78 ±9 Ma (Lee and Fischer, 1985) and 83 ±7 Ma (Cooper et al., 2010) age results for metamorphism in the northern Snake Range, supporting the view that intrusion of the pegmatitic and aplitic leucogranites was associated with ductile thickening, peak regional metamorphism, and partial melting of the underlying basement (Miller et al., 1988; Miller and Gans, 1989; Patiño Douce et al., 1990).

Of the thirty-nine zircons from sample NS3A that were dated, nearly all exhibited a thin (5–30 µm) low (i.e., dark) CL rim domain overgrowing texturally variable interior domains (Fig. 4). Only two of the zircons (NS3A-10 and 106) appear to be void of inherited Precambrian materials (e.g., NS3A-10, Fig. 4). Several zircons contain a high (i.e., bright) CL zone between Precambrian cores and low CL outer rims that yields Late Cretaceous age results (e.g., NS3A-11, Fig. 4). Analyses of the light–in–CL overgrowth domains in eleven zircons plus those from the two grains lacking Precambrian cores yields a weighted mean Pb/U age of 84.3 ± 0.8 [1.7] Ma (Fig. 5i-j). The darker outer rims yielded an anomalously older weighted mean Pb/U age of 90.4 ± 1.0 [1.9] Ma (Fig. 5i-j), but exhibit high U concentrations (average >3500 ppm), which can erroneously affect SIMS Pb/U calibrations and *increase* apparent Pb/U ages (McLaren et al., 1994; Ireland and Williams, 2003). Therefore, the 84.3 ± 0.8 [1.7] Ma result is suggested to be the more accurate age for intrusion of leucogranite sample NS3A, consistent with prior geochronology results (Lee and Fischer, 1985; Huggins, 1990; Cooper et al., 2010). Trace element ratios from the high and low CL domains (presented in next section) are used to further evaluate age relationships between these growth domains. Unlike the northern Snake Range tonalitic orthogneiss samples, oscillatory zoning is faint to unresolvable by CL imaging in the magmatic rim domains of the nearby leucogranites (Figs. 3a, 4). Precambrian ages measured in twenty-nine individual grains from sample NS3A are restricted to the range 0.9-1.9 Ga, with age peaks at 1.1, 1.4 and 1.8 Ga (Fig. 6).

Sample ELM89DM was collected from another equigranular two-mica bearing leucogranite located in close proximity to samples NS2A and NS3A (Fig. 3a). Its zircons exhibit diverse appearances in CL that are distinctive from leucogranite NS3A zircons and those from older samples (Fig. 4). Many of the grains contain oscillatory zoned rims overgrowing inherited cores (e.g., ELM89DM-10, Fig. 4), whereas others have prominent low CL euhedral tips growing over subhedral cores (e.g., ELM89DM-101, Fig. 4). Also present are several grains with high CL cores that yield latest Cretaceous ages that are overgrown by oscillatory zoned domains (e.g., ELM89DM-9, Fig. 4) or dark–in–CL tips (e.g., ELM89DM-113, Fig. 4). Age determination of oscillatory zoned domains and high CL cores provided twenty-eight Late Cretaceous ages from twenty-five zircons, yielding a weighted average age of 76.9 ± 0.8 [1.6] Ma (Fig. 5k-l). Although numerous inherited cores are readily apparent in CL imagery, the ratio of inherited versus syn-magmatic zircon appears to be less in sample ELM89DM than in all of the previous samples presented. Precambrian ages obtained from ten zircons in the sample range 0.95–1.8 Ga, with peaks at 1.7, 1.35, and 1.1 Ga (Fig. 6).

Kern Mountains Tungstonia Pluton

Sample TUNG was collected in the Kern Mountains north of the northern Snake Range from the Tungstonia pluton, which is the largest exposure of a Cretaceous pluton in the study area (Fig. 2) that had been dated 75±9 Ma (zircon, U–Pb TIMS; Lee et al., 1986a). The sample is a two–mica granite with muscovite megacrysts, although other parts of the pluton exhibit more equigranular textures. Zircons from this sample are quite variable in CL appearance, with the exception that most contain inherited cores, exhibit euhedral crystal habit, and are rimmed by low CL overgrowths that range from a few to tens of microns wide (Fig. 4). Many inherited cores appear to be subhedral or fragmental with rounded to rugose margins that are enveloped by euhedral overgrowths (e.g., grain TUNG-25, Fig. 4). Fragmental cores can be readily identified in some cases by unconformity like relationships between zoning patterns in different growth domains (e.g., TUNG-25, Fig. 4). Oscillatory zoned (e.g., TUNG-25) or moderate (i.e., solid gray) CL overgrowths (TUNG-12) are typically visible as “inner rim” domains between inherited cores and outermost low rims (Fig. 4). Combined numerous inner rim results (n=32, including solid and oscillatory zoned domains) and one low CL outer rim with relatively low U content (TUNG-103; 2800 ppm) yielded the youngest age of any Cretaceous intrusion in this study at 70.5 ± 0.7 [1.4] Ma (Fig. 5m-n). The only grains apparently devoid of inherited age domains are two zircons (TUNG-9 and 108) with elongate euhedral crystal habit exhibiting oscillatory zoning that is truncated by a final stage of growth (e.g., TUNG-108, Fig. 4). Although the early oscillatory zoned growth in these grains is truncated by the outer rim growth, suggesting two distinct growth stages, the interior (older) domains yield results that are indistinguishable from the 70.5 ± 1.4 Ma weighted mean age of the sample (Fig. 5m-n).

Eighty-five zircon grains from sample TUNG containing Precambrian inherited cores yielded ages ranging from 0.9–2.65 Ga, with age peaks at 1.15, 1.4, 1.7 and 2.4 Ga (Fig. 6). Inherited cores from this sample exhibit considerably more discordance than Precambrian inherited domains from the other samples (Fig. 6). Zircons that yielded ca. 2.4 Ga peaks have conspicuously high CL cores that yielded these ages (e.g., TUNG-12, Fig. 4). When examined more systematically, although not all high CL cores yield ca. 2.4 Ga ages, all the high CL cores that yield these ages exhibit a typically narrow (10-20 μm wide) low CL band immediately overgrowing the core (Fig. 4). A few of these grains (e.g., TUNG-101, Fig. 4) have low ca. 1.6–1.7 Ga overgrowths on the high CL cores that were dateable (Fig. 7a). The isotopic ratios from the high CL domains exhibit significant scatter, but are bound between two sharply defined discordia trends (Fig. 7a). The older bound is a chord that intersects the concordia curve at

179±140 Ma and 2458±38 Ma, fit through data shown as “outer cores” in Figure 7a (n=14). The younger bound was calculated with a fixed lower intercept at 80±80 Ma that fits results from low to moderate CL overgrowths from TUNG-101, 201 and 355 and low CL core results from TUNG-104 and 122 to an upper intercept at 1711±44 Ma (n=5) (Fig. 7a; “inner cores”). The remaining results (n=12) scatter between these two chords (Fig. 7a; “mixed analyses”). Three grains from the Lexington Canyon pluton (sample SS1) exhibit similar high CL overgrown by low CL textures and also yield results that plot between these two chords (Fig. 7a; lightest shaded ellipses).

Twenty individual zircons from sample TUNG yield Mesozoic ages that predate intrusion at 70.5±1.4 Ma (but are all Mesozoic, and older than 77 Ma) (Fig. 7b). One such result is from a low CL rim (TUNG–2, 78±3 Ma) and is attributed to analytical inaccuracy due to high U content (4592 ppm). The other nineteen zircons with Mesozoic ages may reflect actual geochronology of zircon growth or result from analytical mixtures of age domains due to the sputter pit overlapping multiple generations of growth. Two results that can be ruled out immediately are from TUNG-16.1 and 340, which plot discordantly (74% and 80% discordant, respectively) and appear to have sputtered multiple CL domains (Fig. 7b). Conversely, redundant Jurassic age results were obtained from repeated analyses of two grains (TUNG-105 and 111), suggesting the ages reflect geochronology of zircon growth ca. 160–150 Ma (Fig. 7b). In addition to these two grains, five other zircons (TUNG–2, 302, 322, 346, and 352) yielded pre-magmatic Mesozoic ages from the most interior domains in the CL imagery (Fig. 7b). The other eleven zircons yielded concordant pre-magmatic Mesozoic ages from domains between inherited Precambrian cores and magmatic rims (Fig. 7b). Additional analytical methods used in the study (trace element and isotope geochemistry and laser ablation split stream geochronology) allow further discrimination of geochronologic versus mixed age results from the SHRIMP U–Pb work.

Trace Element Geochemistry

Northern Snake Range Tonalitic Orthogneiss

Linking CL patterns to geochronology of samples NS2A, 20-210, and SCKG reveals Precambrian cores are absent in a few of these zircons (Fig. 4). Instead, they contain unzoned or sector–zoned cores that yielded magmatic ages and are overgrown by oscillatory zoned domains (e.g., 20-210–14 and NS2A–5, Fig. 4). The syn-magmatic cores generally exhibit the lowest Hf and U concentrations and highest Ti concentrations and Th/U ratios of all the magmatic zircons analyzed in this suite (Figs. 8a-f and 9). Relative to the cores, the oscillatory zoned overgrowths exhibit differentiation trends showing enrichment in incompatible elements (U, HREE) (e.g., Claiborne et al., 2010), as indicated by increasing Yb/Gd and decreasing Ti concentration and Th/U, Y/Yb ratios with increasing Hf (Figs. 8a-f and 9). In each analysis, normalized zircon REE concentrations (excluding Ce) exhibit steeply positives slope with increasing atomic mass and relatively minor negative Eu/Eu* anomalies (Fig. 8a,c, and e). Paired decreases in ratios of LREE/HREE (Ce/Yb) and MREE/HREE (Gd/Yb) are observed with increasing Hf and decreasing Th/U, consistent with magma chemistry during zircon growth being controlled by coeval crystallization of one or more LREE and MREE partitioning phases (Fig. 8b,d, and f) (Beard et al., 2006; Grimes et al., 2015).

The ranges in values for trace element data from Precambrian age inherited zircons from samples in this suite generally overlap (Fig. 10). Compared to inheritance from other samples in the study, these concentrations and ratios span the narrowest ranges in value, but overlap with results from inheritance in all the other samples (Fig. 10). When compared to the magmatic domains in the tonalitic orthogneiss samples, the inherited results exhibit both commonalities and contrasts (Figs. 8a-f, 9, and 10). For example, low Hf concentration results measured from inherited core and magmatic domains generally overlap, whereas 17 of 26 magmatic results from NS2A are more enriched in Hf than the most enriched core. Similarly, the range of Th/U ratios from inherited (0.14–1.3) and magmatic (0.02–0.81) domains only partially overlaps and over half (n=29/52) magmatic results have Th/U ratios below the minimum result observed from the inherited domains.

Southern Snake Range Lexington Canyon Pluton

The magmatic domains in Lexington Canyon pluton (Fig. 3b) zircons exhibit a broad and generally systematic range of trace element compositions (Figs. 8g-h and 9). Textural context of how trace elements vary during magmatism in this sample is seen in grain SS1–14, which contains a magmatic high CL sector-zoned interior domain encased by moderate CL, finely oscillatory-zoned overgrowths (Fig. 4). The interior domain of this and similar grains show nominal increases in Hf and U concentrations and decreases in Th/U and Eu/Eu* across the CL texture boundary (Fig. 9, left column). The interior analysis from SS1-14 (14c, in Fig. 9) also yields the lowest Hf, second lowest U, and highest Th/U and Eu/Eu* results of any magmatic domains from this sample. Similar differentiation trends for all SS1 magmatic results are observed: as Hf increases, U, Yb increase, and Ti, Th/U, Eu/Eu*, Gd/Yb, and Ce/Yb decrease (Figs. 8g-h and 9, left column). Analysis SS1-20.1, obtained from a narrow, un-zoned overgrowth that is interior to a low CL rim (Fig. 4), notably deviates from these trends by exhibiting relatively higher Hf/Yb, Yb/Gd and lower Y/Yb, Th/U (Figs. 8g-h and 9). Paired Ce/Yb, Gd/Yb results generally show these ratios are highest in domains with higher Th/U and lower Hf concentrations and vice versa (Fig. 8h). Like the tonalitic orthogneisses, magmatic zircon growth from sample SS1 also exhibits broad ranges in the magnitude of Ti, Yb, and U concentrations, but is distinctive in having lower magnitude HREE/MREE ratios (e.g., Yb/Gd) and more negative Eu/Eu* anomaly (Fig. 9).

Trace element compositions of inherited Precambrian zircons in sample SS1 exhibit a nearly identical range of values as those from the inherited Precambrian zircons in the tonalitic orthogneiss suite discussed above (Fig. 10). Like those samples, numerous magmatic overgrowths in SS1 yield Th/U ratios lower than the lowest values observed in inherited Precambrian zircons (Figs. 9 and 10). The single ca. 130 Ma inherited zircon (SS1-9) from this sample is a relatively large and equant crystal with oscillatory zoning (Fig. 4). Three analyses of the grain show variable zonation in Hf (11650–14863 ppm) and U (604-1164 ppm), but consistent ratios of Th/U (0.05–0.06), and LREE, MREE/HREE (e.g., Ce/Yb, 0.004–0.008; Gd/Yb, 0.034–0.037; Y/Yb, 2.7–2.8) (Fig. 11a). The Ce/Yb–Gd/Yb–Hf–Th/U plot shows these results overlap results from a 158±6 Ma Tungstonia inherited zircon (grain TUNG-2) as well as results from dark–in–CL outermost rims on samples TUNG and NS3A (Fig. 11c).

Northern Snake Range Leucogranite

Contrasting CL appearances of zircons from the “early” and “late” leucogranite samples (NS3A and ELM89DM) (Figs. 3a and 4) are associated with distinctive differences in trace element characteristics of magmatic domains in the respective samples (Figs. 8i-l, 9). The older leucogranite (sample NS3A; 84±2 Ma), having a relatively higher proportion of inherited cores and consistent presence of low CL outermost rims (Fig. 4), exhibits the most heterogeneity in HREE concentrations in the study (>2 orders of magnitude variation in chondrite normalized Yb;

Fig. 8i). Comparing results of moderate CL inner magmatic domains to low CL rims of zircons from this sample shows that the rims are relatively enriched in Hf, Yb, U, depleted in Ti, and exhibit the lowest LREE, MREE/HREE ratios and most negative Eu/Eu* anomalies (Fig. 8i-j). Trace element concentrations and ratios (including Eu/Eu*) grossly correlate to changes in Hf concentration, although there is notable scatter for the moderate CL domains (Fig. 8i). In addition to low relative abundance of HREE vs. MREE, LREE, measured concentrations of Yb in moderate CL domains are quite low, with several grains yielding results <10 ppm (Fig. 9).

Magmatic zircon domains from the younger leucogranite (sample ELM89DM; 77±2 Ma) readily stand out from those in the older sample in a number of ways. Sample ELM89DM exhibits relatively high ranges in Ti concentrations and Th/U ratios, and over the same span of Hf concentrations, exhibits higher U, Yb and HREE/MREE, LREE (Fig. 9). Conversely, the magnitude and trends in Eu/Eu* anomalies in these two samples overlap over the same range of Hf concentrations (Fig. 9, left column). Of all the samples in the study, ELM89DM exhibits the most regular pattern in Th/U changing with the magnitude of LREE, MREE/HREE ratios, and is in stark contrast to the scatter exhibited by NS3A at high LREE, MREE/HREE values (Figs. 8j, l).

Although relatively few Precambrian cores were analyzed from the leucogranite samples (NS3A, n=29; ELM89DM, n=10), notable similarities and contrasts in trace element characteristics exist at characteristic ages peaks (Fig. 10). Both samples contain grains in the age range 1.65±0.1 Ga with Th/U ratios <0.03 (n=3 and 2, respectively), nearly an order of magnitude lower than any results from the tonalitic orthogneiss or Lexington Canyon pluton samples (Fig. 10). These grains also have anomalous MREE/HREE ratios relative to other results, although the sample NS3A grains represent the most MREE/HREE depleted end member whereas ELM89DM grains are most enriched (Fig. 10). Narrow pre-magmatic Mesozoic age domains in two zircons from NS3A have very low Th concentrations (<2 ppm) and Th/U ratios (<0.01) (Fig. 11a). These two grains also exhibit contrasting MREE/HREE ratios, with greater relative depletion of MREE over HREE in NS3A-19 and vice versa for NS3A-21 (Fig. 11a). Sample ELM89DM had one grain that yielded an apparently pre–magmatic Mesozoic age (ELM89DM-2.2; 93±10 Ma), but that spot is immediately adjacent to analysis ELM89DM-2.1 that yielded an age of 78±4 and has identical appearance in CL. Ti concentration of ~0.2 wt. % and $^{204}Pb/^{206}Pb$ measured ratio of 0.0121 (one to several orders of magnitude greater than other analyses of this sample) suggest the ELMDM89-2.2 age result is problematic, potentially due to accidental analysis of a Ti– and ^{204}Pb–bearing inclusion such as rutile.

Kern Mountains Tungstonia Pluton

Trace element geochemistry in magmatic domains from sample TUNG shows two end member sets of results that correlate to variations in CL intensity (Figs. 4 and 7). Moderate CL intensity "inner rims" yield a restricted range of Hf concentration [average 9360±868 ppm (2 s.d.); n=42/44, excluding spots 15.2 and 123.2 that appear to overlap dark rims] and moderate Th/U values (most between 0.2–0.8) (Fig. 9). Conversely, low CL outer rims are enriched in Hf concentration (16,000-24,000 ppm) and have low Th/U values (0.01–0.1) (Fig. 9). Chondrite normalized REE spectra from the inner and outer rim domains are easily distinguished, the former characterized by relatively higher LREE, lower HREE, and less pronounced negative Eu/Eu* anomaly (Figs. 8m,n). At lower Hf concentration (i.e., in inner rims), correlating increasing Hf with other trace element data is difficult due to the narrow range of Hf concentrations observed, but at higher Hf (i.e., in outer rims), increasing Hf tracks together with increasing U and decreasing Th/U, Eu/Eu*, and LREE, MREE/HREE (Fig. 9, left column). However, systematic covariance of Ti versus Yb/Gd and Th/U is evident in both inner and outer rim domains (Fig. 8o).

Precambrian inheritance in sample TUNG exhibits a broad range of element ratios (Fig. 10). Three age–based subsets (*a*-*c*) of the data are defined based on similarities in trace element results within the subsets (Fig. 8a). Subset (*a*) grains have <1.5 Ga Pb/Pb ages and are predominantly similar to inherited domains <1.5 Ga from the other samples in the study, with the exception of several low Th/U results (Fig. 10). Subset (*b*) grains have 1.5–2.1 Ga Pb/Pb ages and predominantly consists of grains with greater than 10,000 ppm Hf (Fig. 10). Numerous subset (*b*) results have Th/U ratios <0.1 and several grains have either relatively high or low MREE/HREE ratios (Fig. 10). Subset (*c*) grains have >2.1 Ga Pb/Pb ages, Hf concentrations predominantly <10,000 ppm, Th/U >0.3 (with one exception) and little variability in Hf/Yb and MREE/HREE ratios (Fig. 10).

Mesozoic age results that predate the intrusive age of the Tungstonia pluton are observed in only a minor proportion of zircons (in 20 out of 113 zircons), as either wholly Mesozoic age xenocrysts (e.g., TUNG-111, Fig. 4) or as overgrowths on Precambrian cores (e.g., TUNG-12, Fig. 4). For some of these zircons (TUNG–2, 5, 12, 102, 105, 111 and 113), trace element–only analyses were made in subsequent analytical sessions to confirm results and collect Ti concentration data (trace element sputter pit locations in GSA Data Repository[1]). Ti, Y, Hf, and U concentrations and Th/U, Y/Yb, Yb/Gd, Ce/Yb, and Eu/Eu* ratios from Mesozoic pre-magmatic domains are ordered by decreasing age, and shown with the mean result from magmatic overgrowths (Fig. 11b). Trace element results from inherited Precambrian cores overgrown by Mesozoic age pre-magmatic domains are also shown for the few grains that produced these data (TUNG–5, 12, 24, 102, and 112) (Fig. 11b). Only Hf, Th, and U concentration data (in addition to ages) were obtained for grains TUNG–302, 311, 317, 322, 324, 332, 346, and 352. Results shown in vertical grey bands in Figure 11b are from domains that appear to be Mesozoic age cores.

Trace element data were obtained for Mesozoic age pre-magmatic overgrowths on older cores from ten grains (TUNG–5, 12, 24, 102, 112, 113, 311, 317, 324, and 332) (Fig. 11b). The data are displayed with the means of all TUNG moderate–CL magmatic domain analyses for the respective variable (dark dashes, value in italics), and, for grains TUNG–5, 12, 24, 102, and 112, results from their Precambrian cores (hexagon icons) (Fig. 11b). Relative to the mean values of the Tungstonia pluton magmatic domains, the pre-magmatic overgrowths all exhibit lower concentrations of Ti, Y and lower Th/U ratios (Fig. 11b). Most overgrowths also have higher Hf and lower U concentrations than the average value of magmatic domains (Fig. 11b). The pre-magmatic Mesozoic overgrowths uniformly show lower Y concentration and higher Eu/Eu* ratios than their Precambrian cores (Fig. 11b). Some temporal trends are suggested by the pre-magmatic overgrowth data when they are arranged by age. Ti content and Th/U generally increases over time (Fig. 11b). For Late Cretaceous results, increasing Y, Hf, and U concentrations and decreasing MREE/HREE (Y/Yb, Gd/Yb), LREE/HREE (Ce/Yb), and Eu/Eu* ratios are generally observed with younger age results (Fig. 11b).

Jurassic cores (i.e., wholly Mesozoic age xenocrysts) (TUNG–2, 105, and 111) were each analyzed at least twice for trace elements, and show consistent results within each grain that are presented for intergrain comparison of Jurassic results (Fig. 11b). TUNG–2 has the highest U and Hf concentrations, and lowest Ti concentration, MREE/HREE (Y/Yb, Gd/Yb), LREE/HREE (Ce/Yb), and Eu/Eu* ratios (Fig. 11b). TUNG–111 has the highest Ti and Y concentrations and

Th/U, LREE/HREE (Ce/Yb), and Eu/Eu* ratios and lowest Hf and U concentrations (Fig. 11b). TUNG–105 has the lowest Y concentrations and Th/U ratios, and highest MREE/HREE (Y/Yb, Gd/Yb) (Fig. 11b). LREE, MREE/HREE ratios of the three zircon cores plot in distinctly different fields, with TUNG–2 overlapping results from the ca. 130 Ma zircon microxenolith from Lexington Canyon pluton (SS1-9) and the results of dark–in–CL outermost rims from samples TUNG and NS3A (Fig. 11c). The mean ages obtained for the Jurassic cores all overlap at 2–sigma uncertainty, so no temporal trends are evident.

SIMS Zircon Oxygen Isotopes

Northern Snake Range Tonalitic Orthogneiss

Oscillatory-zoned rims from tonalitic orthogneiss zircons have consistent oxygen isotope compositions ranging between +7.1±0.2‰ and +8.4±0.4‰ ($\delta^{18}O$; 2 s.d. uncertainties) (Fig. 12a-c). Calculated means of results from each sample generally cluster within this range, with sample SCKG exhibiting the heaviest mean value (+8.1±0.1‰; n=7, Fig. 12b), sample NS2A having a relatively intermediate result (+7.9±0.3‰; n=13, Fig. 12a), and sample 20–210 having the lightest result (+7.6±0.4‰; n=9, Fig. 12c). Magmatic–age zircon cores from each of the samples that are characterized by sector zoning and low Hf concentrations gave $\delta^{18}O$ results that were within 1‰ of the respective results from their oscillatory-zoned rim domains (grains NS2A–1, 3, 5 and 20-210–1). The calculated mean result from sample SCKG includes data from one grain (SCKG–1) that has a core that is assumed to be of magmatic age based on its similarity in CL appearance and $\delta^{18}O$ result to other magmatic age cores.

Precambrian cores from the tonalitic orthogneiss samples have $\delta^{18}O$ values ranging from +3.9±0.2‰ to +9.4±0.3‰ (Fig 12h-j). A consistent systematic relationship between $\delta^{18}O$ in inherited (Precambrian) cores and their surrounding magmatic rims is not apparent and it is possible that the more radiation-damaged cores are altered in $\delta^{18}O$. For example, the lowest $\delta^{18}O$ result observed among the tonalitic orthogneiss zircons (spot NS2A-4.1 on mount ESG43) corresponds to the highest full α-dosage and highest $^{16}O^{1}H/^{16}O$ result of the inherited cores from that sample. In general, each sample is notable because regardless of the $\delta^{18}O$ values of inherited cores, the $\delta^{18}O$ values of magmatic rims show inter–grain consistency (Fig. 12a-c, h-j).

Southern Snake Range Lexington Canyon Pluton

Values of $\delta^{18}O$ results from eight magmatic age domains and two undated oscillatory-zoned rims are plotted as the "magmatic" results for sample SS1 (Fig. 12d). The results scatter between +7.4±0.2‰ and +9.3±0.2‰ with one heavy outlier (SS1–20.1) at +14.0±0.2‰ (Fig. 12d). Excluding the outlier, the mean of results (±2 s.d.) is +8.3±1.2‰ (n=9). The zircon that yielded the anomalously high result is encased by a low CL rim (Fig. 4) and a co-located U-Pb + TE spot exhibits some trace element characteristics (low Th/U, relatively depleted in REE) that are distinctive from the rest of the magmatic results in the sample (Figs. 8g-h, 9). Grain SS1–14 has a high CL magmatic age interior and moderate CL overgrowth, with no difference in age and nearly indistinguishable increase from +7.6±0.2‰ to +8.3±0.2‰ for $\delta^{18}O$ values from interior to overgrowth (Fig. 4). Combining trace element and magmatic age information with oxygen isotope results from multiple grains shows that $\delta^{18}O$ increases from +7.5 to +9.5‰ with increasing U/Th and decreasing Eu/Eu* and the increase in $\delta^{18}O$ from interior to overgrowth in SS1–14 plots along these trends (Fig. 13a). The lowest-$\delta^{18}O$ magmatic result from the sample (SS1–16.1; +7.4±0.2‰) plots off the fractionation trends of these trace elements. They may have resulted from mixing domains if the primary beam sputtered through the targeted rim and into inherited core material, as lower-$\delta^{18}O$ material is observed in the core of this grain (SS1–16.2; +5.3±0.2‰).

Anomalously low values of $\delta^{18}O$ <+2.5‰ were observed in 3 of the 7 Precambrian cores from sample SS1 analyzed for oxygen (Fig. 12k). Of these analyses, two of the grains (SS1-22 and SS1-114, Fig. 4) exhibit composite age structures and CL textures similar to other anomalously low $\delta^{18}O$ cores from Tungstonia pluton (Figs. 4 and 13d), and were in fact targeted for oxygen analyses based on these similarities. Thus, sample SS1's high proportion of analyzed grains with anomalously low $\delta^{18}O$ cores is likely not representative of the ratio in the entire inheritance population from the sample The other anomalously low $\delta^{18}O$ result is from grain SS1-15, which yielded a near concordant $^{207}Pb/^{206}Pb$ age of ~1.25 Ga, and is the only Precambrian zircon in the study that gave an anomalously low $\delta^{18}O$ result and is not from a 2.45 or 1.7 Ga zircon (or mix thereof). Three zircon cores (grains SS1-16,20, and 121) yielded more typical $\delta^{18}O$ results ranging +5.3±0.2‰ to +6.3±0.2‰. The highest-$\delta^{18}O$ result from an inherited zircon (+8.3±0.2‰) is from the oscillatory–zoned ca. 130 Ma zircon xenocryst (grain SS1–9) (Fig. 4), and overlaps the mean results from northern Snake Range tonalitic orthogneisses samples NS2A and SCKG (Fig. 12a-b).

Northern Snake Range Leucogranite

Northern Snake Range leucogranite sample NS3A exhibits the most scatter in magmatic $\delta^{18}O$ observed in the study (Fig. 12e). All results are from moderate CL domains, and all but one (NS3A–10) are definitely from overgrowths on inherited cores (e.g., grains NS3A–11 and 22) (Fig. 4). Two distinct sub–populations appear when trace element results are plotted against $\delta^{18}O$ (Fig. 13b), offering some systematic insight to the degree of scatter seen in the trace element data from moderate CL overgrowths (Figs. 8i-j and 9). The first group (smaller symbols, all with $\delta^{18}O<7.5‰$) is relatively depleted in trace elements and has less scatter associated with the mean $\delta^{18}O$ value (+6.8±0.7‰; n=4) (Fig. 13b). The other group (larger symbols, $\delta^{18}O$ ranging +7.0±0.2‰ to +13.1±0.2‰) exhibits a trend of depletion in trace elements with increasing $\delta^{18}O$ values (Fig. 13b). In each group, decreases in U and Yb concentrations and increases in Hf/Yb appear correlated with increasing $\delta^{18}O$, although at overlapping $\delta^{18}O$ values the larger symbol group is at least an order of magnitude more enriched in concentration of U and Yb (Fig. 13b). The groups also differ in that the first group generally sees increases in Th/U, decreases in Eu/Eu* and exhibits little change in Gd concentration with increasing $\delta^{18}O$, whereas the second group decreases in Gd concentration and Th/U, and increases in Eu/Eu* as $\delta^{18}O$ increases (Fig. 13b).

Values of $\delta^{18}O$ determined for inherited cores in sample NS3A range from +4.6±0.2‰ to +10.2±0.2‰ (Fig. 12l). Core–to–rim patterns are variable, with some magmatic overgrowths being heavy relative to their cores (e.g., NS3A–22), some being light (e.g., NS3A–11), and some being indistinguishable (e.g., NS3A–15). Notably, two of the higher results (>9‰) are from analyses NS3A-3.2 and 22.2 that have considerable U-Pb discordance (20-50%) and the highest $^{16}O^{1}H/^{16}O$ values observed from this sample, raising the possibility that many of the oxygen isotope results from Precambrian zircon domains may be related to alteration.

Few zircons were analyzed for oxygen isotopes from the younger northern Snake Range leucogranite sample (EL89DM) and the grains that were analyzed do not have accompanying U–Pb ages (Fig. 12f, m). Three of the four analyses were done on grains with CL textures that appear magmatic and yielded overlapping results that gave a mean value of +6.2±0.3‰ (Fig. 12f, m). The fourth analysis was done on a core domain of uncertain age, and yielded a heavier result of +8.7±0.2‰ (Fig. 12f, m).

Kern Mountains Tungstonia Pluton

Tungstonia pluton (sample TUNG) zircon domains that exhibited low CL outer rims and moderate CL, oscillatory-zoned inner rims were analyzed for oxygen isotopes (e.g., TUNG-25 and 200, Fig. 13c). Low CL outer rims yielded overlapping $\delta^{18}O$ results (min. +6.8±0.5‰; max 7.4±0.5‰; average +7.0±0.6‰; n=3) (e.g., grain TUNG–25; Fig. 13c). Moderate CL oscillatory zoned inner rims with magmatic ages gave similar results (min. +6.7±0.3‰; max 7.1±0.5‰; average +7.0±0.3‰; n=6), as did undated oscillatory zoned domains (min. +6.8±0.3‰; max 7.1±0.3‰; average +7.0±0.3‰; n=6). All three groups of results yield a mean result of +7.0±0.4‰ for the magmatic domains in sample TUNG (Fig. 12g).

Oxygen isotopic results from pre–magmatic zircon domains from sample TUNG range broadly from +1.2±0.2‰ to +11.9±0.2‰ (Fig. 12n). Many of these results are significantly lighter than the oxygen isotopic composition of zircon equilibrated with mantle rocks (+5.3±0.6‰, 2 s.d.; Valley, 2003), and thus require examination regarding their petrologic context/validity (see Appendix A). For Precambrian age inheritance in sample TUNG, grains with high CL "inner cores" overgrown by lower CL "outer cores" ("Group A" zircons, Fig. 7a) yield numerous results between +1.7±0.2‰ and+5.3±0.2‰ for these domains, with few results higher than +5‰. Zircon domains that gave ages which plot along the 1.7 Ga discordia trend (Fig. 7a) exhibit low-$\delta^{18}O$ results between +1.2±0.2‰ and +3.4±0.3‰. The remaining pre–magmatic oxygen results are from core domains with Pb/Pb ages <1.6 Ga and yield the majority of results that are higher than +5‰ (Fig. 12n).

Three Jurassic age pre–magmatic domains were analyzed for oxygen. Grain TUNG–2, which has trace element ratios that overlap the field of low-CL magmatic rims and the lowest Ti content of any Jurassic domains, gave a +8.7±0.2‰ result (Figs. 11b-c, 13d). Grain TUNG–105, which has notably low HREE/MREE ratios gave the heaviest result of any inherited domain in the sample at +11.9±0.2‰ (Figs. 11b-c, 13d). Conversely, TUNG–111 gave the lowest oxygen result (+7.1±0.2‰) from an inherited Jurassic zircon domain, and is also noted for having Th/U >1 and the lowest Hf concentration of any Mesozoic pre-magmatic domain (Figs. 11b-c, 13d).

Only a single analysis of a directly dated Cretaceous age pre–magmatic domain was made. Grain TUNG–12 was analyzed in a part of the zircon that gave an 86±5 Ma age (Fig. 4) and trace element results that are distinct from its core and rim domains (Fig. 11b). This domain gave a +5.7±0.3‰ result, notably lighter than the moderate CL rim domain (+6.9±0.3‰) but heavier than core results (+3.0±0.3‰, n=2) (Fig. 13d). Grain TUNG–24 yielded a similar result (+5.6±0.5‰) in a part of a zircon that was not directly dated but appears to be in the same CL domain as an analysis on the opposite side of the zircon that gave a Cretaceous pre-magmatic age (94±3 Ma) (Fig. 13d). This grain's core yielded another relatively low result of +4.2±0.5‰ (Fig. 13d).

LA–ICPMS Zircon Lutetium–Hafnium Isotopic Ratios

Northern Snake Range Tonalitic Orthogneiss

Hf isotopes were analyzed in oscillatory–zoned magmatic domains of five zircons from sample NS2A (e.g., grain NS2A-12 in Fig. 4). All of these domains appear to overgrow inherited cores, and those cores that were dated (n=4) yielded ages between 1.2 and 1.8 Ga. Hf isotopic results from the overgrowths yield an average $\varepsilon Hf_{102\ Ma}$ value of -5.0±0.2 (2SE, n=5), and are indistinguishable within individual uncertainties (Fig. 14a).

Southern Snake Range Lexington Canyon Pluton

Hf isotopes were analyzed in seven zircon grains from sample SS1, with most analyses focused on magmatic age domains which yielded straightforward results (Fig. 10). Integration windows for analyses SS1-6, 12, and 121.2 were clipped at the end of the analyses due to rapid decrease in signal intensity due to the laser drilling out of the grains. Grain SS1-14 (Fig. 4), which exhibits a CL-bright magmatic age interior with moderately dark CL overgrowths, produced results that exhibit a pronounced positive step function in the Hf isotope ratio, suggesting multiple domains with discrete Hf isotopic characteristics were sampled by this analysis. The positive step from $^{176}Hf/^{177}Hf_{corrected}$ ratios of <0.282 to >0.2823 (~15 εHf units) demonstrates that the analysis measured core then rim on the buried side of the grain, attesting to an inherited core, despite a lack of CL and U–Pb evidence (Fig. 4).

Results from magmatic domains are quite variable on an *intergrain* basis, ranging from $\varepsilon Hf_{94\ Ma}$ of -11.0±0.9 to -20.2±1.0, averaging -14.7±2.4 (2SE, n=8)(Fig. 14). Repeat analyses in two grains (SS1–10 and 109), however, produced indistinguishable *intragrain* results. Four analyses of magmatic domains have accompanying oxygen isotope results (SS1–10, 12, 14, and 121). Of these, the most negative εHf result comes from a heavy $\delta^{18}O$ domain (SS1-12; -20.2±1.0 and +9.3±0.2‰). The other three grains produced less negative εHf and slightly lighter $\delta^{18}O$ results.

Hf isotopes results from two analyses of ca. 130 Ma zircon xenocryst SS1–9 (Fig. 4) overlapped each other and were notably less negative ($\varepsilon Hf_{130\ Ma}$ = -5.9±0.2; 2SE, n=2) than the magmatic results from sample SS1, but were much closer to results from northern Snake Range tonalitic orthogneiss sample NS2A (Fig. 14). Hf isotopes were only obtained on two inherited cores (SS1–14 and SS1–121). The age of the SS1–14 core is unknown, inhibiting calculation of $\varepsilon Hf_{initial}$ for this grain's inheritance, but its εHf_0 is only observed in a grain that crystallized <1.9 Ga (assuming it's $\varepsilon Hf_{initial}$ plotted at or below depleted mantle values). The other Precambrian core (SS1–121, 2.4 Ga) gave the most negative εHf_0 result obtained in the study (-62.6±1.0).

Northern Snake Range Leucogranite

Six magmatic domains from leucogranite sample NS3A were analyzed for Hf isotopes, yielding $\varepsilon Hf_{84\ Ma}$ results ranging -13.5±1.1 to -17.8±0.7, with a mean of -15.7±1.3 (2SE, n=6)(Fig. 14). These magmatic Hf results exhibit less scatter as a population than magmatic domains from sample SS1. Generally, more negative $\varepsilon Hf_{84\ Ma}$ values are associated with relatively lower $\delta^{18}O$, trace element depleted domains, and vice versa. Three of the analyses (NS3A–11, 15, and 110) yield overlapping $\varepsilon Hf_{initial}$ values ranging -16.1±1.3 and -17.8±0.7, and are from domains that are depleted in trace elements and relatively lower $\delta^{18}O$ values ($\delta^{18}O$ <7.5‰) (Fig. 13b, smaller diamonds). The two other domains that have accompanying $\delta^{18}O$ analyses (NS3A–114, and 115) have less negative $\varepsilon Hf_{84\ Ma}$ values of -14.5±1.1 and -15.6±1.3 respectively. These domains are more enriched in Yb (HREE), likely a result of the analysis ablating into the CL-darkest rim. The magmatic overgrowth domains from those grains produced $\delta^{18}O$ results that range from 7.0±0.2‰ to 9.2±0.2‰ (Fig. 13b). The least negative $\varepsilon Hf_{84\ Ma}$ result (-13.5±1.1, NS3A–16) does not follow the above pattern, having trace element results that are more typical of the more negative group of $\varepsilon Hf_{initial}$ results.

Kern Mountains Tungstonia Pluton

Assessing the accuracy and geologic relevance of results from sample TUNG is complex due to age and geochemical zonation in most zircons from this sample (e.g., Figs. 4, 7, and 13d). Because obtaining present day Hf isotope ratios (εHf_0) data does not require knowing the age(s) of a volume of material analyzed, these results provide a useful baseline (Fig. 14c). Laser ablation split stream (LASS) analyses on zircons from sample TUNG yielded εHf_0 ranging from -11.8±1.1 to -55.0±1.0 (Fig. 14c). Syn-magmatic domains analyzed yielded εHf_0 results ranging -21.5±1.3 to -24.6±1.3, averaging -23.4±0.5 (2SE, n=13) (Fig. 10c). The only analysis that targeted a CL-dark outermost rim (TUNG-401) gave an εHf_0 result (-22.1 ±1.1) indistinguishable from the remaining syn-magmatic domain analyses. The most negative εHf_0 result from samples SS1 and NS3A overlap the least negative εHf_0 magmatic results from sample TUNG. The $\varepsilon Hf_{71\ Ma}$ results from the syn-magmatic TUNG domains range -18.8±1.3 to -21.9±1.3, averaging -20.8 ±0.5 (2SE, n=13) (Fig. 14a).

Nearly all inherited domain results (n=20) are within the range (n=7) or more negative than (n=12) the range of εHf_0 values obtained for the magmatic domains (Fig. 14c). Grain TUNG-2.2, a Jurassic zircon xenocryst is the only analysis that is more positive, and overlaps εHf_0 values obtained for ca. 130 Ma zircon xenocryst SS1-9 from the Lexington Canyon pluton (Fig. 14c).

Values of εHf_0 from five inherited domains with Mesozoic ages range -11.8±1.1 to -29.3±1.3 (Fig. 14c). Three of these results were from Jurassic zircon xenocrysts and are highly variable in εHf_0. Another was from a Late Cretaceous overgrowth overgrowth (TUNG-12), and the fifth (and most negative) was TUNG-13 that yielded a 1.4 Ga SHRIMP-RG result, and is thus highly suspect (see next subsection). The -7.1±1.1 $\varepsilon Hf_{158\ Ma}$ result from grain TUNG 2,2 is the most isotopically positive Jurassic result, overlaps the range of 130 Ma zircon microxenolith SS1-9, and is only slightly more negative than NS2A analyses (Fig. 14a,b).

Laser Ablation Split Stream (LASS) Uranium–Lead Ages

Comparing LASS and SHRIMP-RG age data illustrates some complexity in interpreting the LASS data. LASS age results are grossly correlative to SHRIMP results, but typically not reproducible at 95% confidence. However, minor differences in the age used to calculate $\varepsilon Hf_{initial}$ are insignificant compared to analytical uncertainty of the Hf isotope measurements.

Zircon LASS age results <200 Ma are either equivalent to or slightly younger than SHRIMP ages from the same domains, with one exception. The exception is zircon TUNG-13, for which the SHRIMP age result is Precambrian (1.4 Ga) and LASS is Late Cretaceous (ca. 85 Ma). This result indicates the LASS analysis sampled an additional inherited domain not sputtered by the SHRIMP analysis. Given the SHRIMP analysis yielded a Precambrian age, the subsequent LASS analysis likely ablated a Precambrian core, then continued into a Cretaceous overgrowth. Thus the εHf_0 result is suspected to be a mixture in the case of analysis TUNG-13.

Two analyses (TUNG 4.67 and 352.1) yielded LASS ages >200 Ma and <400 Ma. Both are evidently mixtures between older inherited domains and younger overgrowths. Grain TUNG-4 contains a ca. 2.4 Ga core. The εHf_0 of the core is -51.5±1.2, and a magmatic domain εHf_0 of ~-23±2 can be assumed, demonstrating the εHf_0 result of -33.9±1.1 obtained for analysis TUNG–4.67 is consistent with mixed domains. SHRIMP results from TUNG 352.1 were highly discordant ($^{206}Pb/^{238}U$ age 108±10 Ma, $^{207}Pb/^{206}Pb$ age 758±438 Ma) and unlike the LASS results ($^{206}Pb/^{238}U$ age 374±27 Ma, $^{207}Pb/^{206}Pb$ age 2223±60 Ma Ma). Using the LASS $^{207}Pb/^{206}Pb$ age (2223±60 Ma) and εHf_0 (-28.5±1.6) to calculate $\varepsilon Hf_{initial}$ yields a geologically improbable result (+23.0, ~15 εHf units above the depleted mantle trajectory), suggesting the analysis ablated into multiple domains. The discordance between $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages obtained by LASS in each of these analyses (316±37 Ma vs. 1531±30 Ma and 374±53 vs. 2223±60 Ma, respectively) further attests to the complexity plaguing each of these analyses.

Of the LASS ages >400 Ma, analyses TUNG–104.1, 4.1, 201.1, 201.2, 329.1 and 355 yielded the most negative εHf_0 results and have SHRIMP and LASS $^{207}Pb/^{206}Pb$ ages that are predominantly indistinguishable. These LASS ages fall into two groups, ca. 1.65-1.7 Ga and 2.3-2.4 Ga, in agreement with the observation of distinct age domains from SHRIMP-RG U-Pb results shown in Figure 6. LASS $^{207}Pb/^{206}Pb$ ages from TUNG 123.1 and 336.1 fall between these age groups and the gap between uncertainties from SHIRMP and LASS results is >5% in both cases. The disagreement of SHRIMP and LASS results is these grains is attributed to them being mixtures of "inner core" and "outer core" domains in different proportions due to relative differences in sampling volume between the two methods. Also, LASS $^{207}Pb/^{206}Pb$ results from the 1.65–1.7 Ga group are remarkably consistent (mean age=1674±10 Ma; weighted mean age=1674±21 Ma, MSWD=0.07, n=3) whereas the SHRIMP $^{207}Pb/^{206}Pb$ results are less so (mean age=1697±90; weighted mean age=1715±21 Ma, MSWD=0.07, n=3). Calculated total α-dosages (Wang et al., 2014) for these domains are above the first percolation point, suggesting they experienced enough radiation damage to significantly increase Pb diffusion (Cherniak et al., 1991). The greater precision of LASS ages may be due to greater sampling volume yielding higher counts and reducing sampling bias between geochemically heterogeneous sub-domains within the zircon (e.g., Valley et al., 2014; 2015; Peterman et al., 2016).

Whole Rock Geochemistry

Northern Snake Range Plutons and Dikes

Sample NS2A was the only tonalitic orthogneiss sample analyzed for whole rock geochemistry. It has the highest LREE-MREE, Sr, Zr, and Ti in the study and lacks a negative Eu/Eu* anomaly (Fig. 15b). Whole rock geochemistry of NS3A and NS3B show enrichment in K, Rb, and Pb and depletion in Th, REE, Sr, Ti, Nb and Zr relative to sample NS2A (Fig. 15). Both of these leucogranite samples exhibit a positive Sr anomaly on a spider diagram (more prominent in NS3A) and NS3A exhibits Eu/Eu* >1, whereas in NS3B it is slightly <1 (Fig. 15b). Although both samples are depleted in Zr relative to NS2A, NS3B exhibits a negative anomaly in Zr content on the spider diagram, whereas NS3A does not. NS3A (garnet-free) is enriched relative to NS3B (garnet-bearing) in Sr and REE's from La to Eu and depleted in REE's from Gd to Yb (Fig. 15). Sample NS5 is a pegmatite, and exhibits the lowest concentrations of any sample in the study of Ba, Sr, Ti, Sc, V, and the light rare earth elements, but is most enriched in Pb, U, the rare earth elements from Dy and above, and Y (Fig. 15b).

The Sr-Nd isotopic composition of NS2A and the age equivalent Horse Canyon orthogneiss (sample 20-210) plot as the most isotopically juvenile results in the study (Fig. 15c) ($^{87}Sr/^{86}Sr_i$=0.70707 and 0.70708; $\varepsilon Nd_{(t)}$= -3.4 and -2.8, respectively), despite being located well east of the $\varepsilon Nd_{(t)}$= -7 isopleth (Wright and Wooden, 1991) (Fig. 1a). Sr-Nd isotopes from the leucogranite samples are considerably more evolved compared to NS2A, with NS3B exhibiting the most evolved isotopic ratios (Fig. 15c). Calculated model $\varepsilon Hf_{(t)}$ results (Vervoort et al., 1999) for sample NS2A are less negative (-1.3 to -1.8) than the analytical results from zircon (-5±0.4). For sample NS3A, this pattern is reversed, with calculated $\varepsilon Hf_{(t)}$ results (-18.0 to -18.7) plotting on the more negative end of the uncertainty envelope for the zircon results (-15.7±3.1).

Southern Snake Range Plutons

Relative to sample NS2A, Lexington Canyon pluton sample SS1 is more enriched in compatible (K, Rb, Cs, Pb) and depleted in incompatible (Sr, Zr, Hf, LREE's) elements (Fig. 15). Like the tonalitic orthogneiss samples from the northern Snake Range, this intrusion exhibits minimal negative Eu/Eu* anomaly. Pole Canyon pluton sample SS4 is noted as having the highest concentration of highly mobile elements K, Rb, and Cs, and is uniformly depleted in rare earth elements in comparison with sample SS1.

The Lexington Canyon pluton sample (SS1) has a Sr-Nd isotopic composition that is considerably more evolved (i.e., higher $^{87}Sr/^{86}Sr_i$ and more negative εNd_t) than the 8-10 m.y. older tonalitic orthogneiss samples (Fig. 15). The mean $\varepsilon Hf_{initial}$ result (-14.7 ± 6.8) overlaps model εHf results (-14.2 to -14.9) calculated from the whole rock Sm-Nd data (Vervoort et al., 1999).

Without new age data, Sr-Nd calculations for sample SS4 were made with an 80 Ma Rb-Sr age (Lee et al., 1986b) used by Wright and Wooden (1991). Alternatively, in a theoretical age range of 95-70 Ma (the age range of muscovite-bearing Cretaceous granites in the study), the isotopic results vary over relatively restricted ranges of $^{87}Sr/^{86}Sr_i$=0.7140 to 0.7154 and $\varepsilon Nd_{(t)}$= -15.6 to -15.8. In comparison to other Cretaceous samples from this study, the εNd result is most similar to sample NS3A, whereas the $^{87}Sr/^{86}Sr_i$ result is in an intermediate range between NS3A and NS3B (Fig. 15).

Tungstonia Pluton

Chondrite normalized spider diagrams of the samples from the Tungstonia pluton show strongly negative anomalies for concentrations of Ti and Nb, and slightly negative anomalies for

Sr, Zr, and Eu. Sample K6 is enriched in REE's La to Eu and depleted in REE's Gd to Lu relative to sample TUNG.

Whole rock isotope geochemistry results are nearly identical for each of the Tungstonia samples (Fig. 15). They are the most evolved in Sr, Nd and $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios of all the samples in the study (Fig. 15c). The whole rock $\varepsilon Nd_{(t)}$ value for sample TUNG equates to a model $\varepsilon Nd_{(t)}$ value of -21.4 to -22.2 (Vervoort et al., 1999), within uncertainty of the mean $\varepsilon Hf_{initial}$ value of -20.8±1.8 obtained from LASS analyses of zircon.

REFERENCES

Beard, J.S., Sorensen, S.S., Gieré, R., 2006, REE zoning in allanite related to changing partition coefficients during crystallization: implications for REE behavior in an epidote–bearing tonalite. Mineralogical Magazine, v. 70, p. 419–436.

Cherniak, D.J., Lanford, W.A., and Ryerson, F.J., 1991, Lead diffusion in apatite and zircon using ion implantation and Rutherford Backscattering techniques. Geochimica et Cosmochimica Acta, v. 55, p. 1663-1673.

Claiborne, L.L., Miller, C.F., and Wooden, J.L., 2010, Trace element composition of igneous zircon: A thermal and compositional record of the accumulation and evolution of a large silicic batholith, Spirit Mountain, Nevada: Contributions to Mineralogy and Petrology, v. 160, p. 511–531, doi:10.1007/s00410-010-0491-5.

Cooper, F.J., Platt J.R., Anczkiewicz R., and Whitehouse M.J., 2010, Footwall dip of a core complex detachment fault: Thermobarometric constraints from the northern Snake Range (Basin and Range, USA). Journal of Metamorphic Geology v. 28, p. 997-1020.

Ireland, T.R. and Williams, I.S., 2003, Considerations in zircon geochronology by SIMS. Reviews of Mineralogy and Geochemistry, v. 53, p. 215-241.

Lee, D.E., and Christiansen, E.H., 1983, The granite problem as exposed in the southern Snake Range, Nevada: Contributions to Mineralogy and Petrology, v. 83, p. 99–116.

Lee, D. E., and Fischer, L. B., 1985, Cretaceous metamorphism in the northern Snake Range, Nevada: A metamorphic core complex: Isochron/West, v. 42, p. 3–7.

Lee, D.E., Stacey, J.S.D., and Fisher, L., 1986a. Muscovite-phenocrystic two-mica granites of northeast Nevada are Late Cretaceous in age, *in* Shorter contributions to isotope research. U.S. Geological Survey Bulletin 1622, p. 31-39.

Lee, D. E., Kistler, R. W., and Robinson, A. C., 1986b, The strontium isotope composition of granitoid rocks of the southern Snake Range: U. S. Geological Survey Bulletin 1622, p. 171-179.

Lee, J., Miller, E.L., Gans, P.B., Huggins, C.C., 1999, Geologic map of the Mount Moriah quadrangle, Nevada. Field Studies Map FS-19, Nevada Bureau of Mines and Geology.

McLaren, A.C., Fitz Gerald, J.D., and Williams, I.S., 1994, The microstructure of zircon and its influence on the age determination from Pb/U isotopic ratios measured by ion microprobe. Geochimica et Cosmochimica Acta, v. 58, p. 993-1005.

Miller, E. L., and Gans, P. B., 1989, Cretaceous crustal structure and metamorphism in the hinterland of the Sevier thrust belt, western U.S. Cordillera: Geology, v. 17, p. 59–62.

Miller, E. L., Gans, P. B., Wright, J. E., and Sutter, J. F., 1988, Metamorphic history of east central Basin and Range Province, in Ernst, W. G., ed., Metamorphism and crustal evolution of the western United States: Englewood Cliffs, New Jersey, Prentice-Hall, Rubey Volume VII, p. 649–682.

Miller, E.L., Dumitru, T.A., Brown, R.W., and Gans, P.B., 1999, Rapid Miocene slip on the Snake Range–Deep Creek Range fault system, east-central Nevada: Geological Society of America Bulletin, v. 111, p. 886–905.

Patiño-Douce, A.E., Humphreys E.D., Johnston A.D., 1990, Anatexis and metamorphism in tectonically thickened continental crust exemplified by the Sevier hinterland, western North America: Earth and Planetary Science Letters, v. 97, p. 290–315.

Peterman, E.M., Reddy, S.M., et al., 2016, Nanogeochronology of discordant zircon measured by atom probe microscopy of Pb-enriched dislocation loops. Science Advances, v. 2, DOI: 10.1126/sciadv.1601318

Valley, J.W., 2003, Oxygen Isotopes in Zircon: Reviews in Mineralogy and Geochemistry, v. 53, p. 343-385.

Vervoort, J.D., Patchett, P.J., Blichert-Toft, J., and Albarede, F., 1999, Relationships between Lu-Hf and Sm-Nd isotopic systems in the global sedimentary system: Earth and Planetary Science Letters, v. 168, p. 79–99.

Wang, X.L., Coble, M.A., Valley, J.A., Shu, X.J., Kitajima, K., Spicuzza, M.J., and Sun, T., 2014, Influence of radiation damage on Late Jurassic zircon from southern China: Evidence from in situ measurements of oxygen isotopes, laser Raman, U–Pb ages, and trace elements. Chemical Geology, v. 389, p. 122-136.

Wright J.E., Wooden J.L., 1991, New Sr, Nd, and Pb isotopic data from plutons in the northern Great Basin: Implications for crustal structure and granite petrogenesis in the hinterland of the Sevier thrust belt: Geology, v. 19, p. 457-460.