Jurassic Barrovian metamorphism in a western U.S. Cordilleran metamorphic core complex, Funeral Mountains, California

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ABSTRACT

Large-magnitude retroarc shortening of Cretaceous age is well documented in the Sevier orogenic belt of the western United States, and has been associated with eastward Franciscan subduction that began in the Middle–Late Jurassic, but evidence for major Late Jurassic retroarc shortening has been lacking. Here we report new Lu-Hf garnet geochronology, pressure-temperature (*P-T*) paths, and $^{40}Ar/^{39}Ar$ thermochronology data that document tectonic burial of Late Jurassic age in a Barrovian metamorphic terrain, the Funeral Mountains metamorphic core complex, California, located in the hinterland of the Sevier orogenic belt. The *P-T* paths determined from growth-zoned garnets in upper greenschist facies pelitic schist show steep *P-T* trajectories consistent with metamorphism during thrust loading. The age of thrust loading is constrained by a five-point Lu-Hf garnet isochron to be 158.2 ± 2.6 Ma (2σ). Partial exhumation, recorded in 146–153 Ma $^{40}Ar/^{39}Ar$ muscovite cooling ages, closely followed garnet growth. Late Jurassic Barrovian metamorphism has not been previously recognized in Cordilleran metamorphic core complexes, possibly due to being obscured by Late Cretaceous to Tertiary deformation, magmatism, and metamorphism. This study finds that the period of large-magnitude crustal shortening in the retroarc extended into the Late Jurassic, and may have closely followed the formation of the coherent orogenic system associated with east-dipping Franciscan subduction.

INTRODUCTION

The late Middle to early Late Jurassic marked a fundamental change in the geodynamic setting of western North America. Protracted Late Triassic–Middle Jurassic plate convergence, punctuated by collisions of island arcs with the continental margin (e.g., Schweickert and Cowan, 1975; Dorsey and LaMaskin, 2007; Dickinson, 2008), was followed by a westward step of the plate margin during initiation of Franciscan subduction and the Late Jurassic to early Cenozoic Andean-style (noncollisional) Cordilleran orogen (Burchfiel et al., 1992; Coney and Evenchick, 1994; DeCelles, 2004). The response within the retroarc to the tectonic reorganization in the forearc remains poorly understood. Cretaceous shortening in the retroarc Sevier fold-thrust belt and its hinterland, broadly contemporaneous with the Cretaceous development of the Franciscan accretionary complex, Great Valley forearc basin, and Sierran magmatic arc (e.g., Cowan and Bruhn, 1992) (Fig. 1), is commonly attributed to strong coupling between the eastward-underflowing Farallon plate and the westward-moving North America plate (e.g., Burchfiel et al., 1992; Coney and Evenchick, 1994). In contrast, Early to Middle Jurassic retroarc shortening (e.g., Wyld, 2002; Dunne and Walker, 2004) may have been driven by arc collision and/or accretion (e.g., Dorsey and LaMaskin, 2007). Through combined Lu-Hf garnet geochronology, pressure-temperature (*P-T*) paths, and $^{40}Ar/^{39}Ar$ thermochronology of metamorphic rocks from the central Funeral Mountains, California, we present the first conclusive evidence for Late Jurassic (ca. 158 Ma) Barrovian metamorphism in a metamorphic core complex of the Sevier hinterland, marking some of the earliest retroarc shortening to follow the development and consolidation of the coherent orogenic system associated with east-dipping Franciscan subduction (e.g., Coney and Evenchick, 1994; DeCelles, 2004).

GEOLOGIC SETTING OF THE FUNERAL MOUNTAINS

The Funeral Mountains comprise a thick (~13 km) sequence of Mesoproterozoic to early Paleozoic metasedimentary rocks (Wright and Troxel, 1993) exposed in a tilted crustal section beneath a low-angle normal fault, the Boundary Canyon detachment fault. The deepest and oldest rocks record upper amphibolite facies metamorphism and migmatization in the northwest part of the range in Monarch Canyon (Fig. 2) (Labotka, 1980; Hoisch and Simpson, 1993; Applegate and Hodges, 1995; Mattinson et al., 2007). Progressively younger Neoproterozoic protoliths are exposed to the southeast, coinciding with a systematic decrease in metamorphic grade to

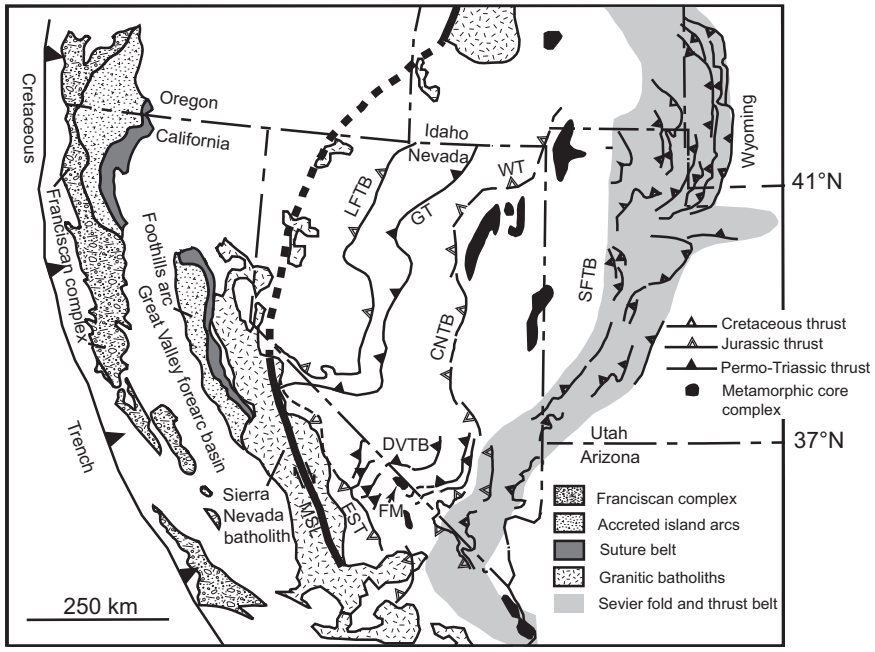

Figure 1. Tectonic elements of western Cordillera of North America. CNTB—Central Nevada thrust belt; DVTB—Death Valley thrust belt; EST—East Sierran thrust system; FM—Funeral Mountains; GT—Golconda thrust; MSL—Mojave–Snow Lake fault; LFTB—Luning-Fencemaker thrust belt; SFTB—Sevier fold-thrust belt; WT—Windermere thrust. Sources: DeCelles (2004), Dickinson (2006, 2008), Dunne and Walker (2004), Schweickert and Lahren (1990), Snow and Wernicke (2000), Stevens and Stone (2005), Wyld and Wright (2001), and this study.

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subgreenschist facies over a distance of ~40 km. Low-angle normal faults of low displacement occur within the lower plate package (Fig. 2).

Geochronologic studies from the highest grade metamorphic rocks in Monarch Canyon have encountered difficulties with excess argon in hornblende (DeWitt et al., 1988; Applegate, 1994) and highly discordant U-Pb ages (Applegate, 1994), and metamorphic rocks have undergone multiple episodes of shearing and the thermal effects of protracted Late Cretaceous to Paleocene leucogranitic injection and partial melting (Applegate and Hodges, 1995; Mattinson et al., 2007). In contrast, the lower grade rocks in the central portion of the range (Indian Pass area; Fig. 2) lack the Late Cretaceous thermal overprint, shear fabrics, and granitic injections, and include garnet schists that are ideal for resolving the age of metamorphism and for determining pressure-temperature (*P-T*) paths.

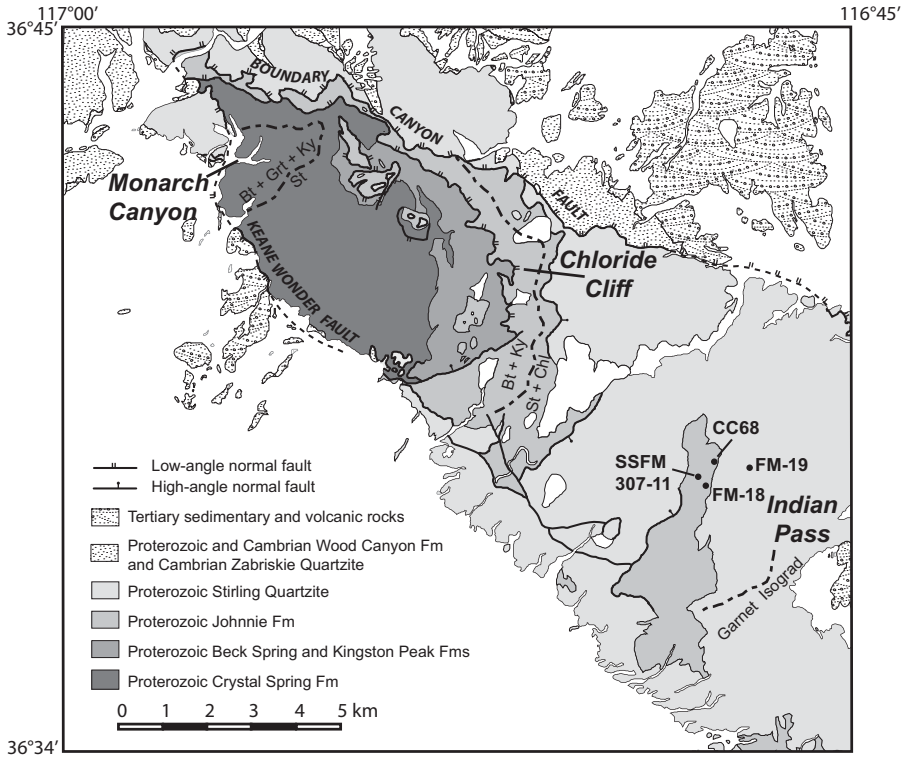

Figure 2. Geologic map of central and northern Funeral Mountains, California (simplified from Wright and Troxel, 1993), and sample locations (black dots). Bt—biotite; Grt—garnet; Ky—kyanite; St—staurolite; Chl—chlorite.

CONDITIONS OF METAMORPHISM AND *P-T* PATHS

Two garnet schist samples (CC68I and SSFM307–11D) from the upper Johnnie Formation near Indian Pass were studied to determine *P-T* paths. Both contain the mineral assemblage quartz + muscovite + chlorite + chloritoid + garnet with accessory ilmenite, apatite, zircon, and tourmaline. Mineral chemistry and major element maps on garnet were generated by electron probe microanalysis (see the GSA Data Repository[1] for run conditions). In each sample, two garnets were mapped and analyzed with line traverses; the other major phases were also analyzed.

Pseudosections

Pseudosections were calculated using the G-minimization approach of de Capitani and Petrakakis (2010) to show mineral assemblage stability fields (Fig. 3) and compositional isopleths for garnet cores (Xpy, Xal, Xsp, and Xgr, values ± 0.01; for details on the method, see the Data Repository). The isopleths for each garnet core converge within a narrow region of *P-T* space (Fig. 3), interpreted to represent the conditions of garnet nucleation. The combined isopleth intersection fields in sample CC68I occur at conditions of 523–527 °C and 4400–5200 bar, and in sample SSFM307–11D occur at 520–530 °C and 4450–5150 bar (Fig. 3). In both samples, the core isopleth intersections plot outside the stability field of the rock's mineral assemblage and inside a field that includes one additional phase, margarite. Thus we conclude that the garnets nucleated in the presence of margarite, which was then entirely consumed as the garnets grew. The *P-T* path followed a trajectory that ended inside the peak mineral assemblage field. This is confirmed by garnet growth simulations (see the following).

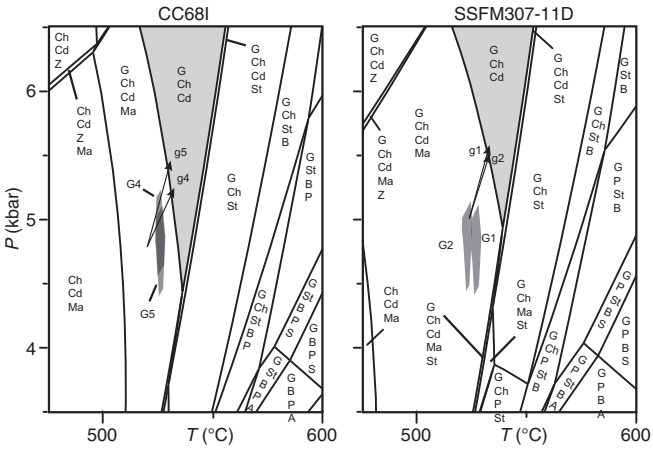

Figure 3. Pseudosections showing mineral assemblage stability fields (rock's assemblage is light gray), intersections of garnet core compositional isopleths (medium gray) and calculated pressure-temperature (*P-T*) paths. All mineral assemblages include quartz, muscovite, and excess H_2O. Garnet core isopleth intersection fields are labeled by garnet number with uppercase G (e.g., G1). Ends of *P-T* paths are labeled by garnet number with lowercase g (e.g., g1). *P-T* paths for sample CC68I were shifted –5 °C and –200 bar to align ends of paths with start of margarite-absent field. A—andalusite, B—biotite, C—cordierite, Ch—chlorite, Cd—chloritoid, G—garnet, K—kyanite, S—sillimanite, St—staurolite, P—plagioclase, Z—zircon.

P-T Paths from Garnet Growth Zoning

P-T paths were determined by simulating garnet growth zoning using the Gibbs method based on Duhem's theorem (program GIBBS; Spear et al., 1991). Garnets in these rocks preserve growth zoning, as indicated by symmetrical bell-shaped Mn profiles formed by Rayleigh fractionation and symmetrical profiles for Mg, Ca, and Fe (Fig. DR1; see the Data Repository). Inputs for GIBBS consist of the initial mineral assemblage, mineral compositions, modes, and the *P-T* conditions. The initial *P-T* conditions used were 524 °C at 5 kbar for all 4 garnets, consistent with the garnet core isopleth intersections (Fig. 3). The program Theriak (de Capitani and Petrakakis, 2010) was used to determine all

[1]GSA Data Repository item 2014146, Figure DR1 (garnet element maps, line traverses and garnet growth simulations), Table DR1 (mineral and model data), Table DR2 (Lu-Hf garnet geochronology data), and Table DR3 ($^{40}Ar/^{39}Ar$ muscovite data), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

other initial conditions (Table DR1 in the Data Repository). Theriak applies G-minimization to a specified bulk composition, pressure, and temperature to determine the equilibrium mineral assemblage, modes, and compositions.

The Gibbs method based on Duhem's theorem requires that changes in the values for two monitor parameters be specified in order to solve for changes in all other parameters that describe the system, including pressure and temperature. The mole fractions of grossular and spessartine in garnet (Xgr and Xsp) were selected as monitors. All four garnets were simulated up to the break in slope along the Ca profile (Fig. DR1). As expected, the calculated *P-T* paths (Fig. 3) extend from the starting conditions toward the field in which margarite is absent. To a good approximation, margarite is fully consumed along the paths upon reaching the margarite-absent field (Table DR1a). It was not possible to simulate garnet growth past the break in slope in the Ca profiles due to the disappearance of margarite from the assemblage and the absence of other suitable Ca sources from among the mineral components of the model assemblage. All garnets yielded very similar *P-T* paths involving 11–12 °C of temperature increase and 450–680 bar of pressure increase (Table DR1b). (For additional details on the methods used to calculate *P-T* paths, see the Data Repository.)

Lu-Hf AND $^{40}Ar/^{39}Ar$ GEOCHRONOLOGY

One schist sample (SSFM307–11f) of the Johnnie Formation was analyzed for Lu-Hf garnet geochronology. The analyses were performed at Washington State University using the methods described by Cheng et al. (2008). Six 200–250 mg fractions of visually clear garnet and two 250 mg fractions of crushed whole rock were selected for isotopic analysis. The Lu-Hf isotopic data are plotted in Figure 4 and provided in Table DR2. A regression through all garnet points and the whole rock prepared by hotplate dissolution in a Savillex beaker yields an age of 162.1 ± 5.8 Ma (2σ) with an initial $^{176}Hf/^{177}Hf$ = 0.28243 ± 0.00016 and high mean square of weighted deviates (MSWD, 39) (Fig. 4A). Both whole-rock compositions have very high Hf contents (10.2 ppm for the bombed fraction, 7.1 ppm for the Savillex fraction), consistent with the incorporation of zircon Hf in the dissolutions. We interpret both whole-rock points, particularly the bomb-dissolved fraction, to contain unradiogenic Hf from detrital zircons within the schist protolith that are not in isotopic equilibrium with the garnets. Consequently, we have excluded these from our preferred regression. Further elimination of garnet fraction G8 (also with higher Hf concentration perhaps indicating incorporation of some zircon Hf) yields an age that is identical within error [158.2 ± 2.6 Ma (2σ)] to the regression including all points, but with a much lower MSWD (1.9). This is our best estimate of the timing of garnet growth.

Variations in the ages in the individual garnet fractions are shown (Fig. 4B) by calculating two-point isochron ages using the Hf isotopic composition of the individual garnet fractions and the initial $^{176}Hf/^{177}Hf$ determined from the five-point garnet isochron (0.28258 ± 0.00007). Garnet fractions G1, G2, G3, G6, and G7 yield identical ages, within error, and fraction G8 yields a slightly younger age. This difference in the garnet composition gives further justification for removing G8 from our preferred regression.

Two samples were analyzed for muscovite $^{40}Ar/^{39}Ar$ thermochronometry (Fig. 4C; Table DR3). FM-18 is coarse-grained chloritoid schist in the Johnnie Formation, and FM-19 is from a marble layer within the Stirling Quartzite. Sample FM-18 yielded a plateau age of 152.6 ± 1.4 Ma for steps 4–8, which represents 58.6% of the ^{39}Ar released, and a total gas age of 141.6 ± 0.8 Ma. Sample FM-19 yielded a muscovite plateau age of 146.0 ± 1.2 Ma for heating steps 9–17, during which 51.0% of the ^{39}Ar was released, and a total gas age of 144.2 ± 0.8 Ma. Analyses have consistently low components of atmospheric argon precluding the utility of isochron analysis.

DISCUSSION AND CONCLUSIONS

The new geochronology and *P-T* path determination clarify the previously enigmatic timing and tectonic significance of metamorphism in the Funeral Mountains. The Lu-Hf garnet age of ca. 158 Ma records the timing of prograde garnet growth during a pressure increase of ~500 bar, beginning at ~5 kbar (~19 km) and ~525 °C (Fig. 3). The stratigraphic burial for these rocks, however, is estimated to be only ~9–10 km. Therefore, the Neoproterozoic strata need ~10 km of tectonic burial to achieve the depth at which garnet growth began (~19 km). Garnet growth captured only the last part of the burial history. Cooling recorded in 146–153 Ma $^{40}Ar/^{39}Ar$ muscovite ages, likely due to partial exhumation, shortly followed burial. Recognition of Late Jurassic metamorphism and thrust burial in the Funeral Mountains has both local and regional implications for Cordilleran tectonics.

In the vicinity of the Death Valley area, the Permian Death Valley fold-thrust belt, Jurassic East Sierran thrust system, and Sevier fold-thrust belt are adjacent to and locally overlap one another, forming a composite thrust belt (Fig. 1) (Snow, 1992; Dunne and Walker, 2004). Structural burial by the Permian thrust belt, including the Last Chance thrust (e.g., Snow, 1992; Stevens and Stone, 2005), is insufficient to achieve the ~9 kbar metamorphic pressures in Monarch Canyon rocks (Hodges and Walker, 1990; Snow, 1992; Hoisch and Simpson, 1993; Applegate and Hodges, 1995). Jurassic thrust faults have not been recognized in the Funeral Mountains and the relative component of Jurassic versus Permian burial is uncertain. We propose that the Miocene Boundary Canyon detachment fault either cuts out a Jurassic thrust plate or is a reactivated Jurassic thrust. Resolution of the relative magnitudes of Late Jurassic versus Permian burial will require further study of the deepest metamorphic levels near Monarch Canyon aimed at seeing through the extensive thermal overprint of protracted Late Cretaceous to Paleocene partial melting, dike

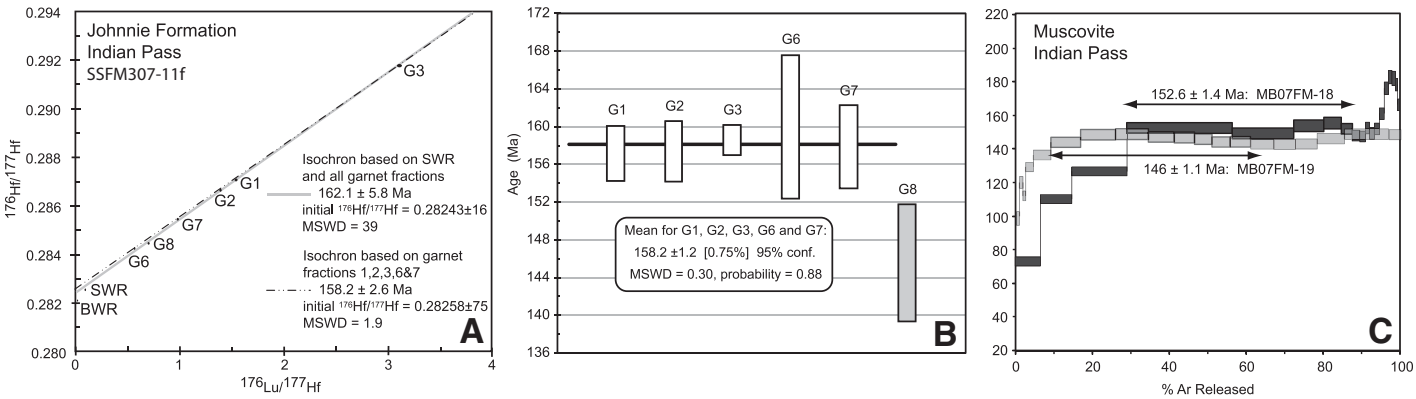

Figure 4. Geochronology from Indian Pass area, California. A: Lu-Hf garnet isochrons (G—garnet, SWR—Savillex whole rock, BWR—bomb whole rock, MSWD—mean square of weighted deviates). B: Two-point ages (±2σ) calculated for each garnet fraction (see text for details). C: $^{40}Ar/^{39}Ar$ muscovite step-heating age spectra.

and sill injection, and metamorphism (Mattinson et al., 2007).

Thrust burial in the Funeral Mountains was contemporaneous with the middle interval of shortening in East Sierran thrust system (Dunne and Walker, 2004) (Fig. 1), but younger than shortening in the Early to Middle Jurassic Luning-Fencemaker fold-thrust belt, which accomplished closure of a backarc basin perhaps driven by arc collision (Wyld, 2002; Dorsey and LaMaskin, 2007). Neither thrust system accomplished sufficient tectonic loading to produce regional metamorphism.

The Late Jurassic (ca. 158 Ma) thrust burial recorded in garnet growth in the Funeral Mountains took place shortly after a late Middle to early Late Jurassic tectonic reorganization and formation of a new coherent noncollisional convergent plate margin. Reconstruction of Cretaceous dextral strike-slip displacement along the Mojave–Snow Lake fault places the Funeral Mountains east of the northern Sierra Nevada and Franciscan complex of the northern Coast Ranges (Fig. 1; Schweickert and Lahren, 1990; Wyld and Wright, 2001; Dickinson, 2006). Although there is debate about when Franciscan subduction initiated, most agree that subduction was underway by 170–160 Ma, the time of metamorphism of high-grade metamorphic rocks within the Franciscan complex (e.g., Anczkiewicz et al., 2004; Wakabayashi and Dumitru, 2007). Large-magnitude crustal shortening of Cretaceous age is extensively documented in the Sevier orogenic belt; however, this study shows that it extends back into the Late Jurassic, and may have closely followed the initiation of a noncollisional convergent plate margin. The unambiguous result of this study suggests that the record of Late Jurassic crustal thickening may be commonly obscured by the Late Cretaceous metamorphism that is pervasive in the mid-crustal rocks of western U.S. core complexes (e.g., Miller and Gans, 1989; McGrew et al., 2000; Wells et al., 2012).

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