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RIM-CORE U-PB GEOCHRONOLOGY AND HF DATING OF DETRITAL ZIRCONS FROM THE SCHIST OF SIERRA DE SALINAS, CALIFORNIA

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INTRODUCTION

The schist of Sierra de Salinas is a middle amphibolite facies metasandstone, that includes small amounts of metapelite, marble, amphibolite, and metachert (Ross, 1976; Barth et. al., 2003). The schist of Sierra de Salinas is located in the Salinian Block, often referred to as Salinia, sitting in between the San Andreas fault to the east and the Sur-Nacimiento Fault to the west (Hall, 1991). The geology of the Salinian block is part of what is known as the California triad, composed of the Franciscan complex, the Great Valley Group, and the Sierra Nevada batholith. Respectively, these assemblages comprise trench, forearc, and arc assemblages of a paleosubduction zone (Ernst et. al., 2008). Salinia contains all three parts of the triad: Franciscan; Great Valley; and granitic rocks of the arc. The metasedimentary schist of Sierra de Salinas underlies a significant portion of the Salinian block and, like the Franciscan complex, represents trench assemblages. However, the schist of Sierra de Salinas differs markedly from the Franciscan complex in terms of metamorphic grade, with the schist exhibiting amphibolite- to granulite-grade mineral assemblages in contrast to the generally sub-blueschist facies rocks of the Franciscan complex.

The granitic rocks in the Salinian block were originally believed to have intruded into the schist, but structural and geo-/thermochronologic studies indicate that the schist was unroofed along the Salinas shear zone, cooling through argon closure ~5 Myr later than adjacent granitic rocks, suggesting that metamorphism of the schist postdates intrusion (Barth et al., 2003; Kidder and Ducea, 2006). However, the precise timing of peak metamorphism in the schist is not well-constrained. Was the schist metamorphosed as Salinian plutons were being emplaced, or did schist metamorphism post-date plutonism? Addressing this question is important for understanding whether schist emplacement had the effect of terminating arc magmatism or “stoking” a pulse of magmatism prior to arc shutoff. The purpose of this work is to constrain the timing of peak metamorphism, by rim-core U-Pb dating, in the schist of Sierra de Salinas and to determine if the schist was metamorphosed during or after termination of the Salinian arc. In addition, Hf isotopic analysis was done on detrital and metamorphic grain domains to place constraints on the provenance of schist protoliths and to assess whether isotopic equilibrium was achieved during metamorphism.

Geologic background

The post-metamorphic cooling of the Santa Lucia Range (Fig. 1) constrains the age of burial and subsequent metamorphic events. The Santa Lucia Range is important because it contains the schist of Sierra de Salinas, the tectonic block has been translated northward to its current location along the San Andreas, and it is a critical piece of the tectonic puzzle in this area (Chapman, 2016). Published cooling ages of the Santa Lucia Range for K-Ar hornblende and biotite range from 75 to 78 Ma, and the fission track ages are the same or younger (Naeser and Ross, 1976). Because the biotite and hornblende closure temperature is so high, the peak metamorphism was reached at about the time of cooling of these minerals.

The schist of Sierra de Salinas is correlated with the Pelona-Orocopia-Rand Schists and restoration of ~310 km of Neogene dextral slip along the San Andreas fault system places these terranes in the same area (Barth et al., 2003; Grove et al., 2003; Jacobson et al., 2011; Chapman, 2016). Thus, this restored position suggests a comparable structural evolution of the different schist groups that formed in the same area. The Pelona-Orocopia-Rand Schists structurally underlie batholithic rocks of the Sierra Nevada-Peninsular Ranges arc. Underthrusting of the arc by this schist was driven by low-angle subduction during the Laramide Orogeny, and the general timing coincides with the extinction of arc magmatism in the Sierran Arc (Chapman, 2016). The Sierra de Salinas Schist was structurally emplaced beneath the Salinian arc (an allochthonous element of the Sierran-Peninsular Ranges arc), and therefore it would have an analogous setting to the Pelona-Orocopia-Rand Schists that were emplaced beneath southern California (Barth et al., 2003).

The schists of California are interesting because they have been dispersed by strike-slip throughout central California but their reconstructed position suggests they formed near each other. The shists formed in a critical time when the Sierra Nevada shut down and the Laramide Orogeny started (Chapman, 2016). The schist also represents a critical time and location because of the aseismic ridge that was being subducted, the Shatsky conjugate (Liu et al., 2010).

METHODS

Four samples of schist of Sierra de Salinas (SdS) were collected in the field. Samples 16SLM6 and 16SLM7 were collected from the northern Sierra de Salinas, within a few hundred meters of the Salinas shear zone. Sample 16SLM9 is a low-grade sample collected along the east-central edge of the Sierra de Salinas. Sample 16SLM11 was collected along the western flank of the Sierra de Salinas.

Following fieldwork, mineral separation was done at Macalester College in St. Paul, MN, using standard mineral separation techniques of crushing, sieving, magnetic separation, processing through heavy liquids, and hand picking. Mounts were made with the

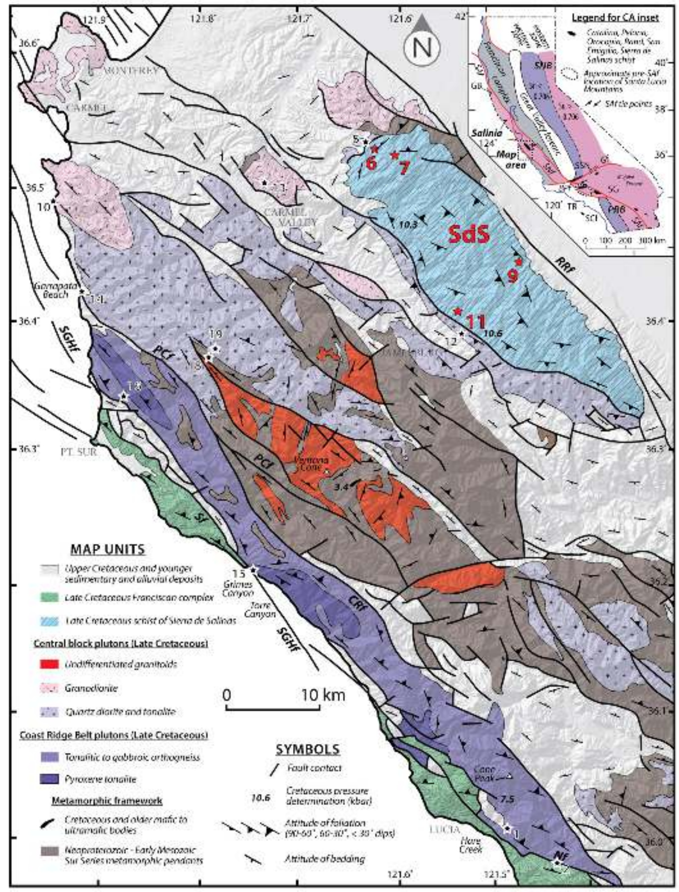

Figure 1. Sample locations of schist of Sierra de Salinas (red stars) in the Salinian Blocka

samples, imaged on the SEM at Macalester, and then members of the Keck group did U-Pb dating of the schist (and other samples) at the University of Arizona LaserChron Center.

Rim-Core Dating

A double-dating experiment was performed on sample 16SLM-11G. Seventy zircons were handpicked from this sample, lined up onto a mount, polished, imaged for BSE, CL, and for some grains color CL using a Zeiss EVO MA15 and a Horiba Clue CL imaging system at Union College. The zircons were mounted in a grid, and one axis is labeled with a letter and the other by a number, so each grain has a unique address. The imaged puck, with targeted grains, was then analyzed at the University of Arizona Laserchron Center (ALC). Both rim and core measurements were done with 12 µm laser (as opposed to 20 µm). On the mount, a careful selection was made of those candidate zircons that had clearly different cores and rims, and from this 32 grains were selected.

Hafnium

Sample mounts were carbon coated and re-analyzed on the Zeiss Scanning Electron Microscope (SEM). BSE and CL images were taken of the grains and clear digital maps were made of U-Pb dated grains using Adobe Illustrator. Forty grains from sample 16SLM6 was chosen for Hf analysis because it had the best distribution of different U-Pb age populations. Chosen to acquire Hf data were 5 grains younger than 81 Ma, 5 grains from 85-95 Ma, 6 grains from 140-155 Ma, 2 grains from 1000-1200 Ma, 5 grains from 1350-1450 Ma, and 5 grains from 1625-1800 Ma. The sample was re-imaged on the SEM so that we had high-quality images of the dated grains with holes. The sample numbers were also re-mapped, because very clear maps are necessary for Hf. Then, at the University of Arizona, the mount was loaded, calibrated, standardized, and analyzed, using the Nu Plasma multicollector-inductively coupled plasma-mass spectrometer.

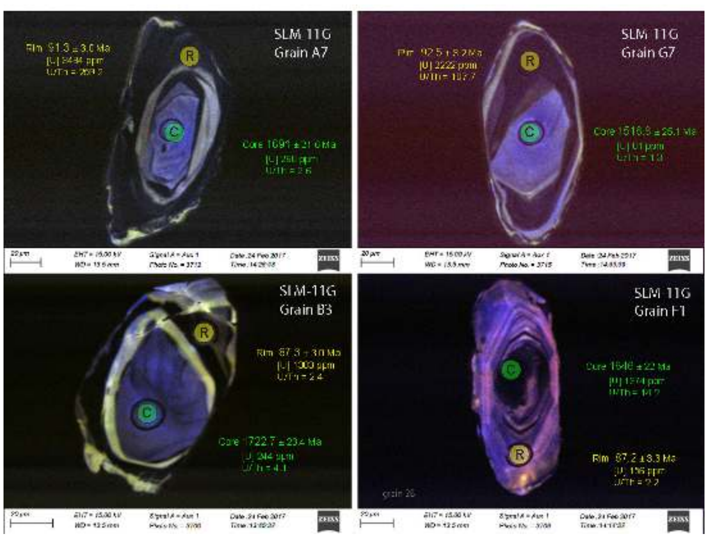

Figure 2. Double-dated grains from 16SLM11G: B3, F1, G7, and A7, showing zircons with Cretaceous rims on Precambrian cores.

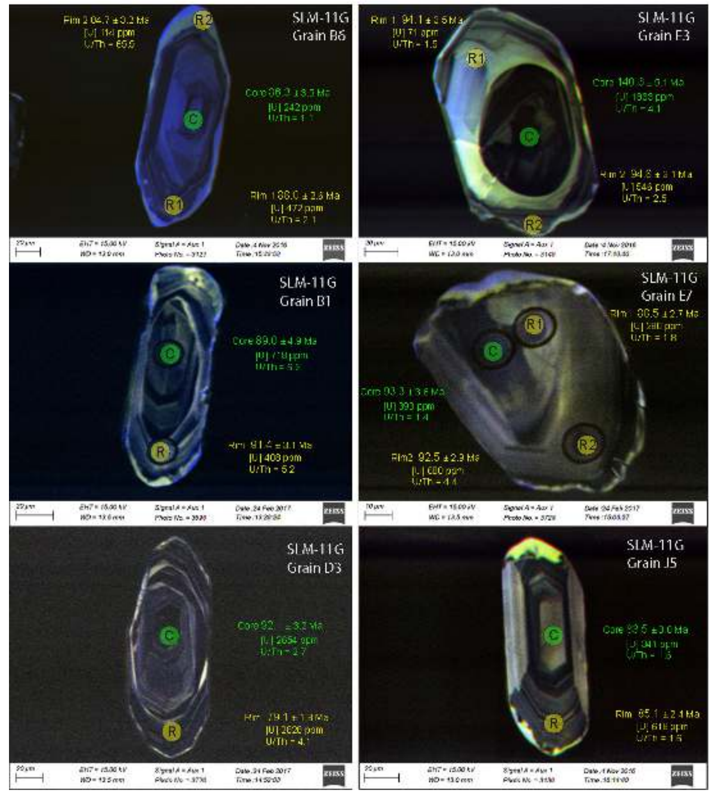

Figure 3. Double-dated grains from sample 16SLM11-G showing Cretaceous rims on Cretaceous cores

RESULTS

Rim-Core Dates

Rim-core U-Pb dating was done on two SdS samples, which revealed three distinct categories: 1) four grains with Cretaceous rims (87-93 Ma) and Proterozoic cores (~1300 to 1700 Ma) (Fig. 2); 2) nineteen grains with Cretaceous rims (79-100 Ma) and cores (84-140 Ma) (Fig. 3); 3.) two grains made up of Precambrian rims (1400-1696 Ma) with Precambrian cores (1365-1649 Ma).

Hafnium

The data from Lu-Hf isotopes have been divided into six categories, and can be seen in Figure 4. The results show: [1] There is a distinct age population from 77-80 Ma, these are the youngest dated grains from the sample. Within this population, 6 of 7 grains have εHf values between -7.3 to -33.3 with an average of -8.4; [2] Grains between 85-107 Ma have εHf values of -6 to +10, but the average is 0.7; [3] Grains that have Late Jurassic and Early Cretaceous ages of 142-154 Ma, have εHf values of +2.6 to +12.5, with an average of +7.3; [4] Three grains are between 1043 and 1071 Ma, with εHf values between -5.7 and +4.9, with an average of 0.2; [5] Grains that fall between 1350-1484 Ma, most being around 1365 Ma, have εHf numbers are all positive, ranging from +0.3 to +9.4, and an

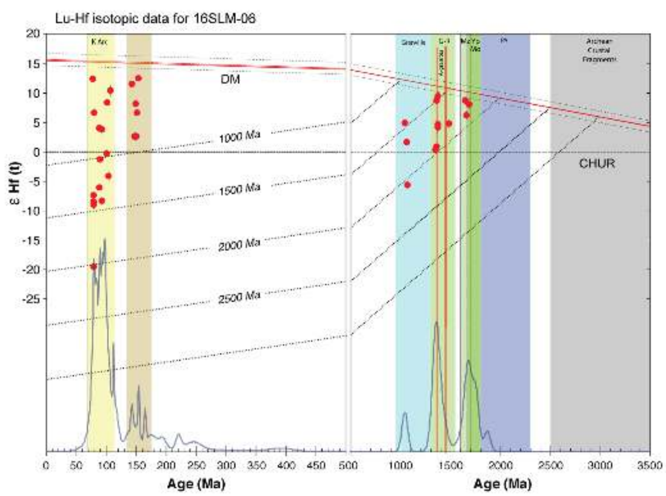

Figure 4. Lu-Hf data from sample 16SLM-06 plotted with U/Pb data from the same sample shown below.

average of +4.6; [6] The oldest population ranges from 1650 to 1685 Ma and εHf values are entirely positive, with an average of +7.6.

DISCUSSION

Young Population Age

A key question with rim growth is whether the rims grew in the source area and are "detrital" or whether they grew later in the schist during metamorphism, so here the age of the sediment deposition is evaluated. The Young Population Age (YPA) is defined by the youngest dated zircons; here YPA is used instead of maximum depositional age (MDA; e.g., Dickinson and Gehrels, 2009) because this young population may constrain the timing of deposition and/or the timing of schist metamorphism. The four samples from the schist of Sierra de Salinas, 16SLM6, 16SLM7, 16SLM9, and 16SLM11 were U/Pb dated, and a YPA was determined of these using the average of the youngest five ages. The YPA of 16SLM6 was 78.3 Ma, 16SLM7 was 78.0 Ma, 16SLM9 was 84.1 Ma, and 16SLM11 was 81.2 Ma. Thus, all zircons from samples from all outcrops of the SdS fell into the range between 78-84 Ma, with an average being 80.4 Ma.

The YPA of sample 16SLM-11 is 81.2 Ma, within the YPA range of all four dated schist samples. If these young grains are detrital, then they would have formed in the source area and any metamorphic growth related to the schist formation must be 78 Ma or younger. But in all the double-dated grains rim dates are older than this YPA (most 85-92 Ma). A critical exception to this is grain D3, which has a 79.2 +/-1.8 Ma rim with core of 92.1 +/-3.2 Ma. It is possible this grain could have been deposited at 78 Ma, buried deeply, grown, and given a metamorphic age of 79.2 Ma, but analytical uncertainty prevents further interpretation.

In sample 16SLM11-G, rim-core dates indicate there was an event that created abundant Cretaceous rims on Cretaceous and Precambrian zircon grains. There were four grains with Precambrian cores, (Fig. 2) and it is likely the Mojave block is the source of where the magma is intruding old contaminated crust, because the Mojave has a Precambrian basement between 1.3 and 1.7 Ga, and had Cretaceous plutonic and volcanic activity (Lanphere, 1964).

Hafnium

[1] The population from 77-80 Ma are the youngest dated grains from the sample and these grains have negative εHf values, meaning one of two things: 1) that an old crustal signal is contributing to zircon growth in the source or 2) Lu-Hf of a Precambrian grain was retained but all lead (Pb) was expelled. To determine whether these are magmatic zircons or metamorphic zircons, the grain textures need to be analyzed on the SEM to see if textures reveal whether they are igneous or metamorphic zircons. A problem, however, is that the grains were generally small and were largely obliterated by the Hf ablation (40 μm). One option is that the zircons are metamorphic and grew from negative εHf fluids, in which case their composition was probably affected by dissolution of preexisting zircons. Another option is that these are detrital grains and there are Precambrian rocks in source area that were affected by magmatic events at ~77-80 Ma. The Mojave block is one place in Southern California where this relationship occurs (Wooden et. al., 2013).

[2] Grains between 85-107 Ma with εHf values of -6 to +10, are likely from the Sierra Nevada-Peninsular Ranges arc (Lackey et. al., 2012).

[3] Grains that have Late Jurassic to Early Cretaceous ages of 142-154 Ma, with εHf values of +2.6 to +12.5

may represent erosion of plutonic rocks from the Jurassic pulse of magmatism in the western Sierra Nevada and/or Mojave Desert, and possibly portions of the Coast Range ophiolite (Chapman et. al., 2016). Given that εHf values are positive, the sources of these grains must be juvenile (Coleman and Glazner, 1997).

[4] Three grains are between 1043 and 1071 Ma with εHf values between -5.7 and +4.9, and were most likely ultimately derived from the ca. 1.0 to 1.2 Ga Grenville orogen. Grenvillian zircon hafnium signatures are not very diagnostic, as studies have shown there are some groups in the isotopic province that give positive eHf values and some negative groups of εHf (Mueller et. al., 2016).

[5] Grains that fall between 1350-1484 Ma, with εHf numbers that are all positive ranging from 0.3-9.4 are assumed to be from the anorogenic granites, in the Granite-Rhyolite province. This is consistent with what is recognized in the literature; these anorogenic granites are all positive, resulting from juvenile crust (Garver and Davidson, 2015).

[6] The oldest population ranges from 1650 to 1685 Ma and εHf values are entirely positive, with an average of 7.6, probably representing Precambrian basement with a Yavapai-Mazatzal isotopic signature (Garver and Davidson, 2015).

Nature of Young grains

The schist of Sierra de Salinas yields YPAs of ca. 80 Ma. If YPAs are detrital, the source producing sediments until as late as ~77-78 Ma must be a different source than the SNB. There are additional young zircon ages in the schist of Sierra de Salinas (Grove et. al., 2003 and Chapman, 2015), suggesting that it is an important population. To determine more about these young grains, specifically if they are igneous or metamorphic, metamorphic effects on the grains in CL were analyzed as well as the uranium content and U/Th ratios.

Transgressive Recrystallization is the alteration of pre-existing zircon through elemental exchange (Pidgeon et. al., 1998), and is one of the primary metamorphic effects on zircon. When this occurs, the grains do not grow, but alteration causes them to become rich in rare earth elements, and the uranium content tends to remain neutral. If formation of the zircon is not complete, sometimes relict internal oscillatory zoning is visible (Hoskin and Black, 2000). Almost all the lead (Pb) in the grain is expelled during transgressive recrystallization, and when not all the lead is expelled the date will be slightly older than the actual metamorphic event (Hoskin and Black, 2000). Uranium concentration is typical, but U/Th can be high due to loss of Th. Because light rare earth elements are more likely to be expelled during recrystallization than the heavier, smaller cations, the effect of transgressive recrystallization does not change Hf isotopic ratios (Hoskin and Black, 2000).

If not transgressive recrystallization, other possible metamorphic effects include: 1) precipitation during anatectic melting; 2) Subsolidus nucleation, also called Ostwald Ripening; and 3) precipitation from metamorphic fluids (Hoskin and Black, 2000). Subsolidus nucleation results in high Uranium concentrations, usually seen in a dark rim with CL that excludes Pb and Th, leading to high U/Th ratios (Nemchin et. al., 2001). While the primary isotopic Hafnium composition will stay the same even when U-Th-Pb data and zoning is altered with metamorphic effects along the lines of transgressive recrystallization, the formation of a zircon due to precipitation from a fluid or melt will result in distinct Hafnium isotopic compositions (Zeh et. al., 2010).

Evidence for both Transgressive Recrystallization and Ostwald Ripening are observed in grains from the samples from SdS, along with igneous, oscillatory zoning. Because transgressive recrystallization does not affect the Lu/Hf system, but resets U-Pb ages, the young zircons with high εHf could have been altered Precambrian zircons that were metamorphosed at ~78 Ma, and had their ages reset. However, there is only one grain in 16SLM11G where this is seen, and could have been the case, so it appears unlikely that transgressive recrystallization is the dominant process in this population. With the metamorphic effect of Ostwald ripening, where new zircons are grown in a liquid melt, the εHf values would all be the same. However, we see that the εHf values for this young population are not the same as each other, they range from +6 to -33, so this scenario is also unlikely.

The hafnium range of the young population is distinct because it has such a wide range. In the age population from ~77-80 Ma, 6 of the 7 grains show εHf values from -7.3 to -33.3. These negative values set the grains apart from the positive values in older zircon grains (>85-115 Ma). There are two options for the formation of these young radiogenic grains: 1) If detrital, this means there is a wide range of source rocks, and in this case many would have been Precambrian and magmatism in the source must have been active until ~77-78 Ma. If this is the case, the negative εHf values are probably from melting of crustal rocks and igneous activity in the source area. These Hafnium values are characteristics seen in the Mojave (Wooden et. al., 2012, see Fig. 5). The Mojave block contains 1.6 and 1.4 Ga basement rocks, and has cover strata that are rich in zircon, including the Zabriski Quartzite, Wood Canyon, Big Bear, and Pinto Mountain Group (Wooden et. al., 2012). These strata in the Mojave have a Hafnium pattern comparable to that found in our young population of zircons in the schist of Sierra de Salinas. 2) If these young zircon dates are metamorphic and formed in the schist, this represents disequilibrium and potential modification of pre-existing grains. If these grains are metamorphic and formed in the schist, the wide variation in hafnium would reflect either alteration of heterogeneous grains already existing, or new grains forming in disequilibrium.

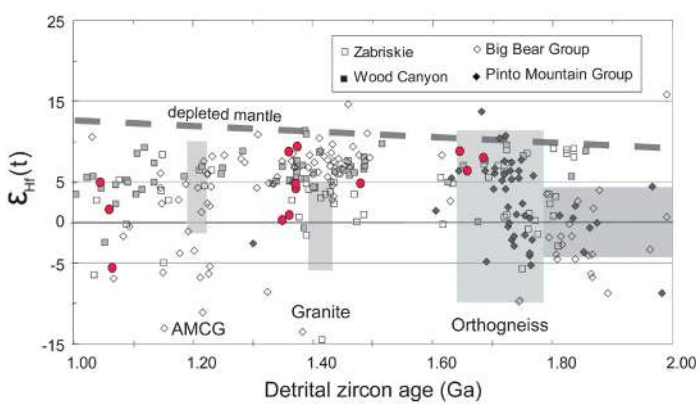

Figure 5. Hafnium analyses of spots within individual detrital zircons from siliclastic cover sequences overlying southern Mojave province basement from Zabriskie, Wood Canyon, Big Bear Group, and Pinto Mountain Group, plotted with the Hafnium results from the schist of Sierra de Salinas (red circles), sample 16SLM-06. The U-Pb zircon ages are plotted vs. eHf(t)

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