Pliocene–Quaternary subsidence and exhumation of the southeastern San Joaquin Basin, California, in response to mantle lithosphere removal

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# ABSTRACT

Thermomechanical models of mantle lithosphere removal from beneath the southern Sierra Nevada region, California (USA), predict a complex spatiotemporal pattern of vertical surface displacements. We evaluate these models by using (U-Th)/He thermochronometry, together with other paleothermometry estimates, to investigate such topographic transients. We target Tertiary strata from the Kern arch, a crescent-shaped active uplift located in the southeastern San Joaquin Basin, along the western flank of the southern Sierra Nevada. Kern arch stratigraphy provides a unique record of subsidence and exhumation in a sensitive region immediately adjacent to the delaminating mantle lithosphere at depth. Detrital apatite (U-Th)/He ages from Oligocene-Miocene sandstones collected in Kern arch well cores indicate postdepositional heating to temperatures beyond those corresponding with their present burial depths. When integrated with available geologic and stratigraphic constraints, temperature-time modeling of thermochronometric data suggests partial He loss from apatites at temperatures of 70-90 °C, followed by exhumation to present burial temperatures of 35-60 °C since ca. 6 Ma. By constraining the late Cenozoic geothermal gradient to ~25 °C/km, our results imply 1.0-1.6 km of rapid (~0.4 mm/yr) subsidence and sedimentation, and then subsequent uplift and exhumation of southeastern San Joaquin Basin strata in latest Miocene–Quaternary time. Stratigraphic and geomorphic relations further constrain the principal burial episode to ca. 2.5 Ma or later, and exhumation to ca. 1 Ma or later. Subtle differences in the maximum temperatures achieved in various wells may reflect differing degrees of tectonic subsidence and sedimentation as a function of growth faulting and distance from the range front. Our results are consistent with estimates of surface subsidence and uplift from Sierran delamination models, which predict a minimum of ~0.7 km of tectonic subsidence in regions retaining mantle lithosphere adjacent to the area of delamination, and a minimum of ~0.8 km of rock uplift in regions where delamination occurred recently. We attribute the marked pulse of tectonic subsidence in the San Joaquin Basin to viscous coupling between the lower crust and a downwelling mass in the delaminating slab. The ensuing episode of exhumation is interpreted to result from the northwestward peeling back of the slab and the associated replacement of dense lithosphere with buoyant asthenosphere that drove rapid rock and surface uplift.

## INTRODUCTION

Convective removal of dense lower crust and mantle lithosphere is postulated to have occurred in orogenic systems around the globe (e.g., the Sierra Nevada, central Andes, western Europe, the Coast Mountains of British Columbia, southern Tibet, and the Carpathians, among others), and is now recognized as a fundamental process required to maintain mass balance and to explain crustal compositions in convergent margin settings (see Ducea, 2011, and references therein). Vertical tectonics driven by such removal processes have been shown to have great influence on the magmatic (e.g., Manthei et al., 2010; Gutierrez-Alonso et al., 2011) and topographic (e.g., Garzione et al., 2008) evolution of orogens. In the Sierra Nevada region (California, USA), geophysical observations, mantle xenoliths, and the age, chemistry, and distribution of late Cenozoic volcanic rocks all point to the post-10 Ma removal of dense mantle lithosphere from beneath the southern

Sierra Nevada batholith (Ducea and Saleeby, 1996, 1998a, 1998b; Ruppert et al., 1998; Manley et al., 2000; Lee et al., 2001; Farmer et al., 2002; Saleeby et al., 2003, 2012, 2013a; Zandt et al., 2004). This recent removal event is spatially and temporally linked to topographic transients in the southern Sierra Nevada region, as evidenced by river incision pulses and various other geomorphic indices (Wakabayashi and Sawyer, 2001; Jones et al., 2004; Saleeby and Foster, 2004; Stock et al., 2004; Clark et al., 2005; Maheo et al., 2009; Figueroa and Knott, 2010; McPhillips and Brandon, 2010, 2012; Saleeby et al., 2013a, 2013b); however, the roles that climate and preexisting topography have in determining landscape evolution are not always clear in these studies. Therefore, in order to isolate and study the effect of mantle lithosphere removal on shallow crustal vertical displacements, we target young and anomalous topographic features immediately adjacent, and thought to be dynamically related, to the foundering material at depth. The southeastern San Joaquin Basin is a critical area in that the stratigraphy records both late Cenozoic subsidence and rock uplift, allowing for a more detailed analysis of the vertical displacement patterns most proximal to ongoing removal.

Computational models investigating mantle lithosphere removal indicate that the removal of dense mantle lithosphere invariably leads to modification of surface topography, the style and magnitude of which change with differing model parameters, such as size and rheology of the foundering mass and its degree of coupling with the lower crust (Pysklywec and Cruden, 2004; Le Pourhiet et al., 2006; Elkins-Tanton, 2007; Göğüş and Pysklywec, 2008). Studies all show that the region above the deep mobilized body is highly susceptible to vertical displacement transients, which we refer to as being epeirogenic (after Saleeby et al., 2012, 2013a). Figure 1 shows a block diagram of the southern Sierra Nevada-San Joaquin Basin region with surface topography, and underlying P-wave

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Figure 1. Block diagram showing oblique digital elevation model view of the southern Sierra Nevada topographic surface from the west, lifted off underlying upper mantle structure shown as P-wave tomography of the Isabella anomaly (after Reeg, 2008). Higher velocity core of anomaly is interpreted as actively delaminating arclogite (see text) root of the Sierra Nevada batholith (SNB); the delamination hinge is the approximate locus of separation from lower crust (after Saleeby et al., 2012, 2013a). The Kern arch is over an area where the delamination hinge trace extends into the San Joaquin Basin, and the Tulare Basin is over the principal area of residual attachment of the batholithic root. Abbreviations: SAF—San Andreas fault; GV—Great Valley; Flt.—fault; V—vertical; H—horizontal.

tomographic structure (after Reeg, 2008). The southern margin of the high-wave-speed Isabella anomaly is shown to pass under the eastern San Joaquin Basin along the transition between the Tulare subbasin and the Kern arch. This presents an ideal opportunity to use the stratigraphic record of the eastern San Joaquin Basin to test for epeirogenic transients predicted by the computational models.

Here we present new thermochronometric and thermometric data from the southeastern San Joaquin Basin that are used to constrain the thermal and epeirogenic history of the region directly above the southern margin of the Isabella anomaly. We interpret recent thermal perturbation of Tertiary strata in this region as reflecting rapid burial and subsequent exhumation of those strata, directly linked to the evolution of the Isabella anomaly. Our results allow us to evaluate thermomechanical models of southern Sierra mantle lithosphere removal and to suggest that transients in surface topography can be diagnostic indicators of the mechanisms involved in mantle lithosphere removal. Our results also show that complex subsidence patterns may result in sedimentary basins that arise from processes that are beyond the commonly assumed governing processes of plate tectonic forcing and eustasy.

# GEOLOGIC SETTING

The Sierra Nevada is an ~600-km-long, northwest-southeast-trending mountain range that, with the adjacent Great Valley to the west, constitutes a geodetic microplate (Argus and Gordon, 1991). It is bound to the west by the active Coast Range fold-thrust belt and San Andreas fault and to the east by the Sierra Nevada frontal escarpment, which separates the Sierra Nevada microplate from the Basin and Range extensional province to the east. The Great Valley is an elongate trough that was part of the forearc basin to the Cretaceous Sierran arc and transitioned into an intermontane basin through Cenozoic time. Here we focus on part of the San

Joaquin Basin, which forms the southern half of the Great Valley. Although the Sierra Nevada is typically described as a rigid, westward-tilted block, the geologic, topographic, and structural character of the range exhibits marked alongstrike differences. The southern Sierra Nevada has higher crest elevations, greater local relief, and is internally deformed. Unlike the general pattern observed to the north, southern Sierran basement is extensively faulted and the western margin is structurally and topographically complex (Maheo et al., 2009; Nadin and Saleeby, 2010; Amos et al., 2010; Saleeby et al., 2013a, 2013b). Similarly, the regional tilt pattern and linear deposition in the Great Valley are disturbed south of 37°N, where the Tulare Basin embays into the western foothills of the range, south of which (~35.5°N-36°N) the Kern arch forms a salient into the San Joaquin Basin (Figs. 1 and 2).

In addition to its structural complexity, recent studies also indicate that the geomorphic development of the southern Sierra Nevada is notably different than that of the range as a whole (Maheo et al., 2009; Figueroa and Knott, 2010; McPhillips and Brandon, 2010; Saleeby et al., 2013a). Unlike the central and northern Sierra Nevada, which appear to be slowly denuding (e.g., Cecil et al., 2006), the southern Sierra is marked by regions undergoing anomalous rock uplift and anomalous subsidence (see Saleeby et al., 2013a, and references therein). The Kern arch and the Tulare subbasin to its north are areas undergoing such modern uplift and subsidence in association with delamination.

#### Kern Arch

The Kern arch is a late Quaternary epeirogenic uplift that deforms the southeastern San Joaquin Basin along its transition into the western Sierra Nevada (Figs. 1 and 2), and exposes the southeastern facies of the Tertiary section of the San Joaquin Basin. Figure 2 is a generalized map of the southern Sierra Nevada-San Joaquin Basin region that denotes the Kern arch by Tertiary-Pleistocene strata that are currently exposed and undergoing erosion (after Saleeby et al., 2013b). Also shown in Figure 2 are oil wells and oil fields for which we present data herein. Topographic relief across the Kern arch (~500 m) is expressed in the subsurface by a buried and extensively faulted basement horst that locally attains as much as ~2 km of structural relief beneath the area of the arch (Saleeby et al., 2013a). These relations suggest ~1500 m of Kern arch exhumation in the areas of greatest structural relief. Figure 3 is a cross section across the northern part of the Kern arch, 15-20 km north of its topographic and basement surface



Figure 2. Generalized map of the southern Sierra Nevada region showing select geomorphic features, late Cenozoic faults, San Joaquin Basin subbasins, intervening Kern arch, and locations of wells and oil fields studied and discussed in the text (after Saleeby et al., 2013a, 2013b). Also shown by white dots are locations of apatite He basement ages from House et al. (2001), Clark et al. (2005), and Maheo et al. (2009). Delamination hinge trace is taken from Figure 1.



Figure 3. East-west cross section across the northern Kern arch showing principal Tertiary (T) stratigraphic units and erosional truncation of the section along the western Sierra Nevada basement uplift. The approximate eastward extent of exhumed basement nonconformity is also shown. Abbreviations: Cyn.—canyon; V–vertical; H—horizontal. After Saleeby et al. (2009, 2013a, 2013b).

structural culmination. Here the updip erosional truncation of the top of the upper Pliocene San Joaquin Formation suggests ~1 km of erosional exhumation. The basement nonconformity of the Kern arch Tertiary section is exhumed along the eastern margin of the arch (Figs. 2 and 3), and extends eastward across the southern Sierra Nevada, becoming roughly comparable with a low-relief, deeply dissected relict landscape surface (Clark et al., 2005; Maheo et al., 2009; Saleeby et al., 2013b). The Kern arch divides the southern San Joaquin Basin into the Maricopa subbasin to the south and the Tulare subbasin to the north. The Tulare basin is an area of modern anomalous subsidence centered above the area of residual crustal attachment of the delaminating root (Saleeby and Foster, 2004; Saleeby et al., 2012), while the Kern arch sits above the area of most recent root detachment (Saleeby et al., 2013a).

A generalized stratigraphic column is shown for the Kern arch in Figure 4, which also shows log- and core-based columns for wells that we have studied in detail. General descriptions of the stratigraphic units are given in the Supplemental File<sup>1</sup>. Each of the well columns studied have undergone considerable Quaternary exhumation, which is a focus of our work presented herein. In general, the Kern arch Tertiary section approaches 4 km total thickness just west of the arch uplift, where the section continues into the adjacent actively subsiding part of the San Joaquin Basin (Saleeby et al., 2013a). The Kern arch section is primarily siliciclastic sandstones, first-cycle detritus derived from the southern Sierra Nevada batholith (MacPherson, 1978; Bartow and McDougall, 1984; Olson, 1988; Saleeby et al., 2013b). Most of the section is marine, except for the Walker Formation, Kern River formation, and Tulare Formations (Fig. 4). Internal unconformities are not recognized except along the basal contacts of extensive Late Miocene fluvial and deltaic sandstone and conglomerate shown as the Caliente River facies of the Kern River formation in Figures 2 and 4. It has been proposed that the Kern arch was first uplifted as a prominent bulge on the southern Great Valley floor in the Paleocene, based on the absence of Cretaceous and Paleocene strata on the basement surface (MacPherson, 1978). Subsequent studies, however, have shown that initial basement exhumation in the area of the Kern arch was part of a broader Late Cretaceous regional pattern that extended southward from the area of the arch across the area of the Tehachapi-San Emigdio ranges (Reid, 1988; Saleeby et al., 2007, 2013b; Chapman et al., 2012). This extensive region of deeply exhumed batholithic basement was differentially covered nonconformably by Eocene-Early Miocene strata of the Walker Formation (Fig. 4), and now has kilometer-scale structural relief related to Miocene extensional faulting, Quaternary ascent of the Kern arch, and, in the south, Quaternary emergence of the Tehachapi-San Emigdio foldthrust belt (Saleeby et al., 2013a).

High-angle, mainly normal faulting of Miocene and Quaternary age is widely developed across the Kern arch and its basement, and many faults are shown to have been growth structures during sedimentation (Fox, 1929; Nugent, 1942; Maheo et al., 2009; Saleeby et al., 2013a, 2013b). Such growth faulting accounts for the significant changes observed in stratigraphic thicknesses

shown between well sites in Figure 4. The Kern arch Tertiary section is commonly shown to be capped by Quaternary alluvial fans (cf. Bartow and Pittman, 1983), but our studies find little evidence this; in contrast, we interpret the arch to be undergoing erosion, and in many places it is covered by a veneer of coarse colluvial lag (Saleeby et al., 2013b). A permanent global positioning system monument along the eastern margin of the arch yields a vertical uplift rate of  $\sim 2.3 \pm 0.4$ mm/yr (Nadin and Saleeby, 2010; Hammond et al., 2012), presenting the possibility that the ~1-1.5 km of exhumation suggested by structural-stratigraphic relations occurred within the past 0.5 m.y. Such rapid erosion has erased the most recent phases of subsidence and sedimentation from the Kern arch stratigraphic record.

# CRYPTIC SUBSIDENCE IN THE KERN ARCH

The work presented herein was motivated in part by a number of surface and subsurface geologic observations indicating that the Kern arch has been elevated from shallow-marine conditions since late Pliocene time, and has undergone substantial exhumation in late Quaternary time. The ~1-1.5 km of recent exhumation suggested from structural-stratigraphic relations is corroborated by subsurface petrologic features that indicate a cycle of significant subsidence and sedimentation in Pliocene-Quaternary time, immediately prior to the current phase of exhumation. We refer to the most recent phase of subsidence as cryptic because it is not directly observable in the stratigraphic record due to erosion. The observational data that suggest a recent cycle of cryptic subsidence and then uplift and exhumation are summarized in the following, and further pursued using detrital apatite (U-Th)/He thermochronometric and vitrinite reflectance studies.

Coupled stratigraphic and geochronometric relations generally constrain cryptic subsidence to after 6 Ma. This is based on the 6.1 Ma date of an ash within the Caliente River facies of the Kern River formation (Baron et al., 2007), close to the youngest erosionally exhumed stratigraphic level across a significant area of the Kern arch (Saleeby et al., 2013b). Additional stratigraphic relations, however, suggest that most subsidence occurred between the ca. 2.5 Ma termination of San Joaquin Formation deposition and deposition of the 0.61 Ma Corcoran E-clay (Dalrymple, 1980) member of the Tulare Formation (Saleeby et al., 2013a; see Figs. 5 and 8). Based on exhumation relations discussed herein, we interpret ca. 2.5-1 Ma as the time interval of the principal phases of cryptic subsidence.

<sup>&</sup>lt;sup>1</sup>Supplemental File. Elemental data and additional discussion of geology and analytical methods. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00882.S1 or the full-text article on www.gsapubs.org to view the Supplemental File.



Figure 4. Generalized stratigraphic column for strata of the Kern arch, and local columns based on log and core data from oil wells studied by detrital apatite (U-Th)/He thermochronometry, vitrinite reflectance, and downhole thermometry (sampling levels and techniques are indicated). Stratigraphy is modified after Bartow and McDougall (1984) and Olson (1988), as based on surface and subsurface mapping of Saleeby et al. (2013a, 2013b). Abbreviations: EK—Early Cretaceous; Pleist.—Pleistocene; El—elevation; FM—formation; MSL—mean sea level.

In much of the analysis that follows we use temperature relations as a proxy for depth relations in stratigraphic sections. It is therefore critical to have a reasonable approximation of the geothermal gradient through the Kern arch section. Stratigraphic continuity of Eocene through Pliocene strata from the Kern arch to the axial area of the San Joaquin Basin (Bartow and McDougall, 1984; Bloch, 1991; Saleeby et al., 2013a) permits a common geotherm prior to the uplift and partial exhumation of the arch. The observed geotherm in the actively subsiding part of the San Joaquin Basin proximal to the Kern arch is known from well data to be  $\sim$ 20– 25 °C/km (Graham and Williams, 1985; Wilson et al., 1999; Saleeby et al., 2013a). This overlaps with an ~25 °C/km theoretical upper crustal geotherm determined for the entire crustal column of the southern Sierra Nevada batholith based on heat production data determined over an ~35 km range of crustal level exposures, as



Figure 5. (A) Photomicrograph in cross-polarized light of Famoso Formation sandstone from ~1580 m measured depth in the Fuhrman. Note chloritization of matrix and complete replacement by chlorite of deformed biotite grain in the center bottom of the image (plag. is plagioclase). (B) Diagram showing depth relations at Fuhrman well for chloritized matrix and albitized detrital plagioclase grains. The black line is the total subsidence curve for ca. 40 to ca. 6 Ma (after Saleeby et al., 2013a) terminated at the erosional top of top of well column. The red dashed line is the reconstructed cryptic subsidence–rock uplift extension of total subsidence curve based on minimum temperature requirements of 90–100 °C for initiation of chlorite growth and albitization (see text). MSL is mean sea level.

well as a mantle heat flux based on heat production of mantle xenoliths recovered from beneath the batholith (Brady et al., 2006). Considering that the San Joaquin Basin consists almost exclusively of first cycle detritus derived from the upper levels of the Sierra Nevada batholith (Ingersoll, 2012; Saleeby et al., 2013b), and that much of the basin, including the Kern arch section, nonconformably overlies mid-crustal Sierra Nevada batholith (Saleeby, 2007), a reference geotherm of 25 °C/km is used for the Kern arch section.

Of similar importance for temperature-depth relations in the Kern arch section is the temperature used for surface conditions. We put bounds on this unknown by noting that (1) the depositional temperature of marine clastics in the modern San Pedro Basin of southern California, which is similar to the San Joaquin Basin, is 5 °C (John et al., 2012), and (2) the modern average surface temperature of the Kern arch is 18.5 °C (see www.climate-zone.com). We also use an approximate surface temperature of ~15 °C for the area of the Kern arch for early Pleistocene time, though average surface paleotemperatures in California shoreline environments are estimated to vary between 10.4 and 19.0 °C (Valentine and Meade, 1960).

Following the structural-stratigraphic implications of  $\sim$ 1–1.5-km-scale recent exhumation across the Kern arch (Fig. 3), we present corroborating petrographic features from selected cores. We focus on depth of burial and exhumation, and then draw inferences about cryptic subsidence from these and from facies relations.

### **Chloritization and Albitization**

Samples of the Eocene Famoso Formation, recovered from a cored interval at ~1580 m depth in the Fuhrman well (Figs. 2 and 4), have a pervasively chloritized matrix (Fig. 5A). (The full names of all wells discussed in this paper are given in the Supplemental File [see footnote 1].) Petrographic and microprobe analyses show that chlorite developed as a mineral coating on detrital quartz and plagioclase, as a replacement for an undetermined matrix component, and as pseudomorphs after detrital biotite. The current burial depth of the chloritized sandstone corresponds to a temperature of ~50 °C, using a mean surface temp of 18.5 °C and a geotherm of ~25 °C/km. Aagaard et al. (2000) showed that grain coating by chlorite initiates in siliciclastic rocks at ~90 °C. Microprobe imaging and compositional data on 10 spots (Supplemental Table 2 [see footnote 1]) show the chlorites to be aggregates of 5-10 µm grains with small quartz inclusions, resulting in poor (high) silica values. Iron-magnesium ratios, however, indicate an iron-rich (chamositic) composition, which typically develops at temperatures ≥160 °C (Iijima and Matsumoto, 1982). Chlorite overgrowths found in the Fuhrman well are therefore interpreted to have formed at greater temperatures (≥90 °C) and depths (≥2.9 km) than those at which they are currently found (Fig. 5B).

Chloritized Walker Formation core samples from the Fuhrman well also exhibit evidence for albitization of detrital plagioclase grains. Our research shows that tonalitic, granodioritic, and

gabbroic rocks from the axial to western Sierra Nevada and Great Valley subsurface typically contain zoned plagioclase with Ab<sub>28-70</sub>. Detrital plagioclase grains from the chloritized Walker lack zoning; microprobe analysis of cores and rims yielded uniform Ab<sub>70</sub> (Supplemental Table 2 [see footnote 1]). These data show that the plagioclase grains have been pervasively albitized to a uniform composition. A detailed study of the albitization of detrital plagioclase in the actively subsiding San Joaquin Basin showed that albitization initiates at ~85 °C, and is prolific between 110 and 160 °C (Boles and Ramseyer, 1988). The uniform composition of plagioclase grains at  $Ab_{70}$  suggests albitization at the lower end of the temperature ranges determined in this and other studies (Perez and Boles, 2005). The chloritization and albitization data lead us to interpret their mutual development in the Fuhrman well at a minimum of 90-100 °C, which corresponds to depths 1.3 km deeper than those at which the rocks are currently found (Fig. 5B).

Viewing the depth relations of Fuhrman well and using a geotherm of 25 °C/km (Fig. 5B), the chloritized and albitized level of the well was buried to at least ~2.9 km depth. The current depth of the sample studied is 1580 m below the 285 m surface elevation of the well site. Using sea level as the approximate post-6 Ma depositional surface, this indicates minimum rock uplift of 1605 m and a minimum of 1320 m of exhumation following chloritization and/or albitization. Figure 5B shows continuous, stratigraphically constrained total subsidence between ca. 40 Ma and ca. 6 Ma (Saleeby et al., 2013a). The minimum post-6 Ma (cryptic) subsidence can then approximated as ~1350 m by mating the rock uplift and measured depth relations with the ca. 6 Ma termination of the total subsidence curve.

### Mechanical Granulation of Detrital Grains and Zeolite Growth

Link et al. (1990) recognized mechanical granulation of detrital plagioclase and quartz and the bending of detrital biotite grains around framework silicate detrital grains during Ca zeolite formation in the uppermost Miocene(?)lower Pliocene shallow-marine Etchegoin Formation from the Kern Front oil field (Fig. 2). Such granulation textures are observed at measured depths as shallow as ~500 m. Similar granulation textures are prevalent in the in Fuhrman well (Fig. 5A), although in this case recovered from considerably greater measured depth (~1580 m). The type of fracturing of competent grains that Link et al. (1990) observed in the Etchegoin Formation is typically seen at burial depths of >1600-1700 m, requiring high compaction stresses and rapid sedimentation (Merino, 1975; Helmold and van de Kamp, 1984). The marine sandstone found today at 500 m measured depth must therefore have been buried to at least ~1600 m depth, indicating a minimum of ~1100 m of exhumation and a comparable amount of Pliocene–Quaternary cryptic subsidence, considering the shallow-marine setting of Etchegoin deposition (Link et al., 1990).

The ~1600 m minimum burial depth for the granulated Etchegoin Formation translates to ~58 °C conditions during granulation, using a 25 °C/km geotherm and a surface temperature of 18.5 °C. This is at the lower range of temperature formations observed for Ca zeolite (McCulloh et al., 1981), with laboratory synthesis typically requiring temperatures in the 150–200 °C range (Wirsching, 1981).

# APATITE (U-Th)/He THERMOCHRONOMETRY

Following the implications of the stratigraphic and core petrographic data presented above for ~1-1.5-km-scale recent exhumation across the Kern arch, we focus here on detrital apatite grains from oil well cores (Dyer Creek, Fuhrman, and Richfield wells) and cuttings (Parsons well) located within and along the margin of the Kern arch (Fig. 2). We present data on samples from multiple depth intervals in widely spaced wells, although subsurface materials extracted from appropriate depth and lithologic intervals were only available in a limited number of locations. Apatite (U-Th)/He thermochronometry of sampled sandstones allowed us to investigate the postdepositional thermal perturbation of Cenozoic strata across a region. Such thermal perturbation is then used to infer burial and exhumation relations, as well as to constrain prior cryptic subsidence.

We present (U-Th)/He ages for 69 individual apatite crystals, collected from samples that yielded an adequate number of inclusion-free crystals. Single grain detrital apatite (U-Th)/He ages and supporting data are given in Table 1. A minimum of five inclusion-free apatites from each sample were picked on the basis of size, morphology, and lack of visible inclusions using a binocular microscope in cross-polarized light. The dimensions of each crystal were measured and an alpha-ejection correction (from Farley et al., 1996) was applied to each analysis. Compared to previous work on Sierra Nevada apatites (cf. House et al., 1998, 2001; Clark et al., 2005; Maheo et al., 2009), most of the grains analyzed here are small and therefore have larger and more uncertain  $\alpha$  ejection corrections. (For additional information about the (U-Th)/He analytical methods used, see the Supplemental File [see footnote 1].)

Apatite (U-Th)/He ages range from 58 to 0.2 Ma and vary greatly within any individual sample. As expected, maximum ages from all samples decrease with increasing depth and temperature. With the exception of the apatites analyzed from the Dyer Creek well, (U-Th)/He ages show a clear positive correlation with effective uranium concentration, [eU] (defined as  $[U] + [Th] \times 0.235$ ; Flowers et al., 2007). Recent studies have shown that He retentivity increases with increasing radiation damage within the apatite lattice, such that the effective closure temperature of an apatite changes over its lifetime, a phenomenon described by the helium trapping model (HeTM; Shuster et al., 2006) and the radiation damage accumulation and annealing model (RDAAM; Flowers et al., 2007, 2009). The sensitivity of He diffusion to radiation damage means that crystals with higher [eU] have higher effective closure temperatures and will yield older ages than crystals that had the same thermal history, but that have lower [eU]. This is particularly true of samples, like those presented in this study, that may have had prolonged residence in the helium partial retention zone (at temperatures 40-80 °C; Flowers et al., 2007).

In the case of detrital samples, and given no postdepositional heating above ~40 °C, age-[eU] relations within the detrital apatite suite should be random, representing the inherited ages and [eU] of the source rocks. If, and depending on the specific thermal evolution of the system, a suite of detrital apatites with variable initial ages and [eU] is heated above ~40 °C, the HeTM and RDAAM models predict a preferential lowering of ages of low [eU] crystals, thereby creating a positive, typically nonlinear, relationship between age and [eU]. The shape of that relationship, and the spread of ages achieved as a result of postdepositional heating, is sensitive to the peak temperature that is reached, and the duration of residence at that temperature. We exploit this behavior and create thermal history simulations that can reasonably satisfy the observed age-[eU] distributions, elucidating the thermal history of the arch. Note, however, that our data are sensitive to subtle changes in He diffusion due to long residence in the He partial retention zone (Wolf et al., 1998). This means that slight changes to a sample's time-temperature (t-T) path and/or differences in diffusion kinetics could yield ages that are not well predicted by the simplified t-T paths used in our thermal history simulations. Although we recognize that in some cases our simulations do not capture all data points of a given sample, the fact that our results are internally consistent and consistent with other data sets lends confidence to our simulations.

#### Forward Modeling of Age-[eU] Relations

Apatite (U-Th)/He ages become younger, and the age ranges generally decrease, with greater depth in Kern arch wells. As the range of ages young, they typically straddle, or become younger than, host depositional ages, recording postdepositional He loss. To ascertain whether such He loss can be explained simply by slow burial, we perform thermal simulations using HeFTy software (Ketcham, 2005), which incorporates available geologic and thermochronometric constraints. Thermal simulations constructed by HeFTy predict age arrays over a range of typical [eU] values (2-100 ppm). The best fit of measured ages to the predicted age-[eU] envelopes is then taken to be the sample's preferred thermal history.

Kern arch strata were sourced from the adjacent southern Sierra Nevada basement uplift, as evidenced by detrital zircon geochronology, conglomerate clast populations, paleocurrent indices, and fan morphologies (Mac-Pherson, 1978; Bartow, 1991; Maheo et al., 2009; Saleeby and Saleeby, 2010; Saleeby et al., 2013a, 2013b). Unroofing of the southern Sierra Nevada batholith is well constrained by a number of studies using low-temperature thermochronometry (Dumitru, 1990; House et al., 1997, 1998, 2001; Clark et al., 2005; Saleeby et al., 2007; Maheo et al., 2009). Available apatite (U-Th)/He basement ages from the southern Sierra Nevada, shown in Figure 2, cluster around ca. 55 Ma, but are variable with elevation from 42 Ma to 68 Ma. Mean ages, together with age-elevation profiles, suggest relatively slow Cenozoic exhumation rates of ~0.04-0.06 mm/yr (House et al., 2001; Clark et al., 2005; Maheo et al., 2009). Using an exhumation rate of 0.06 mm/yr for the southern Sierra (Maheo et al., 2009), which we prefer because it more accurately accounts for fault offsets in the area, and using a geotherm of 25 °C/km, the cooling rate of the Cenozoic southern Sierra is taken to be 1.5 °C/m.y. We therefore impose a predepositional 1.5 °C/m.y. cooling path in our thermal history simulations (Fig. 6). To account for low-temperature residency at the surface prior to burial, we allow for as much as 25 m.y. of lag time between exhumation to the surface and deposition in the basin. This is represented in Figure 6 as two parallel cooling paths. A 25 m.y. span was chosen because that is typical of the range of cooling ages found in elevation profiles in the southern Sierra (Clark et al., 2005; Maheo et al., 2009). Note that we ignore effects on He age associated with abrasion during transport; these effects are reasonably captured by allowing large variability in the He age of the grains being shed by the Sierra Nevada.

$ \begin{array}{ c c c c c c c c c c c c c c c c c c c$	TABLE 1. APATITE (U-Th)/He DATA								
Subman well (35.5389*N, -118.96795*W)         String to the second s	Sample	Corrected age (Ma)	±2σ	[U] (mqq)	[Th] (ppm)	[eU] (ppm)	[He] (nmol/q)	Radius (µm)	Ft
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	Fuhrman we	ll (35.5389°N, -118.9679	5°W)	,	41 <i>/</i>			, , , , , , , , , , , , , , , , , , ,	
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	FW-2 (1100 i	m measured depth)	,						
W-2.2         49.8         3.6         26.9         67.3         42.8         7.68         4.2         0.669           W-2.4         58.1         5         25.6         60.9         39.9         7.65         37         0.603           W-2.4         58.1         5         25.6         60.9         39.9         7.65         37         0.603           W-2.6         38.4         2.8         32.6         76.4         50.6         6.86         37         0.642           W-2.7         28.1         2.6         7.5         23.9         13.1         1.38         39         0.639           W-2.7         28.1         3.6         0.44.4         5.79         31         0.577           W-2.9         50.5         4.0         34.9         122.2         63.6         10.5         33         0.566           W-2.11         32.4         3.5         14.9         32.2         2.27         12.3         36         0.614           W-2.11         30.3         2.1         16.6         48.0         2.99         3.20         45         0.602           W-3.1         39.9         2.7         13.8         36.4         21.9	FW-2-1*	6.7	0.56	21.3	27.5	27.8	0.647	38	0.631
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	FW-2-2	49.8	3.6	26.9	67.3	42.8	7.68	42	0.659
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	FW-2-3	2.4	0.2	56.4	86.0	76.6	0.56	30	0.55
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	FW-2-4	58.1	5	25.6	60.9	39.9	7.65	37	0.603
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	FW-2-5	51.1	3.6	24.9	60.5	39.1	7.32	41	0.67
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	FW-2-6	38.4	2.8	32.6	76.4	50.6	6.86	37	0.642
$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	FW-2-7	29.1	2.6	7.5	23.9	13.1	1.38	39	0.639
$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	FW-2-8	41.6	3.7	32.3	50.6	44.2	5.79	31	0.577
$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	FW-2-9	50.5	4.0	36.8	84.4	56.6	9.54	36	0.605
$W-2-11$ $32.4$ $3.5$ $14.9$ $32.2$ $22.5$ $2.27$ $34$ $0.667$ $W-2-12$ $50.5$ $4$ $34.9$ $122.2$ $63.6$ $10.5$ $33$ $0.596$ $W-3(1387 m measured depth)$ $W-3(1387 m measured depth)$ $W$ $W$ $30.3$ $2.1$ $16.6$ $48.0$ $27.9$ $3.20$ $45$ $0.692$ $W-3.2$ $19.9$ $1.7$ $13.3$ $36.4$ $21.9$ $1.54$ $40$ $0.645$ $W-3.4$ $28.3$ $2.2$ $13.8$ $21.4$ $15.1$ $1.28$ $40$ $0.663$ $W-3-6$ $19.7^{-1}$ $1.3$ $39.8$ $81.5$ $58.9$ $4.34$ $45$ $0.663$ $W-3-6$ $19.7^{-1}$ $1.3$ $39.8$ $81.5$ $58.9$ $4.34$ $45$ $0.663$ $W-3-7$ $34.3$ $2.8$ $19.3$ $49.2$ $30.7$ $35.7$ $36$ $0.6622$ $W-3-7$ $34.3$ $2.8$ $19.3$ $49.2$ $30.7$ $35.7$ $36.5$	FW-2-10	48.6	3.7	51.1	102.4	75.2	12.3	36	0.614
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	FW-2-11	32.4	3.5	14.9	32.2	22.5	2.27	34	0.567
$\begin{array}{ c c c c c c c c c c c c c c c c c c c$	FW-2-12	50.5	4	34.9	122.2	63.6	10.5	33	0.596
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	FW-3 (1387	m measured depth)							
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	FW-3-1	30.3	2.1	16.6	48.0	27.9	3.20	45	0.692
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	FW-3-2	19.9	1.7	13.3	36.4	21.9	1.54	40	0.645
W-3-4       28.3       2.2       13.8       21.4       18.9       1.96       40       0.663         W-3-5       37.6       2.4       15.6       45.9       26.4       4.05       59       0.745         W-3-6       19.7'       1.3       39.8       81.5       56.9       4.34       45       0.663         W-3-7       34.3       2.8       19.3       48.2       30.7       3.57       36       0.622         W-3-8       9.1       1.5       9.2       26.1       15.3       0.44       34       0.579         W-1       9.9       1.2       29.1       60.2       43.2       1.11       24       0.475         W-1.2       1.2'       0.1       125.8       274       190.2       0.747       29       0.528         W-1-3       11.2       1.3       16.2       68.8       24.8       0.841       31       0.55         W-1-4       37.1       3.6       53.7       82.2       73.0       7.63       27       0.513         W-1-5       4.6'       0.4       142.2       79.7       160.9       2.16       30       0.537         W-16       4.6'	FW-3-3	24.8	2.7	10.8	18.4	15.1	1.28	40	0.613
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	FW-3-4	28.3	2.2	13.8	21.4	18.9	1.96	40	0.663
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	FW-3-5	37.6	2.4	15.6	45.9	26.4	4.05	59	0.745
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	FW-3-6	19.7*	1.3	39.8	81.5	58.9	4.34	45	0.683
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	FW-3-7	34.3	2.8	19.3	48.2	30.7	3.57	36	0.622
W-1 (1510 m measured depth)         W-1.1       9.9       1.2       29.1       60.2       43.2       1.11       24       0.475         W-1-2       1.2*       0.1       125.8       274       190.2       0.747       29       0.528         W-1-3       11.2       1.3       16.2       36.8       24.8       0.841       31       0.55         W-1-4       37.1       3.6       53.7       82.2       73.0       7.63       27       0.513         W-1-5       4.6*       0.4       142.2       79.7       160.9       2.16       30       0.537         Redified well (35.3592°N, -118.80189°W)       24       1269 m measured depth)       24       1.27       7.4       1.27       43       0.645         3*2-2       44.2       2.9       31.2       90.5       52.5       8.52       41       0.6671         3*2-2       44.2       2.9       31.2       90.5       52.5       8.52       41       0.665         3*2-2       44.2       2.9       31.2       90.5       52.5       8.52       41       0.6671         3*2-2       44.2       2.9       31.2       90.5       52.5<	FW-3-8	9.1	1.5	9.2	26.1	15.3	0.44	34	0.579
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	FW-1 (1510	m measured depth)							
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	FW-1-1	9.9	1.2	29.1	60.2	43.2	1.11	24	0.475
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	FW-1-2	1.2*	0.1	125.8	274	190.2	0.747	29	0.528
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	FW-1-3	11.2	13	16.2	36.8	24.8	0.841	31	0.55
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	FW-1-4	37.1	3.6	53.7	82.2	73.0	7.63	27	0.513
Richfield well $(35.3592^{\circ}N, -118.80189^{\circ}W)$ R-2 (1269 m measured depth)R-2 (1269 m measured depth)R-2-147.85.53.417.27.41.27430.645R-2-244.22.931.290.552.58.52410.671R-2-351.83.837.6173.678.513.9410.625R-2-438.72.845.786.866.18.72350.625R-2-529.62.120.460.734.73.75450.669R-1 (1536 m measured depth)R-1-118.81.124.365.739.73.04620.745R-1-225.71.740.661.154.95.41490.704R-1-36.00.68.819.313.30.29420.660R-148.90.536.541.846.31.66540.733R-1512.80.811.758.025.41.31570.742	FW-1-5	4.6*	0.4	142.2	79.7	160.9	2.16	30	0.537
A-2 (1269 m measured depth) $3-2 \cdot 1$ $47.8$ $5.5$ $3.4$ $17.2$ $7.4$ $1.27$ $43$ $0.645$ $3-2.2$ $44.2$ $2.9$ $31.2$ $90.5$ $52.5$ $8.52$ $41$ $0.671$ $3-2.3$ $51.8$ $3.8$ $37.6$ $173.6$ $78.5$ $13.9$ $41$ $0.625$ $3-2.4$ $38.7$ $2.8$ $45.7$ $86.8$ $66.1$ $8.72$ $35$ $0.625$ $3-2-5$ $29.6$ $2.1$ $20.4$ $60.7$ $34.7$ $3.75$ $45$ $0.669$ $3-1.1$ $18.8$ $1.1$ $24.3$ $65.7$ $39.7$ $3.04$ $62$ $0.745$ $3-1-1$ $18.8$ $1.1$ $24.3$ $65.7$ $39.7$ $3.04$ $62$ $0.745$ $3-1-2$ $25.7$ $1.7$ $40.6$ $61.1$ $54.9$ $5.41$ $49$ $0.704$ $3-1-3$ $6.0$ $0.6$ $8.8$ $19.3$ $13.3$ $0.29$ $42$ $0.660$ $3-1-4$ $8.9$ $0.5$ $36.5$ $41.8$ $46.3$ $1.66$ $54$ $0.733$ $3-1-5$ $12.8$ $0.8$ $11.7$ $58.0$ $25.4$ $1.31$ $57$ $0.742$	Richfield wel	l (35.3592°N, –118.8018	9°W)						
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	B-2 (1269 m	measured depth)	,						
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	B-2-1	47.8	55	34	17.2	74	1 27	43	0 645
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	R-2-2	41.0	2.0	31.2	90.5	52.5	8.52	40	0.671
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	R-2-3	51.8	2.3	37.6	173.6	78.5	13.0	41	0.625
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	R-2-4	38.7	2.8	45.7	86.8	66 1	8 72	35	0.025
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	B-2-5	29.6	2.0	20.4	60.7	34.7	3 75	45	0.669
$\begin{array}{c c c c c c c c c c c c c c c c c c c $	D 1 (1526 m	manaurad dapth)	<u> </u>	20.1	00.7	01.7	0.10	10	0.000
$\begin{array}{c ccccccccccccccccccccccccccccccccccc$	n-1 (1550 m			04.0	05.7	00 7	0.04	<u></u>	0 745
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	H-1-1	18.8	1.1	24.3	65.7	39.7	3.04	62	0.745
4-1-3       6.0       0.6       8.8       19.3       13.3       0.29       42       0.660         8-1-4       8.9       0.5       36.5       41.8       46.3       1.66       54       0.733         8-1-5       12.8       0.8       11.7       58.0       25.4       1.31       57       0.742	H-1-2	25.7	1./	40.6	61.1	54.9	5.41	49	0.704
4-1-4         8.9         0.5         36.5         41.8         46.3         1.66         54         0.733           R-1-5         12.8         0.8         11.7         58.0         25.4         1.31         57         0.742	H-1-3	6.0	0.6	8.8	19.3	13.3	0.29	42	0.660
1-1-5 12.8 U.8 11.7 58.0 25.4 1.31 57 0.742	K-1-4	8.9	0.5	36.5	41.8	46.3	1.66	54	0.733
	H-1-5	12.8	0.8	11.7	58.0	25.4	1.31	5/	U./42

Because we are most interested in the postdepositional thermal evolution, we divide that portion of the *t*-*T* history into two episodes: an older (pre–6 Ma) episode, for which the tectonic subsidence of the basin is locally known, and a younger, post–6 Ma episode, for which the subsidence and exhumation history is unconstrained through conventional stratigraphic means, due to the lack of post–6 Ma strata preserved across much of the Kern arch. It is this later period we attempt to constrain with our thermal models.

Total subsidence in the Fuhrman well, shown as a green line in Figure 6A, occurs at a mean rate of 0.055 mm/yr between ca. 30 and 6 Ma (Saleeby et al., 2013a). Because they are located at similar structural positions on the Kern arch, we assume that the subsidence history of the Richfield and Dyer Creek wells is similar to that of the Fuhrman well. Using a geotherm of 25 °C/km, heating associated with subsidence is taken to be 1.37 °C/m.y. between the timing of deposition and 6 Ma. The marine depositional temperature is taken to be 5 °C (John et al., 2012). Unlike the other three wells, the Parsons well is located just west of the topographic expression of the arch (Fig. 2) at an elevation of ~100 m. Subsidence in the Parson well occurred at a much higher rate, as indicated by the ~1350 m modern depth of the ca. 7 Ma top of the mainly littoral Santa Margarita sandstone (Fig. 3). Depth-age relations of the Santa Margarita in the Parson well indicate a subsidence rate of 0.19 mm/yr along the western margin of the arch.

Figure 6B shows predicted age-[eU] relationships as a function of the three different burial histories represented in Figure 6A. The gray areas indicate the range of possible age-[eU] given by the range of depositional apatite He ages. In burial history A, subsidence and heating occurs at a rate of 1.37 °C/m.y. from 6 to 1 Ma, whereupon ~400 m of exhumation occurs, reflecting the erosion and removal of Pliocene-Quaternary strata. Apatite (U-Th)/He (ApHe) ages resulting from this burial scenario range between ca. 50 and 80 Ma and are relatively unchanging at [eU] values above 20 ppm. At lower values of [eU], predicted ages become lower and the predicted range of ages becomes smaller, such that at an [eU] of 2 ppm, corresponding apatite ages are 30-40 Ma. Because of the observations suggesting an episode of cryptic subsidence described earlier, we also simulate burial histories B and C, in which a marked pulse of subsidence initiates at 6 Ma, followed by the inversion of strata to their present burial depths and elevation levels. In burial history B, sediments are heated to 60 °C, and in burial history C, they are heated to 75 °C. Resulting apatite age-[eU] relationships follow trends that are similar to, but more pronounced than, that resulting from burial history A. In both cases, ApHe ages are positively correlated with [eU], becoming younger and 

			TABLE 1. A	PAILLE (U-IN)/He L	DATA (continued)			
	Corrected age	_	[U]	[Th]	[eU]	[He]	Radius	
Sample	(Ma)	±2σ	(ppm)	(ppm)	(ppm)	(nmol/g)	(μm)	Ft
Dyer Creek wel	l (35.3761°N, –119.0	07209°W)						
DC-1 (988 m m	easured depth)							
DC-1-1	36.7	2.1	23.3	46.7	34.3	5.09	53	0.736
DC-1-2	49.7	3.2	17.5	52.9	29.9	5.78	50	0.712
DC-1-3	53.2	3.4	28.9	66.2	44.4	8.21	51	0.711
DC-1-4	55.9	3.2	16.5	55.1	29.4	6.93	65	0.769
DC-1-5	39.2	2.9	28.5	85.4	48.6	6.63	39	0.636
DC-1-6	55.6	3.4	15.6	48.9	27.1	6 16	59	0 748
DC-1-7	43.5	27	33.2	38.1	42.2	7 27	55	0 725
DC-1-8	37.3	22	28.5	77.5	46.7	7.03	56	0.720
DC-1-9	48.3	3.3	28.9	42.7	38.9	7.04	45	0.675
Parsons well (3	5.5289°N, -119.195	688°W)						
RCP-3 (1606 m	measured depth)							
RCP-3-1*	5.4	0.6	63.8	98.4	86.9	1.28	26	0.497
RCP-3-2	1.1	1.0	1.22	0.9	1.4	.005	32	0.562
BCP-3-4	11.9	1.8	15.6	39.8	24.9	799	26	0.488
BCP-3-5	31.7	3	66 1	192.0	111.2	9.85	27	0.512
RCP-3-6	40.7	3.4	138	35.6	146.4	18.1	31	0.558
RCP-7 (1743 m	measured depth)							
RCP-7-1	4.7	0.92	3.2	12.4	6.1	0.09	30	0.543
RCP-7-2	9.8	0.76	25.9	131.8	56.9	1.89	43	0.624
RCP-7-3	27.6	2.2	92.6	136.3	124.6	11.2	36	0.596
RCP-7-4	8.7	0.52	23.5	63.1	38.3	1.28	53	0.708
RCP-7-5	3.1	0.32	5.9	35.6	14.3	0.14	35	0.573
RCP-7-6	5.4	0.6	7.7	46.2	18.6	0.33	34	0.578
RCP-7-7	5.1	0.76	6.6	26.3	12.9	0.19	30	0.538
RCP-8 (1890 m	measured depth)							
RCP-8-1	1.3	0.16	5.9	56.1	19.1	0.08	31	0.558
BCP-8-2	2.9	0.2	24.3	35.5	32.6	0.38	58	0 725
BCP-8-3	1	0.1	10.8	40.3	20.3	0.07	37	0.634
BCP-8-4	13.9	14	25.0	73.5	42.3	1 84	35	0.571
RCP-8-5	2.3	0.2	20.3	26.6	26.6	0.23	44	0.683
RCP-2 (2020 m	measured depth)							
RCP-2-1	11.3	0.92	44.8	35.5	53.1	2.00	35	0.610
RCP-2-2	2.8*	0.22	52.7	89.7	73.8	0.72	39	0.624
RCP-2-3	6.3	0.72	20.9	22.2	26.1	0.52	30	0.570
RCP-2-4	2.5	0.16	5.8	10.6	8.2	0.09	49	0.818
RCP-2-5	12.8	0.8	22.4	55.4	35.4	1.79	53	0.718
RCP-2-6	18.8	11	212.2	136.8	244.3	16.8	43	0 671
BCP-2-7	10.9	0.98	20.9	63.1	35.7	1 24	32	0.582
RCP-2-8	9.8	0.54	28.5	51.6	40.6	1.61	55	0.746
Note: [el l]	offective uranium co	ncentration Et. cor	rection factor based	on anatite grain size		1.01		0.7 10
			iconon lactor based	on apalite grain Size				

\*These apatites are flagged as high [eU], young age grains, as discussed in text.

less variable with decreasing [eU]. There is an overall lowering of all ApHe ages across all values of [eU] and an increase in the predicted age-[eU] slope for samples that are heated to higher temperatures. At maximum temperatures above  $\sim$ 120 °C, diffusive He loss outpaces radiogenic ingrowth and apatite ages trend toward zero, independent of [eU].

Maximum burial and by inference maximum heating ca. 1 Ma is constrained by several factors. In the Kern Front oil field, grain crushing textures that indicate ~1100 m of cryptic subsidence has affected the lower Pliocene strata of the Etchegoin Formation. This indicates that the Etchegoin was buried substantially in late Pliocene to early Quaternary time (ca. 3.4–1 Ma). This constraint parallels the stratigraphic constraints discussed above based on the top of the San Joaquin Formation and Corcoran E-clay, and indicating the principal cryptic subsidence phase between ca. 2.5 and 0.61 Ma. Seismic reflection data across the northwest margin of the Kern arch show large clinoforms dipping into the southern and eastern margin of Tulare Basin that are constrained to 2.2-0.6 Ma (Miller, 1999). These clinoforms signal the rise of the Kern arch as a source area for Tulare Basin detritus. Geomorphic studies suggest that basement incision of the lower Kern River gorge below the nonconformity surface off which the Kern arch section was exhumed occurred over the past 0.5 m.y. (Figueroa and Knott, 2010). These relations together indicate a transition from rapid subsidence and sedimentation to rapid uplift and exhumation between ca. 2.2 and 0.6 Ma, nominally ca. 1 Ma. Because the timing of this transition is not very well constrained, we also investigated the distribution of ages and the shape of age-[eU] envelopes for samples that were heated to 75 °C at 5 Ma and at 0.5 Ma. The model predictions are not shown because they are indistinguishable from that of burial

history C, indicating the inability of the thermal simulations to constrain the timing of cryptic subsidence.

As shown in Figure 6B, apatite age-[eU] distributions are sensitive to the peak burial temperatures. They are also sensitive to grain size. The forward modeling of Figure 6 assumes apatite equivalent sphere radii of 40  $\mu$ m, a typical grain size in our data set. For any given [eU], reduction or increase in crystal radius lowers or raises, respectively, the expected ApHe age (colored areas, Fig. 6B). The effect is pronounced at low [eU], less significant at [eU]  $\geq$  100 ppm, and does not change as a function of the peak burial temperature.

The thermal history simulations shown for individual well samples in the following section assume a grain size equal to the average equivalent sphere radius measured from that sample. The standard deviation in radius for apatites in any given sample, however, can vary



Figure 6. (A) Temperature-time (*T*-*t*) paths used in forward modeling of detrital apatite (U-Th)/He data, showing constraints discussed in the text. The shaded gray polygon represents cooling of the Sierra Nevada batholith, the source of the Kern arch sediments. The black line represents the average pre–6 Ma subsidence rate of Kern arch strata in the Fuhrman well area. Burial histories A–C are discussed in the text. The differences in apatite (U-Th)/He age distributions as a function of burial history are shown in B. (B) Shaded envelopes represent the effect of a recent heating and/or burial event on apatite age-[eU] (uranium concentration) relationships. Blue and red semitransparent polygons represent the change in modeled age-[eU] distributions as a function of apatite radius. See the text for discussion of correlation between age and [eU] and shape of the envelope.

from 2 to 8  $\mu$ m. We note that the 20  $\mu$ m range modeled in Figure 6B is greater than the total variability measured in most samples. We also note that although grain size has an important effect on ApHe age, it is overall less significant than small changes in peak burial temperature. As discussed in the following, an increase of only 3 °C in burial temperature changes the predicted ApHe age by ~49% at an [eU] of 5 ppm and ~3% at an [eU] of 90 ppm. Taking the influence of grain size into consideration and allow-

ing for a range of crystal radii would effectively broaden the predicted age-[eU] envelope, making it easier to match the observed age-[eU] distributions, but potentially less sensitive to small changes in peak burial temperature. Grain size and ApHe age are not correlated in any of the samples, and there are no identifiable examples of data plotting outside the best-fit modeled paths that could be fit better by modeling the same thermal history with a different apatite radius.

#### **Thermal History of Kern Arch Sediments**

Burial histories like those shown in Figure 6 are constructed for Kern arch well samples and adjusted for depositional ages and present burial depths. The age-[eU] envelope that is the best fit to the measured apatite (U-Th)/He ages is chosen as the preferred thermal history for a given sample. The best-fit thermal history was determined to be the path that enclosed the greatest percentage of individual grain data, along with associated uncertainties, for a given sample suite. Results for the Fuhrman, Dyer Creek, Richfield, and Parsons wells are summarized in Table 2, shown in Figures 7–11, and discussed in the following.

#### Fuhrman Well

Detrital apatite (U-Th)/He data were collected from three core samples taken at depths of 1100 m, 1280 m, and 1510 m, and assigned depositional ages of 23 Ma, 33 Ma, and 37 Ma, respectively (Fig. 4). These chronologic and lithologic assignments agree with the interpretation of Fuhrman core and log data by Olson (1988) and Hayes and Boles (1993). Apatite ages vary greatly within each sample, but are generally found to decrease with increasing depth, becoming younger than the host depositional ages. The upper two samples (FW-2 and FW-3) have broad distributions of ApHe ages that positively correlate with [eU], a pattern that can only be generated by partial He loss in crystals having diverse He retentivities prior to reheating. We reject grains that have high [eU], but anomalously low corresponding ages. These grains are flagged in Table 1 and in Figures 7 and 11 (for discussion, see the Supplemental File [see footnote 1]).

The apatite age-[eU] distributions in samples FW-2 and FW-3 can be reasonably reproduced by thermal histories in which detrital grains are monotonically buried from the time of deposition to 6 Ma, and then undergo a rapid pulse of subsidence and exhumation, reaching peak temperatures of 70-75 °C at 1 Ma (Fig. 7). Although this thermal history is not necessarily unique, our simulations show that the measured detrital ApHe ages cannot be explained by simple monotonic burial to their present depths (Fig. 7A). Modeled age-[eU] trends are very sensitive to the peak temperatures during the 1 Ma heating event. As shown in Figure 7B, a decrease in peak temperature of 3 °C creates a modeled t-T envelope that is no longer a good fit to the data. Using a geotherm of 25 °C/km and a mean surface temperature of 15 °C, the modeled peak temperatures for FW-2 and FW-3 imply burial to 2200-2400 m. Based on the burial depths of samples FW-2 and FW-3 at 6 Ma at a rate of 0.55 mm/yr, there has been

TABLE 2. SUBSIDENCE AND EXHUMATION ESTIMATES BASED ON AHE AGE-[eU] DISTRIBUTIONS

	Measured depth*	Subsea depth	Depositional age	Peak T	Burial depth <sup>†</sup>	Post–6 Ma subsidence	Post–1 Ma exhumation
Sample	(m)	(m)	(Ma)	(°C)	(m)	(m)	(m)
FW-2	1100	815	23	70	2200	1670	1385
FW-3	1387	1102	33	75	2400	1320	1293
FW-1	1510	1225	37	85	2600	1520	1375
R-2	1270	953	18	83	2720	2460	1767
R-1	1540	1223	23	88	2920	2390	1697
DC-1	988	740	23	73	2320	1790	1580
RCP-3	1600	1483	18	85	2600	1800	1317
RCP-7	1740	1623	20	89	2960	1560	1337
RCP-8	1890	1773	23	88	2920	1120	1147
RCP-2	2020	1903	27	84	2760	760	857

\*Parsons (RCP prefix) well samples are cuttings collected from depth intervals ~50 m in thickness. The average depth is given here. \*Converted from the peak temperature (*T*); assumes a geothermal gradient of 25 °C/km and a surface temperature of 15 °C.

Figure 7. (A, B, C) Individual apatite (U-Th)/He ages, with  $2\sigma$  analytical errors, are plotted as a function of [eU] (uranium concentration) for Fuhrman well samples. (D, E, F) Simulated thermal histories used to reproduce Fuhrman well data using the **RDAAM** (radiation damage accumulation and annealing model; Flowers et al., 2007, 2009) with HeFTy (software; Ketcham, 2005). Also shown are post-6 Ma subsidence and exhumation estimates that result from the modeled peak burial temperatures (T). Simulated age-[eU] distributions are shown as gray fields in A-C. The results of two thermal history simulations are shown in A: one in which burial occurs monotonically following deposition, and one in which FW-2 (Early Miocene Jewett sandstone) is rapidly buried and exhumed after 6 Ma. Shown in B are the results of thermal history simulations in which FW-3 (Oligocene Vedder sandstone) is buried to a peak temperature of 75 °C (best fit to the data) and to 72 °C. The sensitivity of the model to peak burial temperature is highlighted by the difference in simulated age-[eU] envelopes that results from a 3 °C change in peak temperature.



1300–1700 m of 6–1 Ma subsidence, followed by ~1300 m of exhumation (Figs. 7D, 7E).

Apatite He ages for FW-1, near the bottom of Fuhrman well, do not show as clear a relationship with [eU] (Fig. 7C). Ignoring the two young, high [eU] crystals (see following), the best-fit thermal model requires post–6 Ma heating to 85 °C. Alternatively, if the older (ca. 40 Ma) data point is ignored, the remaining ages cluster in a relatively tight band between 1 and 10 Ma, indicating significant resetting of the grains at temperatures >100 °C. We choose the thermal model that best fits the apatites with the lower [eU] values, but acknowledge that we may be underestimating the degree of resetting in this sample. Using the same assumptions previously outlined, heating of sample FW-1 to 85 °C implies post–6 Ma subsidence of ~1500 m and subsequent exhumation of ~1400 m (Fig. 7F). This agrees well with subsidence and exhumation estimates from the two cores sampled upsection. The apatite He results for the Fuhrman well agree with results based on matrix chloritization and albitization of plagioclase. The lowest core sample for which apatites were analyzed was collected at 1510 m and achieved a minimum burial temperature of 85 °C. Chloritealbitization-based temperature estimates from a core sample collected at 1580 m suggest a minimum burial temperature of 90 °C.

#### Richfield Well

Results from the Richfield well, located near the southern terminus of the Kern arch (Fig. 2), are similar to those of the Furhman well. The two analyzed cores (1270 m and 1540 m depths) yielded apatites with a broad range of He ages, which decreased with increasing depth, also becoming younger than the depositional age of the host units. The upper core is interpreted to be from the Olcese sandstone (18 Ma) and the lower core from the Jewett sandstone (23 Ma). The thermal simulations that most closely reproduce the Richfield data indicate a recent pulse of heating to 83 °C in the upper sample and 88 °C in the lower sample (Figs. 8A, 8B). These temperatures correspond to burial depths of ~2700 and ~2900 m and imply post-6 Ma subsidence of ~2400 m and subsequent exhumation of ~1700 m. The burial depths, subsidence, and exhumation recorded in the Richfield data are greater than those recorded in Fuhrman well. Comparing average subsidence and exhumation values between the two wells indicates 40% more subsidence post-6 Ma and 26% more exhumation in the Richfield area. This could result from the Richfield well site being more proximal to the Sierran range front, as well as its structural position within a range front-bounding graben system (Fig. 2).

#### Dyer Creek Well

Material from one cored interval at 988 m depth in the Dyer Creek well was recovered for this study. Sandstones from this depth interval are interpreted to be from the top of the Vedder Formation and assigned a depositional age of 23 Ma (Fig. 4). Apatite (U-Th)/He ages range from 37 to 55 Ma and do not correlate with [eU], although [eU] values in this sample have a relatively restricted range (27–45 ppm) (Fig. 9). Although there is no apparent relationship between age and [eU], forward modeling of the thermal evolution of the Dyer Creek well indicates that the range of measured ApHe ages

Figure 9. (A) Individual apatite (U-Th)/He ages, with  $2\sigma$  analytical errors, plotted as a function of [eU] (uranium concentration) for the Dyer Creek well sample. (B) Simulated thermal history used to reproduce the Dyer Creek well data using the RDAAM (radiation damage accumulation and annealing model; Flowers et al., 2007, 2009) with HeFTy (software; Ketcham, 2005). Also shown are post–6 Ma subsidence and exhumation estimates that result from the modeled peak burial temperature (*T*). Simulated age-[eU] distribution is shown as the grayed field in A.



Figure 8. (A, B) Individual apatite (U-Th)/He ages, with  $2\sigma$  analytical errors, are plotted as a function of [eU] (uranium concentration) for Richfield well samples. (C, D) Simulated thermal histories used to reproduce Richfield well data using the RDAAM (radiation damage accumulation and annealing model; Flowers et al., 2007, 2009) with HeFTy (software; Ketcham, 2005). Also shown are post–6 Ma subsidence and exhumation estimates that result from the modeled peak burial temperatures (*T*). Simulated age-[eU] distributions are shown as gray fields in A and B.

cannot be reproduced by monotonic burial and heating, and rather are fit best by a thermal pulse at 1 Ma reaching 73 °C.

Because there is considerable scatter in the age-[eU] distribution, we inversely model the individual detrital ApHe ages to investigate the magnitude of post-6 Ma heating required by the data. For each ApHe age, 5000 thermal paths, restricted by available time-temperature constraints (blue boxes in Fig. 10), were tested using a Monte Carlo simulation. The path that best fits the measured age for each grain is shown as a black line. Results of this

model demonstrate a required pulse of post-6 Ma heating to temperatures of 63–90 °C, in agreement with the previously discussed estimate of 73 °C. Such a thermal history indicates ~1790 m of post-6 Ma subsidence, followed by ~1580 m of post-1 Ma exhumation.

### Parsons Well

The Parsons well is different than the other three well sites in that (1) it is located at the western margin of the topographic expression of the Kern arch (Fig. 2), and (2) subsurface materials were only available as cuttings, not





intact cores. Cuttings were collected every 10 m in the Parsons well, but because the volume of material from any given interval was small, we combined cuttings from 50 m depth intervals, and used the average depth for each interval in our analysis. Between 1600 and 2000 m depth. 4 intervals with stratigraphic ages between 18 and 27 Ma were analyzed. Apatite (U-Th)/He ages are positively correlated with [eU] in each interval. Forward modeling results and thermal histories that best fit the ApHe age-[eU] distributions are shown in Figure 11. Post-6 Ma subsidence at the Parsons site is estimated to be between ~800 and ~1800 m and subsequent exhumation is estimated to be between ~800 and 1300 m.

# Summary of Kern Arch Apatite (U-Th)/He Results

Results of detrital apatite He modeling show that a recent pulse of heating, which we assert is a function of rapid burial in the eastern San Joaquin Basin, is required to reproduce the observed spread of He ages from any given subsurface sample. Peak temperatures ranged from 70 to 90 °C depending on burial depths. These peak temperatures are consistent with post-6 Ma subsidence of ~1000-2500 m and subsequent exhumation of ~1000-1800 m; available geologic constraints suggest that the onset of surface uplift of the Kern arch and its exhumation started ca. 1 Ma. Maximum burial at 1 Ma requires rapid subsidence at rates of 0.2-0.5 mm/yr and rapid unroofing from 1 Ma to the present at rates of 1-1.8 mm/yr. Quaternary exhumation rates derived from our apatite He modeling are in rough agreement with the ~2.3 mm/yr contemporary vertical motion of the eastern margin of the Kern arch as determined geodetically (Nadin and Saleeby, 2010; Hammond et al., 2012).

Figure 11. (A, B, C, D) Individual apatite (U-Th)/He ages, with  $2\sigma$  analytical errors, are plotted as a function of [eU] (uranium concentration) for Parsons well samples. (E, F, G, H) Simulated thermal histories used to reproduce Parsons well data using the **RDAAM** (radiation damage accumulation and annealing model; Flowers et al., 2007, 2009) with HeFTy (software; Ketcham, 2005). Also shown are post-6 Ma subsidence and exhumation estimates that result from the modeled peak burial temperatures (T). Simulated age-[eU] distributions are shown as gray fields in A-D.

Figure 10. Thermal histories predicted by inverse modeling simulations for the Dyer Creek sample. Blue boxes represent imposed time-temperature constraints based on geologic observations. Black lines represent the best-fit thermal histories to each of the eight analyzed apatite grains. Results of these model simulations require a post-6 Ma pulse of heating to peak temperatures ranging from 63 to 90 °C.

70 Α

60

50

30

20

10

70 в

60

**AHe age (Ma)** 30 30 30

20

10 0

70 С

60

50

40

30

20

10

0

70

60

40

30 AHe

20

10

0

age (Ma) 50 D

AHe age (Ma)

20

20

AHe age (Ma) 40



[eU]

### VITRINITE REFLECTANCE

Three samples with visible coal fragments were extracted from a sidewall core from the Smoot well (Fig. 2). The host for the analyzed amorphous organic material was a mixture of silt, sand, and clay from the Pyramid member of the Jewett Formation (ca. 23 Ma). Samples were collected from depths of between 335 m and 353 m (Fig. 4). As many as 50 reflected light points were measured in each sample, which yielded mean reflectivity (R<sub>o</sub>) values of 0.38%-0.39%, or maximum paleotemperatures of ~68-71 °C (Sweeney and Burnham, 1990) (Table 3). Elevated paleotemperatures for shallow organic material in the Round Mountain field corroborates the previously discussed evidence for a cryptic subsidence event in the Kern arch. Using a mean surface temperature of 15 °C and a geotherm of 25 °C/km, the peak paleotemperatures determined from vitrinite reflectance analysis indicate burial to at least 2 km depth, and subsequent ~1.8 km exhumation of the Jewett sandstone. The temperatures implied by the R<sub>o</sub> measurements are consistent with estimated peak temperatures (70-90 °C) of detrital apatites from deeper subsurface intervals on the Kern arch, as determined from the (U-Th)/He data. Because vitrinite reflectance develops only after sediments with organic material are deposited, Ro values are insensitive to the predepositional thermal history of the sedimentary detritus. The good agreement between vitrinite reflectance and apatite He thermochronometry estimates of peak temperatures suggest that the modeled predepositional

	Measured depth		Mean reflectivity R	Standard	Peak T	Burial depth*		
Sample	(m)	n	(%)	deviation	(°C)	(m)		
RM-1	335	50	0.38	0.036	68.7	2148		
RM-2	344	19	0.39	0.038	70.5	2220		
RM-3	354	15	0.38	0.054	68.7	2148		
*Convertee	*Converted from the peak temperature ( $T$ ); assumes a geothermal gradient of 25 °C/km and a surface $T$ of 15 °C.							

thermal paths are appropriate for Kern arch detrital apatites, and the assumptions used to construct them are reasonable.

## CONTEMPORARY THERMAL STATE OF THE KERN ARCH

Before applying our thermochronometric findings to the interpretation of recent Kern arch subsidence and exhumation, we first consider the possibility that Neogene volcanism and/or hydrothermal activity influenced our results. Neogene volcanism is well documented in the southeastern Sierra Nevada and Tehachapi-San Emigdio Ranges (Dibblee and Louke, 1970; Sharma et al., 1991) (Fig. 2). These volcanic centers are in regions ≥50 km to the east and south of the Kern arch, and are therefore not thought to have influenced the thermal history of the arch. Late Cenozoic volcanism is absent in the area of the Kern arch, as determined by detailed study of oil well log and core sections in conjunction with this study (and with Maheo et al., 2009; Saleeby et al., 2009, 2013a). Of greater concern is the possibility of disturbance by active hydrothermal systems that may occur locally in the Kern arch. In Saleeby et al. (2013a), it was noted that the southwestern Sierra Nevada and possibly the adjoining Kern arch area are above a contemporary thermal transient zone, defined by the local penetration of warm and hot springs through Sierran batholithic basement, that is characterized by very low observed heat flow (Saltus and Lachenbruch, 1991; Laney and Brizzee, 2003). The Mount Poso and Round Mountain oil fields (Fig. 2) are notable, with regard to the dispersed hydrothermal systems, in that they show anomalously high downhole temperature measurements (Saleeby et al., 2013a).

In Figure 12, the thermometric results of the apatite He HeFTy modeling, vitrinite reflectance, and chloritization-albitization relations are plotted along with downhole temperature determinations for each well studied (Table 4); our thermometric results plot distinctly to the high-temperature side of the downhole temperature determinations. These graphic relationships show that the thermometric systems that we studied were set in a completely different thermal regime than that existing today. We further note that the Parsons, Dyer Creek, and Fuhrman downhole temperature determinations are on the San Joaquin Basin reference geotherm, while the Smoot and Richfield determinations are displaced to the high-



Figure 12. Temperature-depth plots for downhole temperature (*T*) determinations (Table 4) from wells in which detrital apatite (U-Th)/He and vitrinite reflectance studies have been performed. The range of the San Joaquin Basin (SJB) geotherm is after Graham and Williams (1985), Wilson et al. (1999), and Saleeby et al. (2013a). (A) Downhole temperature determination and apatite He results for Parsons. (B) Downhole temperature determination and apatite He results for Dyer Creek. (C) Downhole temperature determination, apatite He results, and chloritization-albitization constraints for Smoot. (D) Downhole temperature determination and apatite He results for Fuhrman. (E) Downhole temperature determinations and vitrinite reflectance results for Richfield.

TARI F 4	DOWNHOI F	TEMPERATI	IRF DATA

		-	-	
Well	Depth (m)	Т (°С)	Year drilled	Location (T, R, S)
Parsons	2768	82	1995	26S 26E 8
Dyer Creek	990	40.5	1946	26S 27E 9
Fuhrman Bishop #85*	1602 1769	 60	1942 1971	28S 28E 28 28S 28E 28
Smoot	571	40.5	2011	28S 29E 8
Richfield Richfield	610 1191	46.6 54	1945 1945	24S 30E 31 24S 30E 31

*Note:* Temperature (T) data were taken from virgin wells drilled prior to fire or steam flooding, or in fields lacking a history of such. Chosen wells were also screened to exclude those without an appropriate equilibration time interval between drilling and temperature logging. T—township; R—range; S—section; Dash—no data.

\*Adjacent well with same log signature as studied well used as proxy for temperature data

temperature side of the geotherm. The Smoot and Richfield well sites have undergone the greatest amount of post-1 Ma exhumation (Table 5), and their downhole temperature determinations were made mainly at shallower depths than for Parsons, Dyer Creek, and Fuhrman wells. At 2-4 km depths, the heating related to 1.5-2 km of sedimentation over ~5 m.y. (6-1 Ma), or more acutely over 1.5 m.y. (2.5-1 Ma), is on order with the cooling related to ~1.5 km of exhumation over the past ~1 m.y. (Turcotte and Schubert, 2002). Thus, the deep downhole thermal measurements, which are along the reference geotherm in the Parsons, Dyer Creek, and Fuhrman wells, were effectively buffered during the cryptic subsidence to uplift and exhumation cycles. At shallower levels, the thermal transients related to the rapid turnaround in subsidence to exhumation are more pronounced, particularly the post-1 Ma exhumation phase. Accordingly, the Smoot and Richfield data points are lifted off the reference geotherm in the observed pattern (Fig. 12). The likelihood of nonequilibration effects during both the burial and exhumation phases undermines the use of the downhole temperature data as a direct constraint for the amount of exhumation.

Our analysis would be incomplete if we did not consider the potential role of active hydrothermal activity in the area of the Kern arch. In Figure 13 we plot all of the downhole temperature data of Table 4 and Figure 12, along with the data for anomalously hot wells of the Mount Poso and Round Mountain oil fields of the Kern arch (after Saleeby et al., 2013a). The Mount Poso field is located along the topographic crest of the arch, and the Round Mountain field is along a topographic culmination within the range front graben system (Fig. 2). Furthermore, the depth of exhumation into the Tertiary section is greatest in the area of these two fields, and is comparable to that of the Smoot well (Fig. 4) that is along the northern margin of the Round Mountain field. The Mount Poso and Round Mountain downhole temperature arrays are clearly displaced to the high-temperature side of the data from the wells we have included as part of our study (Fig. 13). This pattern may reflect truncation of the local geotherm related to rapid exhumation over the past 1 m.y., comparable to that determined for the Smoot and Richfield well sites (Table 5). Alternatively, the Mount Poso-Round Mountain data array defines a significantly steeper local geotherm (~50-60 °C/km) than the reference geotherm. This cannot be accounted for by recent exhumation alone, and suggests the possibility of local hydrothermal systems beneath the Mount Poso and Round Mountain areas. The localized expression of hydrothermal activity beneath the Kern arch, a region having a contemporary thermal state that appears consistent with that of the adjacent actively subsiding San Joaquin Basin (Fig. 12), is consistent with the scattered warm and hot springs that penetrate the adjacent otherwise uniformly cool Sierran basement.

### APPLICATION OF THE KERN ARCH CRYPTIC SUBSIDENCE-UPLIFT RELATIONS TO THE PLIOCENE– QUATERNARY DELAMINATION OF THE SOUTHERN SIERRA NEVADA BATHOLITH HIGH-DENSITY ROOT

The southern Sierra Nevada is unique among localities where mantle lithosphere removal has occurred, in that the foundered material and its area of removal are imaged by numerous geophysical studies (Biasi and Humphreys, 1992; Zandt and Carrigan, 1993; Jones et al., 1994; Ruppert et al., 1998; Zandt et al., 2004; Reeg, 2008; Schmandt and Humphreys, 2010; Frassetto et al., 2011; Gilbert et al., 2012). Still partly attached to the base of the crust beneath the Tulare Basin (Fig. 1), the anomalous body is interpreted as the partially delaminated eclogitic root (cf. so-called "arclogite" [eclogitic cumulates produced during high volume arc magmatic fluxes] after Anderson, 2005) of the southern Sierra Nevada batholith, as well as its lower envelope of mantle wedge peridotites (LePourhiet et al., 2006; Saleeby et al., 2012). Generic dynamic models of mantle lithosphere removal predict viscous coupling between the crust and mobilized mantle lithosphere, which leads to vertical forces that drive subsidence (Binschadler and Parmentier, 1990; Pysklywec and Cruden, 2004). These models also show that once the mobilized body has detached from the overlying crust, there is a rapid transition to rock uplift. Our findings on the cryptic subsidence and rapid transition to rock uplift and exhumation of the Kern arch are consistent with these models, considering the position of the Kern arch over the margin of the Isabella anomaly (Fig. 1). These generic models focus on the dynamics and surface expressions of Rayleigh-Taylor (RT) instabilities. Criteria developed to distinguish between the dominance of RT behavior versus viscous slab delamination were developed in Göğüş and Pysklywec (2008). Asymmetry in both the geometry of the mobilized body and in the surface displacement patterns is suggested to be indicative of viscous slab delamination. The

TABLE 5 SUMMARY OF	KERN ARCH SUBSIDENCE AND	EXHUMATION RESULTS
	THE THE TOP OF DECIDENCE , THE	EXTINUE

Well	Elevation (m)	Range of sample collection depths (m)	Range of peak temperatures (°C)	Average post–6 Ma subsidence (m)	Average post–1 Ma exhumation (m)
Fuhrman	285	1100–1510	70–85	1500 <sup>†</sup>	1346 <sup>†</sup>
Richfield	317	1270–1540	83–88	2425	1732
Dyer Creek*	248	988	73	1790	1580
Parsons	117	1600-2020	84–89	1187§	1110 <sup>§</sup>
Smoot	239	335–354	69–71	1655	1828

\*Only one sample was collected from Dyer Creek, so ranges and averages are not applicable to data from that well.

<sup>†</sup>Averages for Fuhrman well (FW) are weighted according to the data quality of individual samples, as discussed in the text. FW-2 and FW-3 are given weighting factors of 0.4; FW-1 is given a weighting factor of 0.2.

<sup>§</sup>Averages for Parsons well are weighted according to the data quality of individual samples, as discussed in the text. RCP-3 and RCP-7 are given weighting factors of 0.16; RCP-8 and RCP-2 are given weighting factors of 0.33.



Figure 13. Temperature-depth plots for downhole temperature determinations (Table 4) from wells in which detrital apatite (U-Th)/He and vitrinite reflectance studies have been performed, in comparison to downhole temperature data from hot wells of the Mount Poso and Round Mountain oil fields (from Saleeby et al., 2013a). The locations of the Mount Poso and Round Mountain oil fields are shown in Figure 2. The range of the San Joaquin Basin geotherm is after Graham and Williams (1985), Wilson et al. (1999), and Saleeby et al. (2013a).

Isabella anomaly has rather strong asymmetry (Fig. 1; see Saleeby et al., 2012, fig. 3 therein), and in Saleeby et al. (2013a) strong asymmetry to the corresponding surface displacement patterns was documented. Our results viewed in the local context of the Kern arch and its directly underlying mantle structure are equally applicable to RT and delamination mechanisms, but given the asymmetry and other arguments (outlined in Saleeby et al., 2012, 2013a), we choose to interpret our results in the context of arclogite root delamination.

The geometry of the Isabella anomaly is consistent with an arclogite slab that peeled away from the base of the crust in both east to west and south to north directions, and that is nested within a larger RT instability that formed within hosting lithospheric peridotites (Saleeby et al., 2012). The following sequence of events describing Sierran arclogite root removal was proposed (in Saleeby et al., 2012, 2013a): (1) Middle Miocene RT convective mobilization of the sub-Sierran mantle lithosphere that promoted the initial separation of the eastern

margin of the arclogite root from beneath the eastern edge of the Sierra Nevada batholith; (2) latest Miocene-Pliocene east to west accelerating delamination of the northwest-southeast-trending tabular root beneath the southern Sierra Nevada batholith; (3) late Pliocene megaboudin break-off of the northeastern portion of the delaminating root, which drove a distinct focused pulse of delamination volcanism and focused the root load toward its southern end; (4) latest Pliocene-Quaternary transition from the east to west to the south to north pattern of delamination along the southern end of the residual root; and (5) the currently active northward-rolling back of the southern end of the delaminating material, leaving the residual root attached beneath the Tulare Basin (Fig. 1). The transition from the east-west to south-north phases of delamination resulted in the northern linear to southern curvilinear trace of the of the delamination hinge (Figs. 1 and 2). Study of the topographic surface shown in Figure 1 shows that the delamination bulge extends along the southern Sierra region, and turns westward into the eastern San Joaquin Basin as the Kern arch.

Delamination-related epeirogenic patterns that are expressed along the axial to eastern San Joaquin Basin as latest Miocene-Pliocene anomalous subsidence are shown by our work to have paralleled the entire northwest-southeast extent of the east to west delaminating root (Fig. 14). This would correspond to the cryptic subsidence episode of the Kern arch area that we have resolved herein. Such cryptic subsidence was in continuity with anomalous subsidence of Tulare Basin. Delamination-driven anomalous subsidence along the entire eastern San Joaquin Basin was paralleled by eastern Sierra rock uplift in the area of the delamination bulge. As delamination transitioned into the present south-north pattern, the delamination bulge propagated into the southeastern San Joaquin Basin as the Kern arch, leaving the current Tulare Basin centered over the residual root (Fig. 1). This corresponds to the transition from delamination-driven (cryptic) subsidence in the area of the arch to delamination-driven rock and surface uplift of the arch (Fig. 14). This was accompanied by the advection of high temperatures into the lower crust of the area of the arch and adjacent western Sierra, above the area of principal delamination, expressed at shallow crustal levels as localized hydrothermal fluxing. The transition to southnorth delamination also saw a change in eastern Sierra frontal faulting, where in the south, active frontal normal faulting stepped over to the Kern Canyon fault system (Saleeby et al., 2009; Nadin and Saleeby, 2010). Quaternary normal fault scarps of the Kern Canyon system diverge in trend from the main eastern escarpment breaks by fanning westward, and thereby mimicking the younger curvilinear trace of the delamination bulge (Fig. 2).

### CONCLUSIONS

The thermometric data presented here are the first to quantitatively constrain both positive and negative vertical surface displacements predicted by thermomechanical models of mantle lithosphere delamination. We have focused our study on the Kern arch, an uplifted section of Cenozoic strata in the southeastern San Joaquin Basin, because it is strategically located with respect to the current position of the actively delaminating body (Fig. 1). Cryptic subsidence, as evidenced by detrital matrix chloritization and plagioclase grain albitization, and mechanical granulation of detrital grains during Ca zeolite growth all at anomalously shallow modern depths, was further explored using detrital apatite (U-Th)/He thermochronometry, and vitrinite reflectance across the arch. Results from these pursuits are mutually consistent, suggesting a post-6 Ma burial and heating event, followed by rapid unroofing in the past 1 m.y. Burial of the Kern arch strata we studied is estimated to have resulted in heating to at least 70-90 °C ca. 1 Ma, anomalously warm for current depths. By combining burial temperatures with modern burial depths, and constraints on the geothermal gradient, we estimate that Kern arch strata underwent ~1000-2400 m of Pliocene-early Quaternary subsidence that cannot be directly documented by conventional stratigraphic means. This is notable because (1) post-6 Ma rocks have been erosionally stripped from the surface of the arch, making this subsidence cryptic, and (2) our estimates require recent subsidence to have occurred at rates significantly greater than those typical of monotonic burial in a late-stage forearc basin. For example, subsidence in the Fuhrman occurred at a mean rate of 0.055 mm/yr from 40 to 6 Ma (Olson, 1988; Saleeby et al., 2013a), but at rates of 0.2-0.5 mm/yr in the period 6-1 Ma. These rapid Pliocene-early Quaternary subsidence rates can be explained by viscous coupling of dense delaminating arclogite root with the lower crust of the southwestern Sierra Nevada-southeastern San Joaquin Basin region. This cryptic subsidence was in continuity with anomalous subsidence determined for the Tulare Basin (Saleeby et al., 2013a), which is currently centered above the residual arclogite root where it remains attached to the base of the crust, and thus continues its anomalous subsidence.

Elevated temperatures inferred from vitrinite reflectance data and anomalously young detrital ApHe ages in strata at shallow present depths require a rapid pulse of exhumation immedi-



Figure 14. Total (red) and tectonic (dark blue) subsidence curves calculated using methods from Allen and Allen (1990) and Watts (2001) for oil wells located in the Tulare Basin and wells studied by us on the Kern arch. Well locations are shown in Figure 2. Curves A and B are after Moxon and Graham (1987), C and D are after Saleeby et al. (2013a), and others were determined by us (see the Supplemental File [see footnote 1]). In D-H, the post-6 Ma cryptic subsidencerock uplift curves are derived from the Table 5 data compilation as well as geologic relations discussed in the text suggesting a ca. 1 Ma transition from maximum burial to rock uplift. The light blue line on plots is the eustatic sea level from Haq et al. (1987).

ately following the cryptic subsidence event. We interpret the onset of unroofing to have occurred ca. 1 Ma based on a number of geologic relations. We estimate that ~1000-1800 m of Kern arch strata were unroofed after 1 Ma as a function of position on the arch, which in turn suggests Quaternary exhumation rates of 1.0-1.8 mm/yr. An episode of rapid unroofing is expected following detachment of a dense delaminating slab and its replacement by buoyant asthenosphere. Furthermore, exceptionally rapid exhumation estimated through our analysis of the stratigraphic record is consistent with vertical displacement of the Sierra Nevada determined geodetically (Fay et al., 2008; Nadin and Saleeby, 2010; Hammond et al., 2012), providing an important link between geologic and contemporary uplift rates. The profound cryptic subsidence phase and rapidly superposed rock and surface uplift phase that we have determined for the Kern arch segment of the eastern San Joaquin Basin are consistent with the timetransgressive three-dimensional delamination pattern that first drove uplift along the eastern Sierra Nevada principally in the Pliocene, and then rapidly transitioned across the southern Sierra Nevada and into the eastern San Joaquin Basin in the Quaternary.

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