TECTONIC EVOLUTION OF A DEEPLY EXHUMED ARC SECTION: A STUDY OF THE PHYSICAL AND PETROLOGIC EVOLUTION OF THE SALINIAN BOCK, CENTRAL COASTAL CALIFORNIA

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INTRODUCTION

Magmatic arcs are critical players in the formation and evolution of continental crust, and yet many of the processes involved are poorly understood (e.g., Hildreth and Moorbath, 1988; Rudnick and Gao, 2003; Lackey et al., 2005). The Salinia terrane along the central coast of California contains a nearly complete magmatic arc section, the “Salinian arc,” including deep crustal magmatic roots (e.g., Kidder et al., 2003; Chapman et al., 2014). Despite its structural completeness, good exposure, and relatively easy access, Salinia remains understudied. Furthermore, a profound structural relationship is observed at the base of the Salinian arc section: a shallowly dipping shear zone underlain by subduction accretion assemblages of the schist of Sierra de Salinias (SdS; Barth et al., 2003; Kidder and Ducea, 2006). The structural-spatial-temporal relationships between the emplacement of melt-fertile materials (SdS schist) beneath Salinia and arc plutonism are not well constrained. We will focus on two questions: 1) Was the SdS schist emplaced by “cold” or “hot” relamination (e.g., Behn et al., 2011; Hacker et al., 2011)? and 2) What were the petrologic and rheologic consequences of schist emplacement?

Our hypothesis is that the SdS schist was emplaced by “cold” relamination, or progressive underthrusting, and that this addition of weak, melt-fertile material profoundly weakened the crust, sparking construction of the Late Cretaceous (ca. 93-80 Ma) arc section. This project consists of four specific objectives aimed at testing this hypothesis:

1) Distinguish between possible emplacement mechanisms for the SdS schist.
2) Constrain the timing of schist emplacement and arc plutonism.
3) Characterize the petrologic and rheologic consequences of schist emplacement.
4) Determine seismic signature of the SdS schist at depth.

Six undergraduate student projects targeting the objectives above (described in detail under “research” and in individual student contributions to this volume) were undertaken as a part of this research. Our research included fieldwork and sample collection, petrography, plutonic and detrital zircon U-Pb geochronology, zircon Hf isotopic work, and electron backscatter diffraction (EBSD)-based determinations of mineral crystallographic preferred orientations (CPOs).

GEOLOGIC BACKGROUND

Salinia is a NW-trending composite terrane bounded to the east by the San Andreas fault, to the west by the Sur-Nacimiento fault, and to the south by the Big Pine fault (Figure 1; Vedder et al., 1982). These faults juxtapose the Salinian terrane to the west and east with Mesozoic subduction accretion assemblages of the Franciscan complex (Figure 1). The Salinian terrane traveled northward >300 km during the Neogene along the San Andreas fault system (Dickinson et al., 2005; Hall, 1991; Hall and Saleeby, 2013; Huffman,
Three main rock packages underlie the Santa Lucia Range of central Salinia, discussed in the following order below: Paleozoic metamorphic framework rocks, Late Cretaceous plutonic rocks, and subduction accretion assemblages. First, Paleozoic upper amphibolite to granulite grade clastic strata of the Cordilleran passive margin (Barbeau et al., 2005; Compton, 1960, 1966; James and Mattinson, 1988; Trask, 1926; Wiebe, 1970; Mattinson, 1978; Kidder et al., 2003; Chapman et al., 2012, 2014) form the framework for Cretaceous intrusives of the Salinian arc.

Metamorphic framework rocks are intruded by Late Cretaceous intermediate to mafic plutons of the Salinian magmatic arc (Compton, 1960; Hansen and Harlov, 2009; Hansen and Stuk, 1993; Kidder et al., 2003; Mattinson, 1978, 1990; Wiebe, 1970). Existing U-Pb zircon geochronology suggests that Magmatism began in the Salinian arc at ca. 93 Ma and continued until ca. 80 Ma (Kistler and Champion, 2001; Mattinson, 1978, 1990), during an episode of high flux magmatism that produced >80% of the California arc (Coleman and Glazner, 1998; DeCelles et al., 2009; Ducea, 2001; Ducea and Barton, 2007). Plutonic assemblages of the Salinian arc range in composition from quartz monzonite and granodiorite to tonalite, quartz diorite, diorite, and gabbro (Mattinson, 1978; Ross, 1972). The depth of exposure increases from east to west in the Salinian arc from mesozonal in the eastern Santa Lucia Range (~3 to 6 kbar; Chapman et al., 2012; John, 1981; Wiebe, 1970) to ~7.5 kbar levels (Hansen and Stuk, 1993; Kidder et al., 2003; Chapman et al., 2012) in the Coast Ridge belt (CRB) west of the Coast Ridge and Palo Colorado faults along the western flank of the Santa Lucia Mountains (Figure 1). Shallower-level Salinian arc assemblages east of the CRB are referred to as the Central block (Ross, 1978).

Compositional and structural observations (Ducea et al., 2003; Kidder et al., 2003; Chapman et al., 2014) suggest that the CRB represents a window into the root of a continental arc (Hildreth and Moorbath, 1972; Jacobson et al., 2011; Matthews, 1976; Page, 1982; Schott and Johnson, 1998; Sharman et al., 2013; Figure 1). Petrologic, isotopic, geochronologic, structural, and sedimentologic evidence places Salinia near the southern end of the Sierra Nevada batholith in Late Cretaceous time (Barbeau et al., 2005; Chapman et al., 2012, 2014; Hall, 1991; Hall and Saleeby, 2013; James, 1992; Kistler and Peterman, 1978; Sharman et al., 2013; Wood and Saleeby, 1997; Figure 1 inset). When slip along the San Andreas fault is removed, plutonic rocks of the Sierra Nevada, Salinian, Mojave, and Peninsular Ranges blocks form a contiguous ~1500 km long, NNW-trending Mesozoic batholith – the California arc.
The amount of mafic material in the CRB is significantly higher than that in the Central block, suggesting that the CRB was an accumulation site for Late Cretaceous mafic magmas ascending from the mantle. Furthermore, tilt-corrected (Kidder et al., 2003) plutonic and metamorphic fabrics exhibit a gradual transition from subvertical in the Central block, to subhorizontal in the CRB. This observation has been interpreted previously (Kidder et al., 2003) to reflect vertical transport of upper crustal material into the lower crust, where it spread laterally as a gravity current. Therefore, the CRB may represent a zone of mixing of mantle-derived magmas and downward flowing supracrustal assemblages.

Mid-crustal plutons of the Central block structurally overlie the Late Cretaceous SdS schist along the Salinas shear zone, a Late Cretaceous low angle normal fault responsible for the exhumation of the schist (Barth et al., 2003; Chapman et al., 2010; 2011; 2013; Kidder and Ducea, 2006; Kidder et al., 2013; Figure 1). The schist of Sierra de Salinas and related schists of southern California (e.g., Jacobson et al., 2011 and references therein) are trench-related subduction accretion assemblages that were deposited in the Late Cretaceous trench and underplated directly beneath the California arc during an episode of shallow subduction related to the Laramide orogeny (Ducea et al., 2009). A recent study (Chapman et al., 2016) has suggested that the SdS schist represents high-grade inboard equivalents to relatively low-grade rocks of the Franciscan belt exposed west of the Sur-Nacimiento fault (Figure 1).

**RESEARCH PROJECTS**

**Zircon U-Pb geochronology and Hf isotope geochemistry**

Emily Gross (Macalester College) extracted and determined laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICP-MS) U-Pb zircon ages on 338 grains from four samples collected over a range of structural depths from the schist of Sierra de Salinas and correlative schists across the San Andreas faults, the majority of analyzed grains are Late Cretaceous, strongly suggesting that the schist was sourced in large part from the adjacent Sierra Nevada-Peninsular Ranges batholith (Grove et al., 2003; Jacobson et al., 2011; Chapman, 2016). The schist of Sierra de Salinas also contains a population of ca. 1.38 Ga grains, which are rare in the North American Cordillera, with the most probable ultimate sources for these grains in the Mojave Desert and central Idaho (Garver and Davidson, 2015; Dumitru et al., 2016). The most surprising outcome of this work was that the youngest populations of ages in each sample decreased upsection, suggesting that the schist was not assembled by progressive underplating of tectonic slices, which predicts downsection younging. We suggest that the observed upsection younging is an artifact of analysis of metamorphic zircon, which is abundant at structurally high levels and less so at deeper levels. Emily will present this work at the 2017 GSA Cordilleran section meeting (Gross and Chapman, 2017).

Alison Horst (Union College) worked closely with Emily Gross, focusing specifically on crosscutting detrital-metamorphic zircon relationships in schist samples collected from structurally high levels. This work involved LA-MC-ICP-MS U-Pb geochronology of targeted metamorphic rim-detrital core zircon domains and zircon Hf isotopic work on the same analyzed domains. The objective of this project was to constrain: 1) the timing of metamorphism, to determine if metamorphic zircon domains formed in the Sierra Nevada-Peninsular Ranges arc source or within the subduction zone and 2) the source(s) of detrital zircon grains and the Hf isotopic composition of the environment in which metamorphic grain domains formed. This project revealed three rim-core age relationships: Late Cretaceous rims on Proterozoic cores, Late Cretaceous rims on Mesozoic cores, and Proterozoic rims on Proterozoic cores. Rim ages that clearly do not overlap older grain domains range from ~93-77 Ma. It is likely that the older grains in this population recrystallized within the arc source; the younger grains in this population may have formed in the subduction zone. At this point, more work is needed (perhaps ion microprobe U-Pb depth profiling) to resolve age relationships between thin
(<10 µm) metamorphic rims and detrital cores. Zircon Hf work on metamorphic grain domains yielded an enormous spread of isotopic values (~45 epsilon units), suggesting that the isotopic compositions of metamorphic domains were inherited from pre-existing zircon and/or recrystallized from, but did not equilibrate with, melts or fluids. Alison will present this work at the 2017 GSA Cordilleran section meeting (Horst et al., 2017).

Grady Johnson (Macalester College) conducted an investigation into the Hf isotopic evolution and chronology of pluton emplacement in the Salinian arc. This work involved zircon U-Pb geochronology and Hf isotopic work, both done via LA-MC-ICP-MS, on a suite of ten plutons collected from the Salinian arc. Prior to this project, seven U-Pb zircon ages were available from the Salinian arc (Mattinson, 1978; Barth et al., 2003; Kidder et al., 2003). The purpose of this project was: 1) to add to the body of published ages available from the Salinian arc, thereby clarifying the timing of its construction and 2) to contribute the first Hf zircon isotopic data from the arc. The key findings of this project are: 1) the Salinian arc yielded U-Pb ages that decrease from ca. 102 to 86 Ma from SW to NE, suggesting that the arc migrated to the northeast at a rate of ~10 mm/yr, 2) the arc appears to have been constructed in two distinct pulses (102-95 and 90-85 Ma) separated by ~5 Myr, 3) Hf isotope values decrease from +1 to -9 from SW to NE, suggesting an increasing proportion of crust-derived melts to the NE, 4) metamorphic zircon domains from the studied plutons suggest that the arc experienced a thermal event at ca. 80 Ma, and 5) the recognition of three domains, separated by significant age/isotopic breaks (the Coast Ridge belt, plutons east of the Coast Ridge/Palo Colorado fault, and plutons in the vicinity of the schist of Sierra de Salinas).

Electron Backscatter Diffraction

Molly Kover (Smith College) and Veronica Vriesman (Colgate University) both focused on microstructure in the schist of Sierra de Salinas (SdS; Figure 2). We conceptualized two separate projects, one focusing on the Salinbas shear zone, and the other focusing on variations of schist microstructure with depth. In the end, access to the schist was a real challenge, and we were only able to collect 5 samples, so Molly and Veronica both ended up working from the same dataset. We were able to collect EBSD data from all 5 thin sections, but only acquired quality data from quartz. We were unable to get reliable data from biotite for two reasons: 1) the biotite did not produce high quality diffraction patterns, and 2) the biotite match unit available on the instrument was consistently indexing quartz as biotite.

With our focus on quartz, we were able to identify some patterns in the schist microstructure that are related to structural depth. Relative differences in the opening angles of quartz c-axis cross-girdles suggest differences in deformation temperature, with larger opening angles indicating higher temperatures (Law et al., 2004). Differences in the strength of the quartz crystallographic preferred orientation (CPO), which we measured using the orientation distribution function J-value (ODF-J), suggest variations in total strain, with stronger CPOs suggesting higher strain.
Samples 6, 7, and 11 had the largest opening angles at 74°, 83°, and 92°, respectively, suggesting they developed their CPO at the highest temperatures (Figure 2). Samples 6, 7, and 11 also had the strongest CPOs with ODF-J values of 2.5, 2.2, and 2.1, respectively. Samples 8 and 9 had weaker CPOs with ODF-J values of 1.8 and 1.4, respectively. Sample 9 had such a weak CPO that no c-axis cross-girdle could be identified, and sample 8 had the smallest opening angle at 58°. Sample 9 is from the deepest structural level in the schist. The remaining samples are from similarly high structural level, ~1km below the schist-bounding Salinas shear zone (Kidder and Ducea, 2006). The observed patterns in microstructure are consistent with an inverted metamorphic gradient in the schist, where the structurally highest parts of the schist experienced the highest temperature and pressure conditions. These observations support the hypothesis that the schist was emplaced via tectonic underplating beneath a hot continental arc.

Erica Watts (Mt. Holyoke College) measured crystallographic preferred orientation of calcite in marble mylonites from near the Sur-Nacimiento fault zone. The purpose of Erica’s project was to see what we could learn about the deformation mechanisms active during formation of the marble mylonites. Erica used a combination of detailed petrographic observations and EBSD measurements. Calcite develops pretty strong CPOs even at low to moderate temperature, and at high temperature recrystallization usually covers up any preferred orientation that may have developed. Two samples, 2E and 21, had strong c-axis point maxima approximately perpendicular to foliation, with ODF-J values of 2.1 and 1.8, respectively. There may be some slight asymmetry, but not obvious, which is consistent with mostly pure shear deformation. Samples 3 and 4A had the weakest CPOs, both with ODF-J values of 1.1. The c-axis distribution in samples 3 and 4A had a point maxima within a diffuse girdle. Samples 2BI and 2BII were two billets cut from the same hand sample, and both display girdle distributions of c-axes. The girdles are parallel to the thin section surface. 2BI and 2BII did not have a strong lineation, so the orientation of the c-axis girdles relative to lineation is unclear, but this type of CPO is consistent with quartz CPOs produced by constriction (Sullivan and Beane, 2010). No constrictional deformation experiments have been done on calcite, and no similar c-axis girdles have been reported from natural samples. We interpret our marble mylonite CPOs as being consistent with a combination of pure and simple shear, and constriction. Some samples do show some evidence of simple shear, but unfortunately the ultimate shear sense cannot be determined because orientations were not maintained from billet to thin section.

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