# PROCEEDINGS OF THE TWENTY-SIXTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2013
Pomona College, Claremont, CA


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# KECK GEOLOGY CONSORTIUM
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# GEOCHRONOLOGY AND STRAIN ANALYSIS OF THE JURASSIC PLUTONIC COMPLEX ON THE SOUTHERN FLANK OF THE ORTHERN SNAKE RANGE, NEVADA

**EVAN MONROE,** University of California, Santa Barbara
**Research Advisors:** Phillip Gans, Martin Wong

## INTRODUCTION

The southern flank of the northern Snake Range is underlain by Jurassic plutonic rocks that have a complex history of metamorphism and deformation. Two distinct intrusions are present: the Old Mans Canyon pluton to the east and the Silver Creek pluton to the west (Fig. 1). The plutons were emplaced into a Paleozoic miogeoclinal sedimentary sequence of quartzite, carbonate, and shale. Numerous screens and pendants of metamorphosed host rock are present throughout the plutonic complex. Both plutons lie in the footwall of the NSRD and are highly strained and metamorphosed. Published quadrangle maps by (Miller, et al., 1999) of The Cove and Old Mans Canyon illustrate the geometry of the Jurassic plutonic complex and surrounding geology. Limited U-Pb zircon dating reported by (Miller, et al., 1988) suggests that both the Silver Creek and Old Mans Canyon plutons are approximately 160 m.y. old. Subsequent TIMS U-Pb dating of multile sized zircon fractions by (J.E. Wright, unpub. data) and referenced in (Miller et al., 1999) concluded both plutons were emplaced 155±5 Ma. New U-Pb zircon dates from this study broadly support this assignment but indicate that the Silver Creek pluton is distinctly younger than the Old Mans Canyon pluton. New structural data from the plutons as well as quartzite host rock and pendants shed new light on the geometry and conditions of strain.

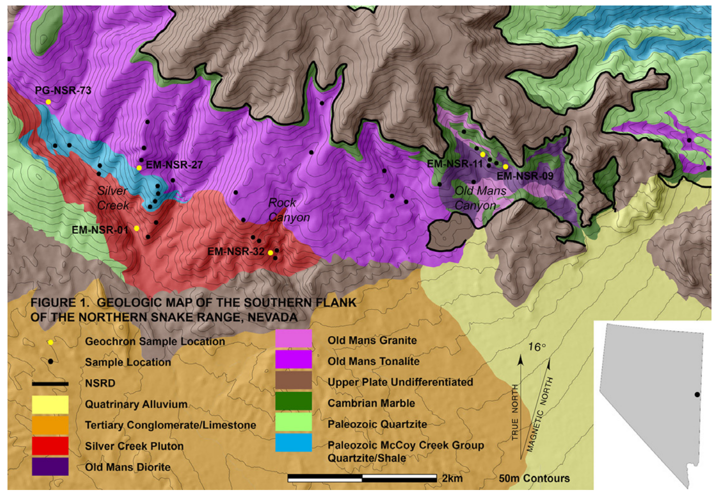

FIGURE 1. GEOLOGIC MAP OF THE SOUTHERN FLANK OF THE NORTHERN SNAKE RANGE, NEVADA

## CHRONOLOGY OF INTRUSIVE ACTIVITY

### Methods

Seven samples were collected from different phases of the Old Mans and Silver Creek composite plutonic complex as well as two younger dikes and were dated by LA-ICP-MS U-Pb zircon geochronology. Sample preparation employed standard mineral separation techniques (crushing, magnetic and density separations) to produce zircon separate from which 50-100 zircons were picked, mounted, polished, and imaged using the cathodoluminescence detector on an FEI Quanta 400F field emission source SEM. U-Pb isotopes in the zircons were analyzed using UCSB's Nu Instruments High Resolution Multi-Collector Laser Ablation Inductively Coupled Plasma Mass Spectrometer (HR-MC-LA-IPC-MS). The 193 nm excimer laser with a HelEx cell has a 10-50 micron spatial resolution, which allows cores and rims of zircons to be analyzed independently. The isotope data was processed using Isoplot, a geochronology software program that runs in Excel.

## Old Mans Canyon Pluton

The Old Mans Canyon pluton is a compositionally diverse suite of rocks that generally grades westward over ~10 km from hornblende-bearing diorite to biotite and muscovite bearing granite. The majority of the pluton is composed of tonalite, which is generally coarse grained and consists of 40 to 50% plagioclase, 20 to 30% quartz, 20 to 30% biotite and 0 to 10% potassium feldspar. Accessory minerals include epidote, sphene, allanite, and lesser apatite and zircon (Miller and Gans et al., 1999). Hornblende-bearing diorite is present on the eastern margin of the pluton (Fig. 1). It grades continuously into the tonalite in some outcrops but also occurs as mafic enclaves. Smaller bodies of granite as well as pegmatite and aplite dikes also are present on the eastern margin of the pluton and near the contact of the Silver Creek granite.

Three new LA-ICP-MS U-Pb zircon dates indicate an emplacement age of ~159 to ~160 Ma for the entire compositional spectrum. EM-NSR-27 is a very coarse grained granitic phase of the Old Mans Canyon pluton located near Silver Creek and yielded an age of 160.31±0.82 Ma (Fig. 2). EM-NSR-09 is a mafic phase of the pluton in Old Mans Canyon. It contains ~3 cm plagioclase laths in a very fine-grained matrix of hornblende and biotite and yielded an age of 159.19±0.97 Ma (Fig. 2). EM-NSR-11 is a medium to coarse-grained hornblende diorite from Old Mans Canyon that grades continuously with the Old Mans tonalite over ~5 meters. It is dated at 159.08±0.49 Ma (Fig. 2). All three of these dates are within analytical error of each other, suggesting that the pluton was emplaced relatively rapidly between ~160 and ~159 Ma. Several other granitoid plutons of similar age are present in the Strawberry-Weaver Creek, Willard Creek, and Snake-Willaims Creek areas of the southern Snake Range (Lee and Christiansen, 1983).

## Silver Creek Pluton

The Silver Creek pluton (Jscg) is smaller and more homogeneous than the Old Mans Canyon pluton. It is a medium-grained biotite and muscovite bearing granite with equant potassium feldspar phenocrysts 0.5 to 1.5 cm in diameter. The average modal composition is 40% quartz, 40% feldspar, 10-15% biotite, and 5-10% muscovite. It borders the southwest margin of the Old Mans Canyon pluton and clearly cuts it (Fig. 1).

Two new LA-ICP-MS U-Pb zircon dates indicate that emplacement occurred between ~154 and ~152 Ma. EM-NSR-01 was collected from the main phase Silver Creek granite exposed in lower Silver Creek and yielded an age of 153.84±0.61 Ma (Fig. 2). PG-NSR-11 was collected from Rock Canyon and is dated at 151.76±0.47 Ma (Fig. 2). These two ages are nearly within analytical error of each other but distinctly younger than the ages obtained from the Old Mans Canyon pluton.

## Younger Intrusions

Both the Silver Creek and Old Mans Canyon plutons are intruded by numerous dikes. Most are irregular leucogranite (aplites and pegmatites) that appear to be late-stage differentiates associated with and concentrated along the margins of the Silver Creek granite. In addition, several compositionally and textually distinct rhyolite and granodiorite dikes cut both the main phase and leucogranite phases of the Silver Creek pluton. Two of these were targeted for dating.

EM-NSR-32 is a ~40cm thick granodiorite dike exposed in Rock Canyon (Fig. 1). It contains fine-grained quartz, feldspar, biotite and muscovite. The contacts are sharp but irregular and strike approximately 225° and dip 60° NW. It has a penetrative fabric and was at least partially involved in the mylonitization. U-Pb zircon dating indicates that it was emplaced 34.61±0.42 Ma (Fig. 2).

PG-NSR-73 is a sample of one of several fine grained rhyolite dikes exposed in Silver Creek (Fig. 1). The contacts strike ~047° and dip ~65° SE. It has no mylonitic foliation or lineation and clearly cuts the fabric of the country rock. U-Pb zircon dating indicates that it was emplaced 22.98±0.08 Ma, thus providing a firm lower bracket on mylonitization.

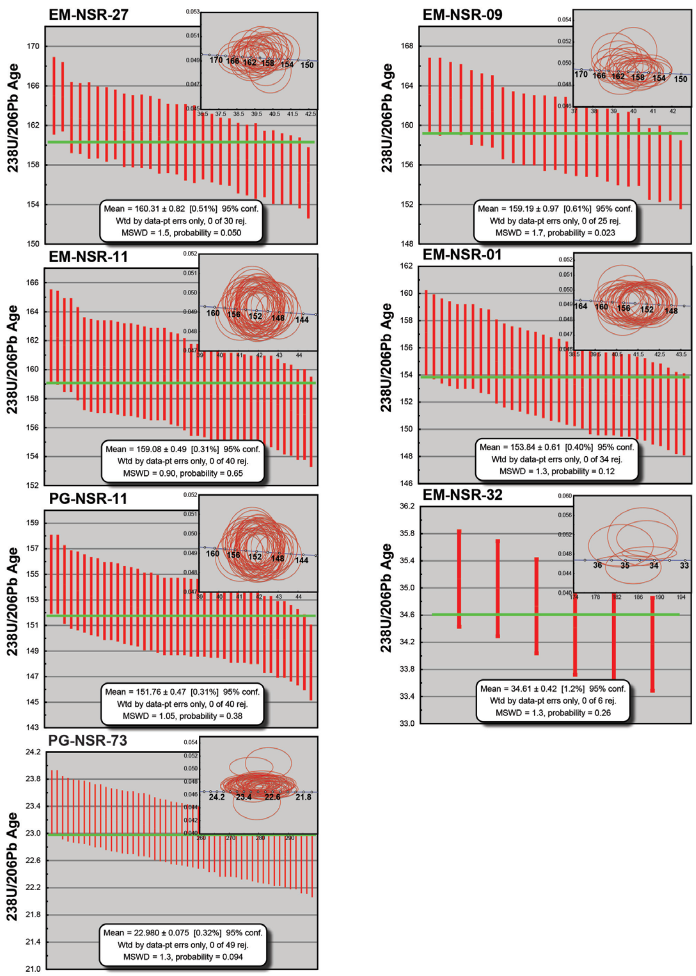


*Figure 2. Mean 238U/206Pb ages with 2σ error bars and Tera–Wasserburg concordia graphs (x-axis: 207Pb/206Pb, y-axis: 238U/206Pb).*

## DEFORMATIONAL HISTORY

### Geometry of Strain

The Old Mans Canyon and Silver Creek plutons both have a tectonite fabric that appears to be strongly constrictional. A well-defined lineation trends ESE, but foliations are only weakly developed and generally subhorizontal. This contrasts the mylonitic fabric to the north, which tends to be closer to plane strain.

The attitudes of foliations are variable with no significant spatial patterns. Lineation trends are far more consistent on a local scale but show a systematic rotation from east to west. The average trend and plunge changes from 105°, 10° SE in Old Mans Canyon to 119, 09° SE in Rock Canyon to 315°, 11° NW in Silver Creek (Fig. 3).

Strain is extremely heterogeneous within the plutonic complex. Some outcrops have very strong (ultramylonitic) fabrics while others have well-preserved igneous textures with little or no deformation at all (Fig. 4a/b). High strain shear zones vary considerably in size, ranging from centimeters to hundreds of meters wide. Although strain is variable on a local scale, generally it is highest in the east.

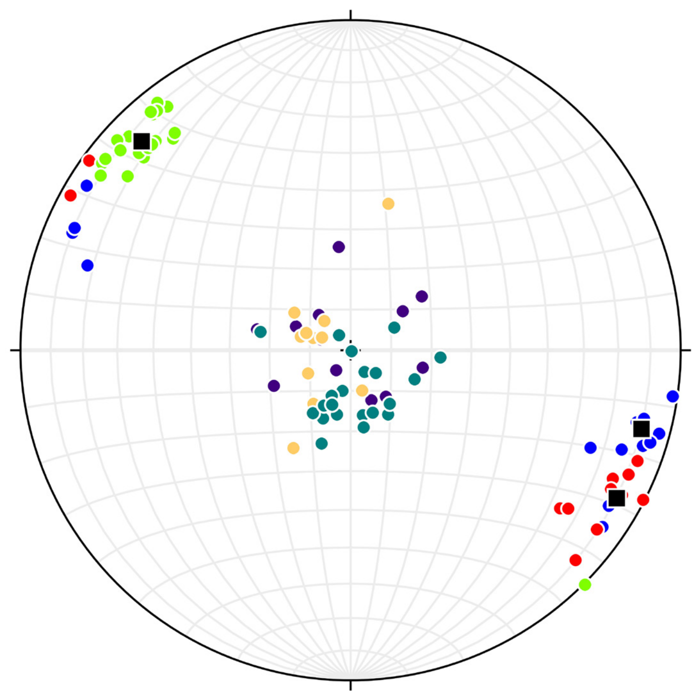

*Figure 3. Lower hemisphere equal area stereonet projection of foliations and lineations in the plutonic complex. Purple: Poles to foliation in Old Mans Canyon, Yellow: Poles to foliation in Rock Canyon, Teal: Poles to foliation in Silver Creek, Blue: Lineations in Old Mans Canyon, Red: Lineations in Rock Canyon, Green: Lineations in Silver Creek, Black boxes: Mean lineations from each area.*

### Fabrics and Microstructures

Abundant microstructures and fabrics are visible in hand sample and thin section and provide key information about the sense of shear and conditions of deformation. Kinematic indicators consistently indicate a component of top-to-SE simple shear. Well-developed sigma clasts of feldspar and mica are present in both plutonic and quartzite samples. Although some samples do not indicate a definite shear sense, ~75% clearly indicate top-to-SE shear. Type I S-C fabrics are ubiquitous in the plutonic rocks, with a sigmoidal S-foliation defined by elongate quartz ribbons and aligned mica between planar C-surfaces, defined by comminuted seams of mica. Quartize samples have a type-II S-C fabric in which the S-foliation is defined by mica “fish” and grain shape foliation in quartz. The S-surfaces are interpreted as being oblique to the shear zone boundary and the C-surfaces are parallel to it. In both the plutonic rocks and quartzites, the S-C fabrics consistently indicate top-to-SE shear.

Other microstructures provide information about temperatures of deformation. Synkinematic biotite growth (generally as pressure shadows on feldspar porphyroclasts) and dynamic recrystallization of feldspar is prevalent in all the plutonic rock samples (Fig. 4d). The dominant recrystallization mechanisms of quartz in both the plutonic rocks and quartzites on the southern flank of the range are subgrain rotation (SGR) and grain boundary migration (GBM). SGR recrystallization occurs when dislocations are continuously added to subgrain boundaries. This progressively increases the angle between the crystal lattice on either side of the grain boundary until the subgrain cannot be classified as part of the same grain. Core and mantle structures form at low temperature and low strain but generally the new grains occur in sheets between elongate ribbon-shaped relict grains. In some cases, all of the old grains may be entirely replaced by subgrains (Fig. 4). At higher temperatures grain boundaries become so mobile that they can rapidly sweep through entire crystals to remove dislocations. This recrystallization mechanism (GBM) is characterized by lobate and irregular grain boundaries and a highly variable grain size. There is extensive evidence for both SGR and GBM recrystallization in all of the samples collected. In many samples both recrystallizaton mechanisms appear to have operated simultaneously.

## EBSD Data

Analysis of crystallographic preferred orientation of quartz provides important information on the strain history of a rock. Three different quartzite samples were analyzed using UCSB’s FEI Quanta 400F field emission source (FEG) scanning electron microscope with an HKL Technology Nordlys 2 electron-backscatter diffraction (EBSD) camera for crystal

a) b) c) d)

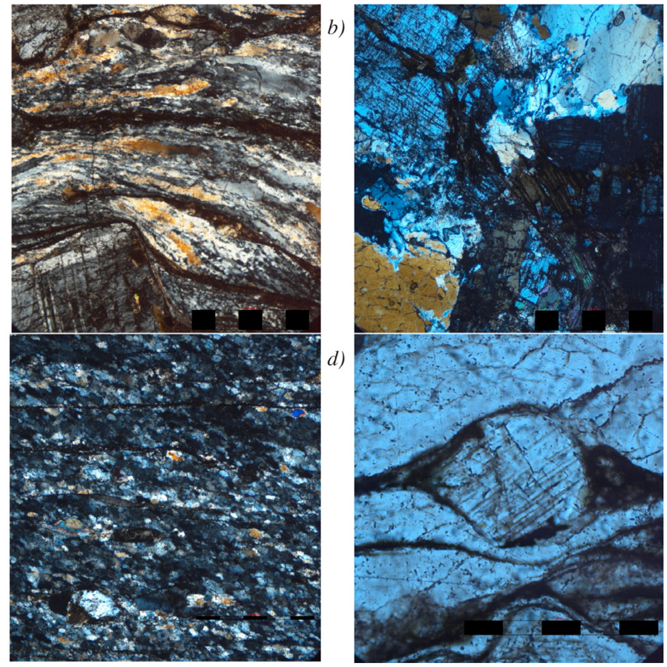

*Figure 4. a) EM-NSR-19: Highly strained Jomt in Old Mans Canyon. XPL, 5x (scale bar=1000μm) b) EM-NSR-27: Very coarse grained Jscg in Silver Creek that has little to no strain. XPL, 5x (scale bar=1000μm) c) EM-NSR-20: Pervasive subgrains with a weak shape preferred orientation indicates recrystallization by subgrain rotation. ~1 meter thick pendant in Jom in Old Mans Canyon. XPL, 5x (scale bar=1000μm) d) EM-NSR-21: Synkinematic biotite growth in pressure shadows of a plagioclase porphyroclast. PPL, 10x (scale bar=400μm)*

orientation determination. The data was plotted and contoured on stereonets for interpretation (Fig. 5).

Sample EM-NSR-36 is from a quartzite raft in the Silver Creek pluton exposed in Rock Canyon. The CPO pattern is a type II crossed girdle (Fig. 5). This indicates that basal <a>, prism <a>, and rhomb <a> slip systems were all active during deformation but rhomb <a> was dominant. It also indicates that strain was constrictional (Schmid, 1986). Sample EM-NSR-20 is of a ~1m thick quartzite raft in the Old Mans Canyon pluton exposed in Old Mans Canyon. It displays a y-axis maxima CPO pattern, which indicates that prism <a> and rhomb <a> slip systems were dominant. Sample EM-NSR-04 is the quartzite host rock to the Silver Creek granite exposed in Silver Creek. It also has a y-axis maxima but is poorly defined because there weren’t as many data points as the two other samples. All three of these CPO patterns have monoclinic symmetry, which indicates that there was a non-coaxial component of deformation. The sense of asymmetry indicates top-to-SE shear.

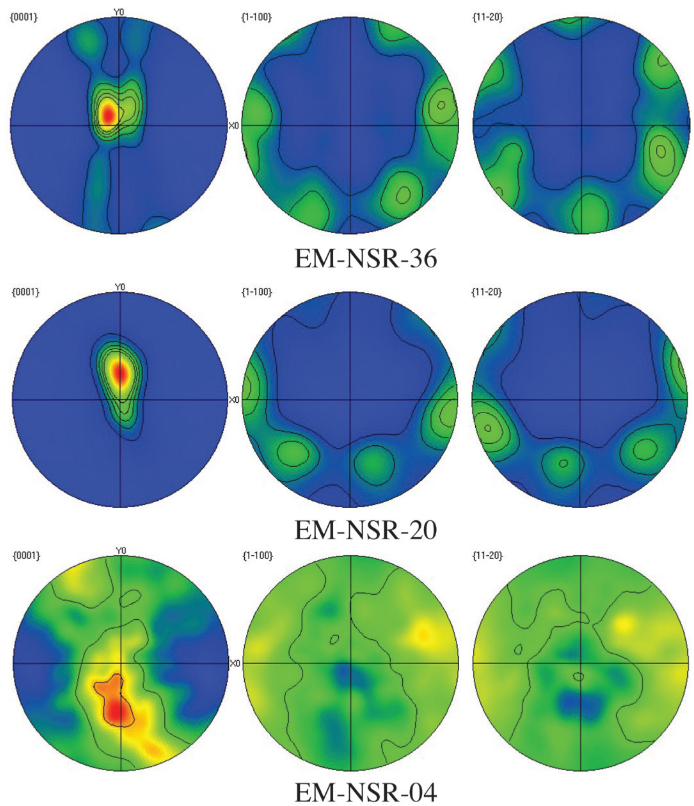


*Figure 5. Lower hemisphere equal area stereonet projections of crystallographic preferred orientations of quartz.*

## DISCUSSION

Analysis of field relations, hand samples, thin sections, EBSD data, and geochronology data provide key constraints on the conditions and timing of deformation as well as other important aspects of the local geology.

### Temperature of Deformation

Several different microstructures suggest that deformation occurred at upper greenschist facies (450-550°C). Perhaps the most convincing temperature proxy is the widespread synkinematic growth of biotite and dynamic recrystallization of feldspar, which is present in many of the samples. This can only occur if temperatures are at upper greenschist facies or higher.

The recovery mechanisms that were active during deformation also suggest that temperatures were between 450-550°C, or regime II or III of Hirth and Tullis (1992). In regime II, the rate of dislocation climb becomes rapid enough to accommodate recovery and dynamic recrystallization occurs by subgrain rotation. In regime III, grain boundary mobility increases to an extent that grain boundaries can sweep through entire crystals to remove dislocations and subgrain boundaries (Hirth and Tullis, 1992). The relative rate of grain boundary mobility and dislocation production determines the type of recovery mechanism that will operate. Assuming reasonable geologic strain rates and minimal influence of water, SGR recrystallization occurs at temperatures of 400-500°C and GBM recrystallization occurs above 500°C (Stipp, 2002).

The slip systems that accommodated deformation as revealed through EBSD analysis also provide temperature constraints (Mainprice, 1986). The activity of slip systems depends on temperature and strain rate; increasing temperature and decreasing strain rate increase the number of active slip planes. Assuming geologically reasonable strain rates, the type-II cross girdle from sample EM-NSR-36 suggests that deformation occurred at temperatures around 450-500°C, while the y-axis maxima CPO pattern of sample EM-NSR-20 and EM-NSR-04 suggest somewhat higher temperature. As EM-NSR-36 has the lowest temperature CPO pattern and is also furthest west, it is possible that the temperature during deformation increased eastward.

### Strain Localization

The heterogeneity of strain within the plutonic complex indicates that some processes was actively localizing strain during deformation. Compositional variations clearly played a role, as the more quartz rich rocks tend to be more deformed. Hornblende and plagioclase rich diorites are the least strained due to the resistance of these minerals to deformation. Quartzite screens in the plutons are generally the most deformed. These act as "strain sponges" and are often surrounded by relatively undeformed rock. Although this pattern generally holds, in some cases granites with high quartz contents are practically unstrained, which suggests that other factors must also have been involved in strain localization.

One possibility is hydrolytic weakening by the infiltration of water. The presence of dissolved water in the crystal lattice of quartz can significantly lower its yield stress because it reduces the activation energy for dislocation creep (Hirth, 1992). Gebelin et al., (2011) suggests that an infiltration of meteoric fluids occurred in the northern Snake Range between 27 and 23 Ma. If the circulating fluids were confined to specific areas, they could have played a part in decreasing the yield stress and localizing strain in these areas.

### Evidence for Large-Scale Rotation

The compositional structure of the Old Mans Canyon pluton suggests that it may have been tilted westward after emplacement. The primary evidence for this is that the pluton generally grades westward from hornblende diorite to granite—a compositional profile that mimics the commonly accepted vertical profile interpreted from many large compositionally zoned magma chambers.

### Timing of Deformation

The new age dates of the granodiorite dike and the rhyolite dike provide key constraints on the timing of deformation in the lower plate. The 22.98±0.08 Ma rhyolite dike is completely undeformed and therefore must have been emplaced after the formation of the mylonitic fabric. The granodiorite dike that was emplaced at 34.61±0.42 Ma has a tectonic fabric and was at least partially involved in the deformation. Therefore, mylonitic deformation must have ceased by ~23 Ma, but was still ongoing at ~35 Ma. These age constraints indicate that the rapid Miocene slip on the decollement is distinctly younger than the lower plate fabrics.

## CONCLUSIONS

a) Deformation occurred at upper greenschist facies (450-550°C).

b) Strain is extremely heterogeneous and strongly constrictional.

c) There is a possibility of westward rotation of the plutonic complex.

d) The mylonitic fabric is late Eocene to early Oligocene and unrelated to slip on the NSRD.

e) The Old Mans Canyon pluton was emplaced between ~159 to ~160 Ma.

f) The Silver Creek pluton was emplaced from ~154 to ~152 Ma.

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