CHEMICAL AND TEXTURAL ANALYSIS OF ENCLAVE TITANITE IN THE OLIGOCENE LITTLE COTTONWOOD GRANITIC STOCK TO DETERMINE CRYSTALLIZATION HISTORY, UTAH

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INTRODUCTION

Small (10 cm to 1.5 m) mafic inclusions in the granitic Oligocene Little Cottonwood (LC) Stock, Utah, could have formed in several different ways. Originally, it was thought that these were fragments ripped from the wall of the crystallizing pluton (Hanson, 1995). Alternatively, they might be residual solids leftover from the partial melting process and could represent restite fragments (White, 2001). Many dark inclusions in granitic intrusions are actually xenoliths—fragments of the wall rock that were not completely assimilated. Finally, the inclusions could have formed via mixing of a mafic and more silicic magma, making them microgranular enclaves. For the purposes of this analysis, these mafic inclusions will be referred to as LC enclaves.

Here, we use textures, whole-rock composition, and the geochemistry of titanite (Ttn, also called sphene, with a chemical formula of $CaTiSiO_5$), an accessory mineral common in granites, to evaluate the these hypotheses for the origin of the inclusions. Ttn incorporates a wide variety of trace elements and shows striking textural and zoning patterns due to temperature fluctuations, oxygen fugacity changes, magma composition, and secondary hydrothermal alteration. This makes it an invaluable source of information when determining the crystallization history of a pluton. Ttn texture, chemical composition, and geothermometry will thus be analyzed to determine whether or not these enclaves formed by magma mixing processes in the Little Cottonwood stock (Fig. 1).

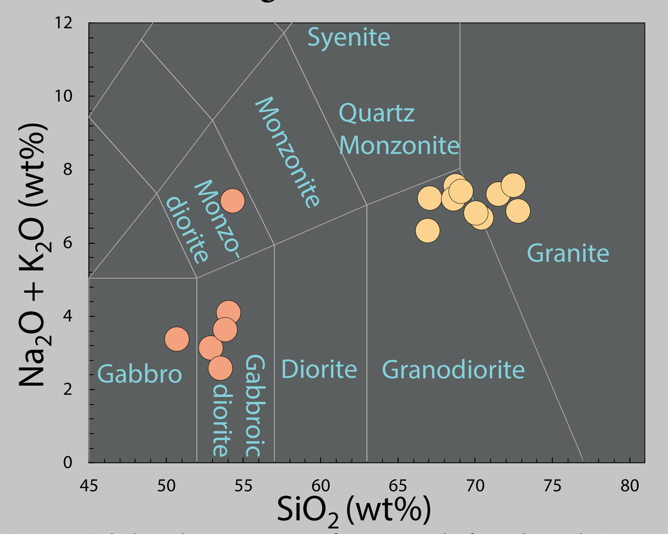

Figure 2. Whole rock compositions of granitic rocks from the Little Cottonwood Stock (yellow) and LC enclaves (orange). The LC stock ranges from granite to granodiorite, and the enclaves range from gabbro to gabbroic diorite. Collected by XRF spectrometry at Brigham Young University.

GEOLOGIC SETTING

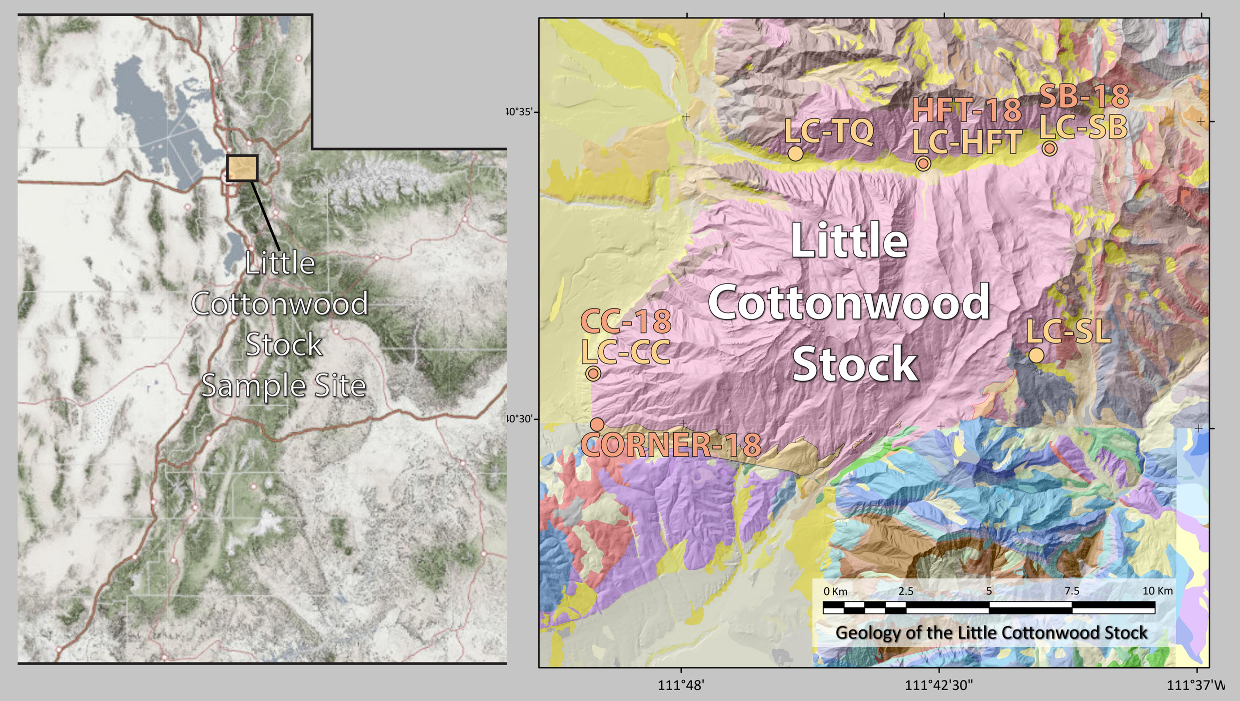

Figure 1. The Little Cottonwood Stock intrudes folded and faulted Paleozoic (and Precambrian) sedimentary rocks in the Wasatch Mountains close to Salt Lake, Utah. Sample locations are noted as yellow (LC stock) and orange (LC enclaves) dots. The LC stock is a composite granodiorite to granite intrusion that formed in the Oligocene during a middle Cenozoic episode of slab rollback. Images modified from USGS.gov (left) and Chadburn (2017) (right).

TEXTURAL ANALYSIS

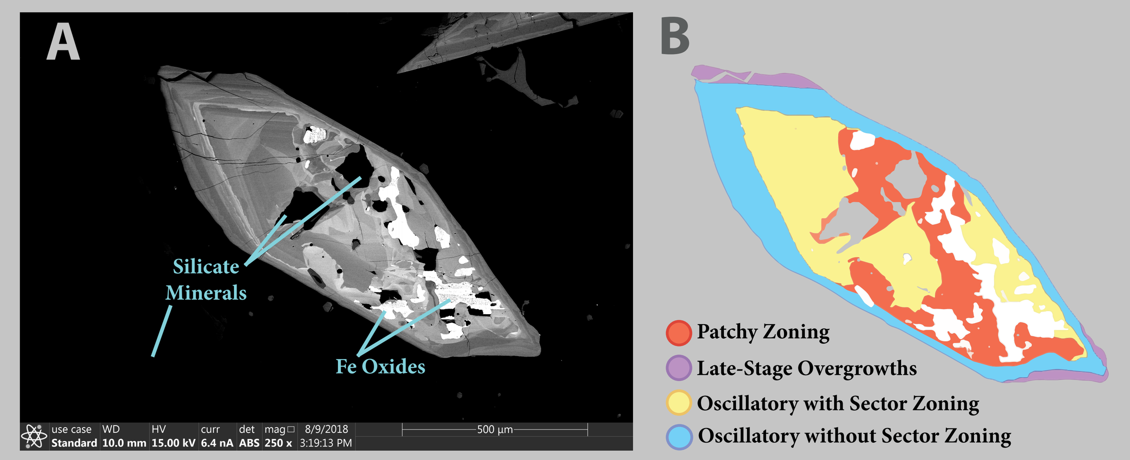

Figure 3. Different zones in a single titanite grain from an enclave in the LCS. A) BSE image of a titanite grain (shades of gray), with several Fe-Ti oxide inclusions-typically ilmenite (with exsolved rutile) and locally magnetite (white) and silicate inclusions-typically potassium feldspar, plagioclase, or quartz (black). This grain is surrounded by quartz, potassium feldspar, and plagioclase (black). Due to the 7-fold decahedral site in titanite's structure, it is a sink for REEs, U, and Zr. Higher concentrations of these heavy elements are revealed in brighter zones, as well as increased Fe levels, while darker zones tend to have higher Al and lower REE concentrations. B) Map of the zoning patterns in the titanite grain in A. Patchy zoning (red) is typically accompanied by anhedral ilmenite inclusions (white), and ranges from dark to light gray. Titanite grains in LC stock and LC enclaves typically have this zoning pattern in the middle of the grains. Other examples are in Figure 5. Late-Stage titanite (purple) includes replacement patches, late-stage rims, and their interstitial extensions. The late-stage titanite grains typically rim grains or formed along cracks and is a minor component of the grain. Secondary titanite is not common in the LC stock or in the LC enclaves. Sector zoning in titanite is accompanied by oscillatory zoning, and presents itself in the form of "fir tree" like structures in BSE images (yellow). Oscillatory zoning can occur without sector zoning (blue), and often rims or entirely composes grains. Further examples are in Figure 4.

LC STOCK TITANITE | LC ENCLAVE TITANITE

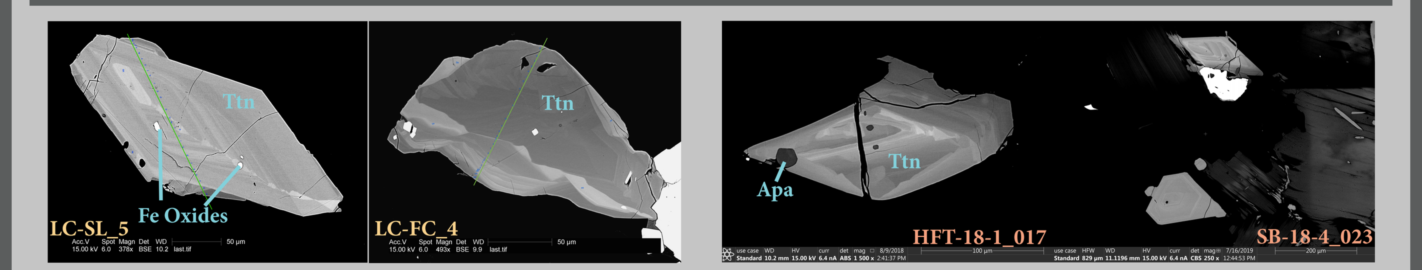

Figure 4. Inclusion-poor titanite. These grains consist almost entirely of oscillatory zoning, with or without sector zoning, or of large swathes of homogeneous titanite. This primary titanite precipitated without much chemical or thermal variation, leading it to have little to no zoning. Late-stage growths are present frequently in/on these types of grains. These titanite grains are typically euhedral. These are common in both the LC stock (left 2 images) and the LC enclaves (right 2 images).

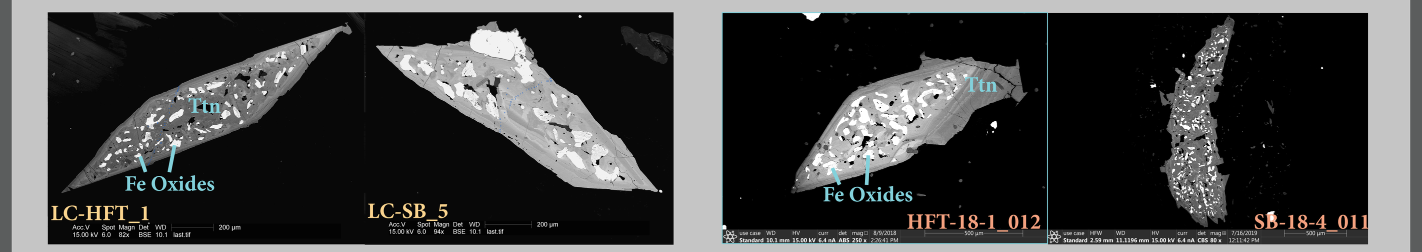

Figure 5. Inclusion-rich titanite. These grains have many amoeboidal inclusions of ilmenite most of which are exsolved to lamellar or patchy ilmenite and rutile/anatase. Magnetite (with low Ti) is present in a few grains, but is more common as large grains outside of or directly next to titanite grains. Most of the titanite surrounding the oxides has patchy zoning, and nearly all of these patchy zones are rimmed by oscillatory growths, with or without sector zoning. Titanite grains of this type are euhedral to subhedral, and very abundant in the LC enclaves (right 2 images), and less abundant in the LC stock (left 2 images).

LC ENCLAVE TITANITE

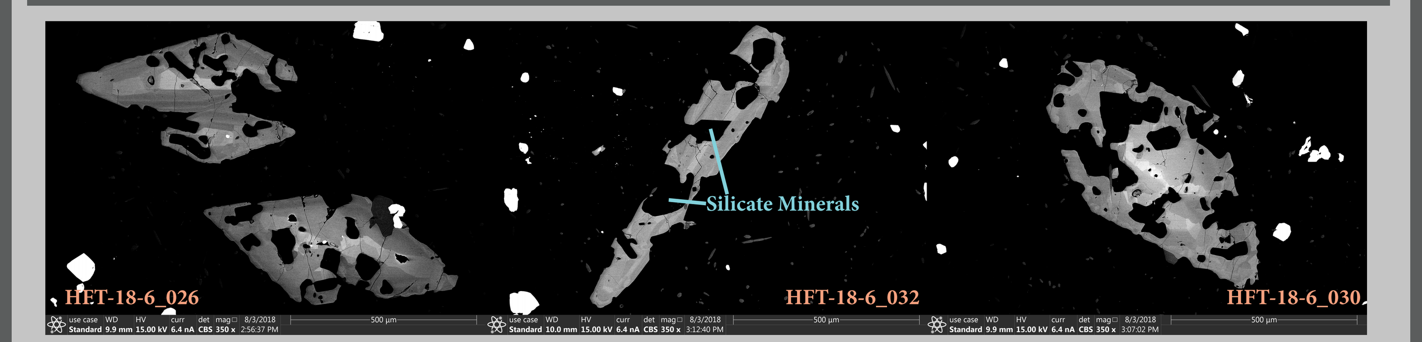

Figure 6. Poikilitic titanite. These grains occur exclusively in LC enclaves and are similar to the inclusion-poor titanite, with oscillatory and sector zoning, and some late-stage overgrowths and very few to no ilmenite inclusions, but are full of euhedral to anhedral silicate minerals such as potassium feldspar, plagioclase, and quartz (black in BSE images). The titanite grains themselves range from euhedral to subhedral, with few grains being anhedral. The textures show that the titanite crystallized late (after the principal silicates) in these mafic enclaves.

CHEMICAL TRENDS

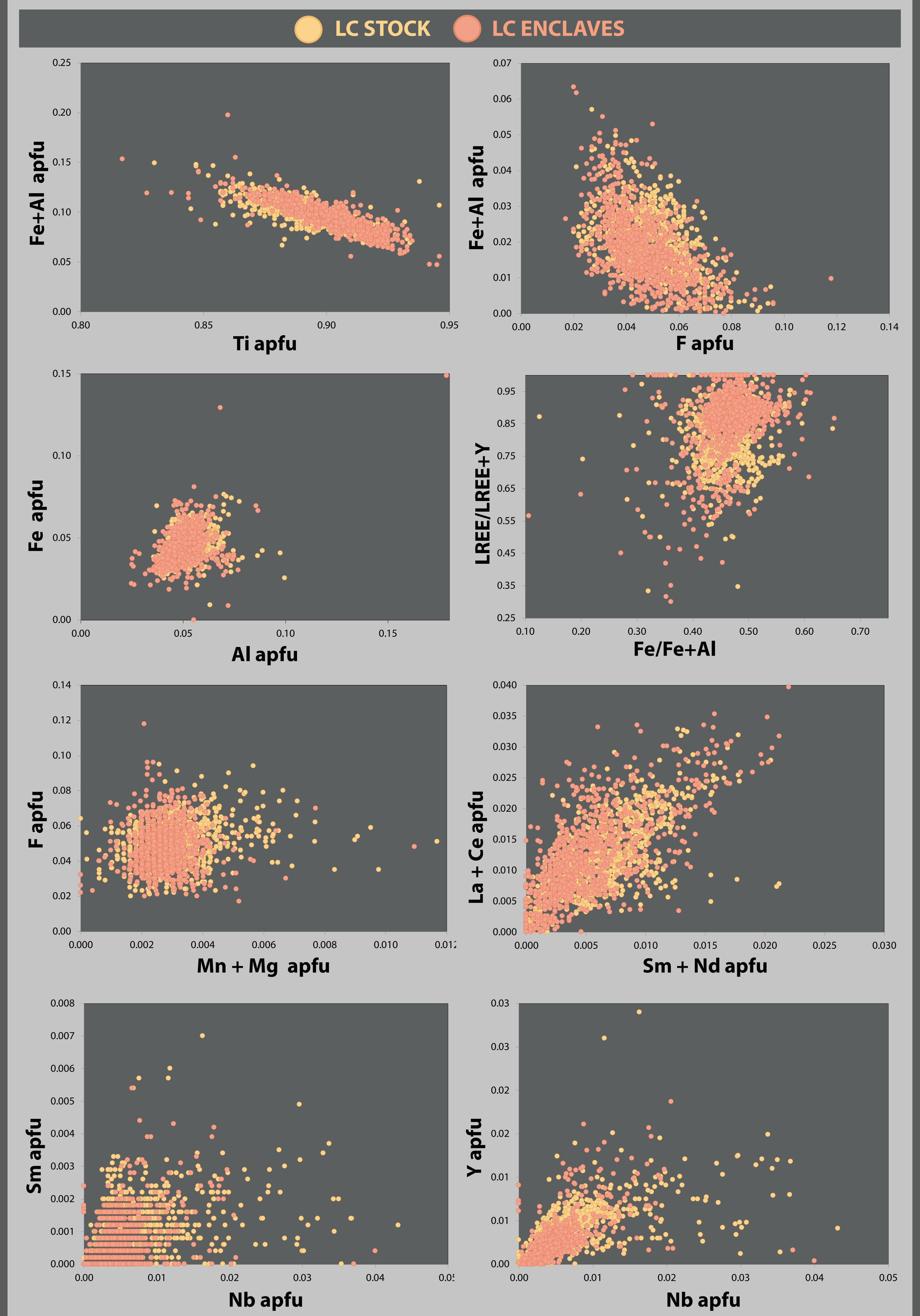

Figure 7. Elemental compositions of Little Cottonwood titanite. Titanite from the enclaves (orange) and from the main intrusion are very similar. Fe and Al tend to substitute for Ti, and F fluorine correlates with Fe and Al as a charge balancing replacement in the oxygen site. Both types of titanite have similar total REEs, similar proportions of Ti, Fe, Al, and F, and show similar trends between heavy (indicated by Y) and light REEs. Data collected via electron microprobe at Brigham Young University.

TEMPERATURE AND $\delta^{18}O$

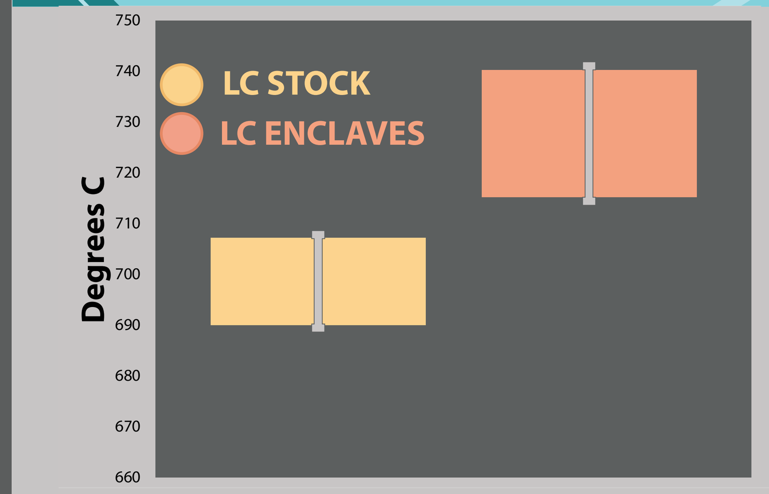

Figure 8. Zr in titanite geothermometry for titanite grains in the LC stock and LC enclaves. Average temperature for LC stock titanite was 699°C +/- 9°C (1 st. dev.); average temperature for LC enclave titanite was 727°C +/- 13°C (1 st. dev). This resulted in an average temperature difference between the LC stock and the LC enclaves of 29°C.

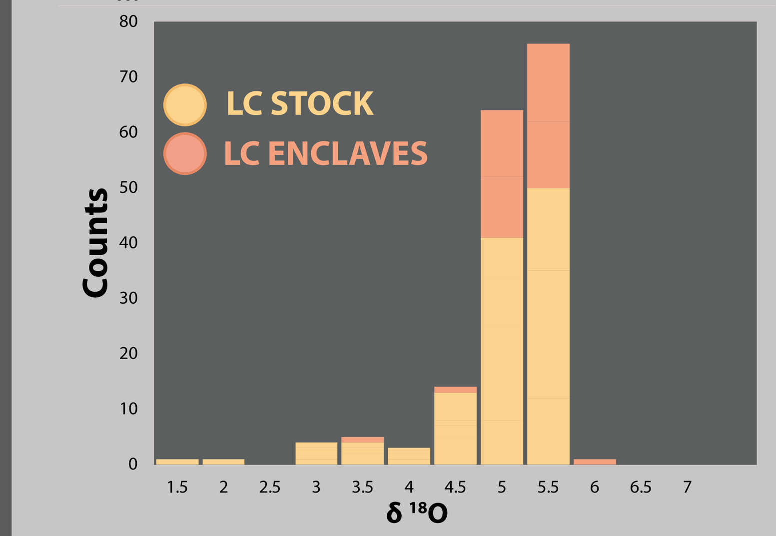

Figure 9. Oxygen isotope values for titanite grains from the Little Cottonwood stock. Average $\delta^{18}O$ for titanite in the LC stock is 5.3‰. As both the averages and the chart indicate, LC enclave grains tend to be slightly higher than LC stock, which had a wider, but lower, range of $\delta^{18}O$. Collected by secondary ion mass spectrometry at the University of Wisconsin, Madison with a spot size of 20 microns.

CONCLUSIONS

The major observations favor magma mixing as the primary origin of these mafic inclusion. Cumulate, xenolith, and restite inclusions would have significantly different chemical compositions and likely different textures, as they would have cooled under different conditions than the pluton. As this is not the case, there must then be some other method of formation. The temperature differential between LC stock and LC enclave as well as the variations in whole rock composition indicate that magma mixing between a mafic (basaltic) magma and a felsic (main Little Cottonwood) magma was likely the cause.

Based on our observations, we propose that a hotter, reduced, TiO_2-rich —and thus ilmenite-rich—mafic magma intruded and mixed into an oxidized, magnetite-bearing felsic magma. This caused ilmenite to dissolve and stabilized titanite, forming the mottled cores with abundant ilmenite amoeboids. Titanite with oscillatory growth and sector zoning then mantled these cores. Simultaneously, the enclave magma quenched against the cooler felsic magma, causing elongate apatite and poikilitic titanite grains to precipitate in the enclaves after feldspars; it is likely that disaggregation of the mafic enclaves introduced some titanite into the felsic magma before complete quenching. Titanite may also have been forming in the felsic magma body prior to and after the mixing event; these are the euhedral grains with no mottled cores.

Such analyses help decipher the crystallization history of the Little Cottonwood stock. By combining macroscale (whole rock composition) with the microscale data collected from a small accessory mineral, we can understand not only the history of the Little Cottonwood pluton, but potentially others as well.