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Raman thermometry and (U-Th)/He thermochronometry reveal Neogene transpressional exhumation in the Nacimiento block of central California, USA

B. Lacroix[1], A. Lahfid[2], C. Ward[1], N.A. Niemi[3], A.D. Chapman[4], W. Jarvis[1] and P.D. Kempton[1]
[1]Department of Geology, Kansas State University, Manhattan, Kansas 66506, USA
[2]Bureau de Recherches Géologiques et Minières (BRGM), 45060 Orléans, France
[3]Department of Environmental and Earth Science, University of Michigan, Ann Arbor, Michigan 48109, USA
[4]Geology Department, Macalester College, St. Paul, Minnesota 55105, USA

ABSTRACT

We present a novel approach for mapping vertical uplifts in exhumed metasedimentary rocks by coupling Raman spectroscopy of carbonaceous material with (U-Th)/He thermochronometry on apatite and zircon. We apply this approach to carbonaceous metasedimentary rocks of the Franciscan subduction complex, exposed in the Nacimiento block of central California, USA, an area that records high-pressure–low-temperature metamorphism prior to entrainment within the present-day transform plate boundary. We reveal the extent and magnitude of previously unrecognized exhumation gradients, which, combined with regional structural observations, can be used to quantify vertical crustal motion associated with localized transpression. We propose that the Nacimiento block was affected by a kilometer-scale, post-subduction thermal anomaly linked to a localized transpressive regime since ca. 25 Ma, with an uplift rate of ~0.3 mm/yr.

INTRODUCTION

Transpression is a common style of deformation along transform plate boundaries that may result from variation in fault geometry, oblique convergence, or strain localization along contrasts in lithospheric strength (Molnar and Dayem, 2010; Cooke et al., 2020). Because regions of localized transpression generally lack syn-deformational sedimentary records, low-temperature thermochronometry is often the preferred tool for reconstructing the initiation age, rate, and magnitude of vertical exhumation (e.g., Ducea et al., 2003). Such studies are frequently undertaken along active restraining bends, where the development of significant topographic relief serves as a proxy for the identification of transpressive uplift (Spotila et al., 2001; Ducea et al., 2003; Niemi and Clark, 2018). However, in cases of minimal topographic expression (e.g., due to low uplift rates, rapid erosional removal of topography, or the cessation of transpressional uplift), the identification and quantification of transpressive deformation may be challenging. Regional thermal structure mapping using Raman spectroscopy of carbonaceous material (RSCM; e.g., Beyssac et al., 2002; Lahfid et al., 2010; Boutoux et al., 2016) can identify regions of localized exhumation, providing both a target for the collection of low-temperature thermochronometric data, as well as information on peak burial temperatures that are complementary to the thermal modeling.

We followed this approach through a study of the Central California Coast Range, USA, which underwent a transition from Late Cretaceous subduction-related metamorphism to early Miocene strike-slip deformation resulting from the northward migration of a slab window associated with growth of the Pacific–North America transform plate boundary (Atwater, 1970; Atwater and Stock, 1998). Significant vertical deformation and topographic uplift have subsequently occurred along the San Andreas fault and associated transform faults (Dumitru, 1991; Ducea et al., 2003), although regional patterns and magnitudes of transpression throughout the Coast Range remain cryptic (Ducea et al., 2003; Steely, 2016). We present a new high-resolution peak temperature map of the Nacimiento block, derived from RSCM and integrated with apatite and zircon (U-Th)/He thermochronometric data, to delineate a complex spatial pattern of late Cenozoic regional heating and exhumation.

THE NACIMIENTO BLOCK

The Franciscan Complex of the Nacimiento block (Fig. 1) is an exhumed accretionary terrane associated with the subduction of the Farallon oceanic plate under the western margin of North America (Ernst, 1980). It is bounded to the east by the Sur-Nacimiento fault, to the south by the Santa Ynez fault, and to the west by the San Gregorio Hosgri fault (Fig. 1). The Franciscan Complex is composed chiefly of Late Cretaceous clastic sedimentary rocks with volumetrically minor inclusions of chert, basalt, and serpentinite, all equilibrated under high-pressure–low-temperature (HP-LT) conditions (e.g., Ernst, 1980; Underwood et al., 1995, Ukar, 2012; Wakabayashi, 2015; Ukar and Cloos, 2019).

Based on metamorphic assemblages of metasandstones, Ernst (1980) divided the Nacimiento block into three zones (from west to east): zone I—calcite and K-felspar–bearing; zone II—pumpellyite-bearing; and zone III—lawsonite ± jadeitic pyroxene–bearing (Fig. 1B). Estimated peak metamorphic temperature and pressure conditions increase from ∼150 °C to ∼300 °C and ∼200 MPa to ∼800 MPa, respectively, from west to east (Cloos, 1982). Age constraints on regional metamorphism of clastic rocks in the Nacimiento Franciscan are sparse, although existing K-Ar whole-rock and $^{40}Ar/^{39}Ar$ detrital K-feldspar ages generally fall in the 93–70 Ma window (Suppe and Armstrong, 1972; Underwood et al., 1995). Based on vitrinite reflectance, Underwood et al. (1995) estimated peak temperatures of up to ∼300 °C and recognized the existence of a local post-metamorphic thermal anomaly in the vicinity of Cape San Martin and Alder Peak (Fig. 1B). The vitrinite

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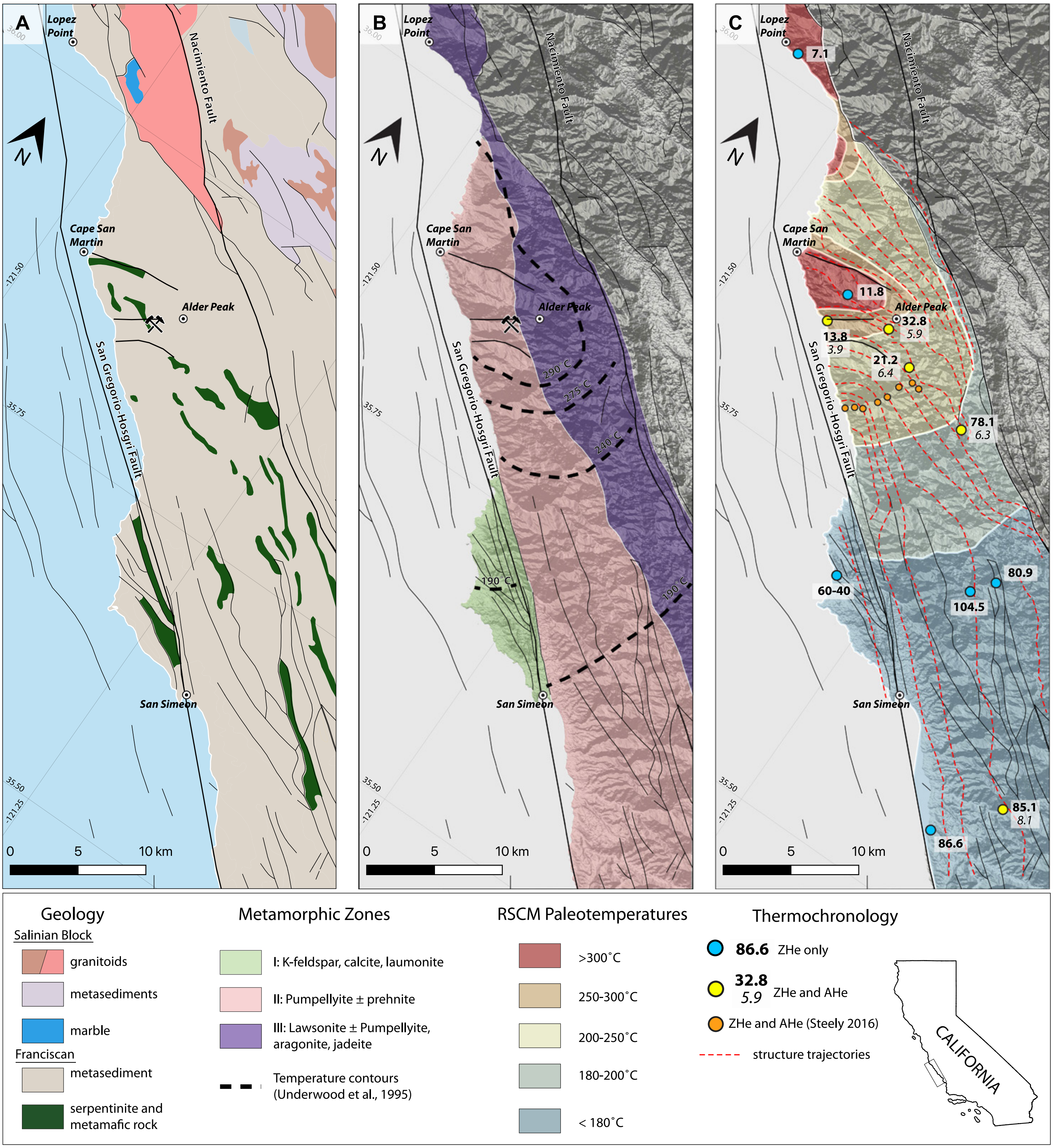

Figure 1. (A) Simplified geologic map of the Nacimiento block. (B) Franciscan metamorphic zones are from Ernst (1980), and paleotemperature contours are from Underwood et al. (1995). (C) Shaded-relief digital elevation models showing the distribution of peak Raman spectroscopy of carbonaceous material (RSCM) temperatures interpreted from 47 analyzed samples and apatite (AHe) and zircon (ZHe) (U-Th)/He ages (in Ma) for the Nacimiento block. Locations of RSCM samples are given in Table S1 (see footnote 1). Regional structural trajectories of the principal fabrics (fold axial trace, bedding, and foliation) are marked with red dashed lines (some of the structural data are from Graymer et al. [2014]).

isoreflectance contours cut across regional metamorphic isograds (Fig. 1B), further supporting that the thermal anomaly post-dates subduction. However, the distribution of Underwood et al.'s samples was primarily along the coast, adjacent to the San Gregorio Hosgri fault, and did not capture the thermal structure of the entire Nacimiento block.

PEAK TEMPERATURE DISTRIBUTION IN THE NACIMIENTO BLOCK

We investigated peak temperature distribution for rock samples across the Nacimiento block by applying RSCM thermometry to 47 samples (Fig. 1C). The samples are lithic sandstones containing abundant quartz, albite, muscovite, chlorite, and carbonaceous material (CM).

Peak temperatures for each sample were calculated using the parameter RA1 proposed by Lahfid et al. (2010), which has been empirically calibrated in the range 200–350 °C (Table S1 in the Supplemental Material[1]). Details on RSCM measurement conditions and data processing are provided in the Supplemental Material. RSCM peak temperature estimates vary from <180 °C near San Simeon to ~300 °C near Lopez Point (Fig. 1C; Fig. S1). The well-defined northwestward increase in peak temperature highlighted by RSCM is consistent with the paleotemperature gradient generated by exposure of more deeply buried metasedimentary rocks through differential uplift (Ernst, 1980; Underwood et al., 1995). Moreover, our RSCM temperature map reveals the presence of a kilometer-scale, east-west–trending paleothermal anomaly (peak temperatures of 300−360 °C) in the area located between Cape San Martin and Alder Peak (Fig. 1C).

[1]Supplemental Material. RSCM methods and results, (U-Th)/He procedures and thermal modeling, and thermal model sensitivity tests. Please visit https://doi.org/10.1130/GEOL.S.21183529 to access the supplemental material, and contact editing@geosociety.org with any questions.

HELIUM THERMOCHRONOMETRY OF THE NACIMIENTO BLOCK

We used the RSCM temperature map to target metasediments that experienced different peak temperature conditions for low-temperature thermochronometric analysis. We collected 11 samples of sandstones of Late Cretaceous depositional age (ca. 82–98 Ma U-Pb detrital zircon maximum deposition ages; Chapman et al., 2016) for (U-Th)/He analysis. The zircon (U-Th)/He (ZHe) system has a closure temperature of ~180–200 °C, below the observed peak RSCM temperatures (Reiners et al., 2002). Apatite (U-Th-Sm)/He (AHe) analysis was undertaken on a subset of samples along a profile across the RSCM thermal anomaly (Fig. 1C). The AHe system has a closure temperature of 40–70 °C (Farley, 2002).

Apatite ages range from 3.9 Ma in the center of the thermal anomaly to 8.1 Ma ~42 km to the southeast (Fig. 1C). These ages demonstrate that the samples were exhumed recently to near-surface conditions. The ZHe ages are more varied and range from 104.5 Ma to 7.1 Ma, with the oldest ZHe age located in the southern (coldest) part of the study area (Fig. 1C). The majority of the ZHe ages are significantly younger than both the detrital age of the samples from which they were collected and the inferred Late Cretaceous timing of regional HP-LT metamorphism (Ernst, 1980; Underwood et al., 1995; Chapman et al., 2016).

To better resolve the thermal history of the Nacimiento block, we performed inverse thermal modeling on subsets of low-temperature thermochronometric data at various distances from the apparent thermal anomaly (Fig. 2). The modeling was performed using the program QTQt (Gallagher, 2012; http://iearth.edu.au/codes/QTQt/), and our thermochronometric

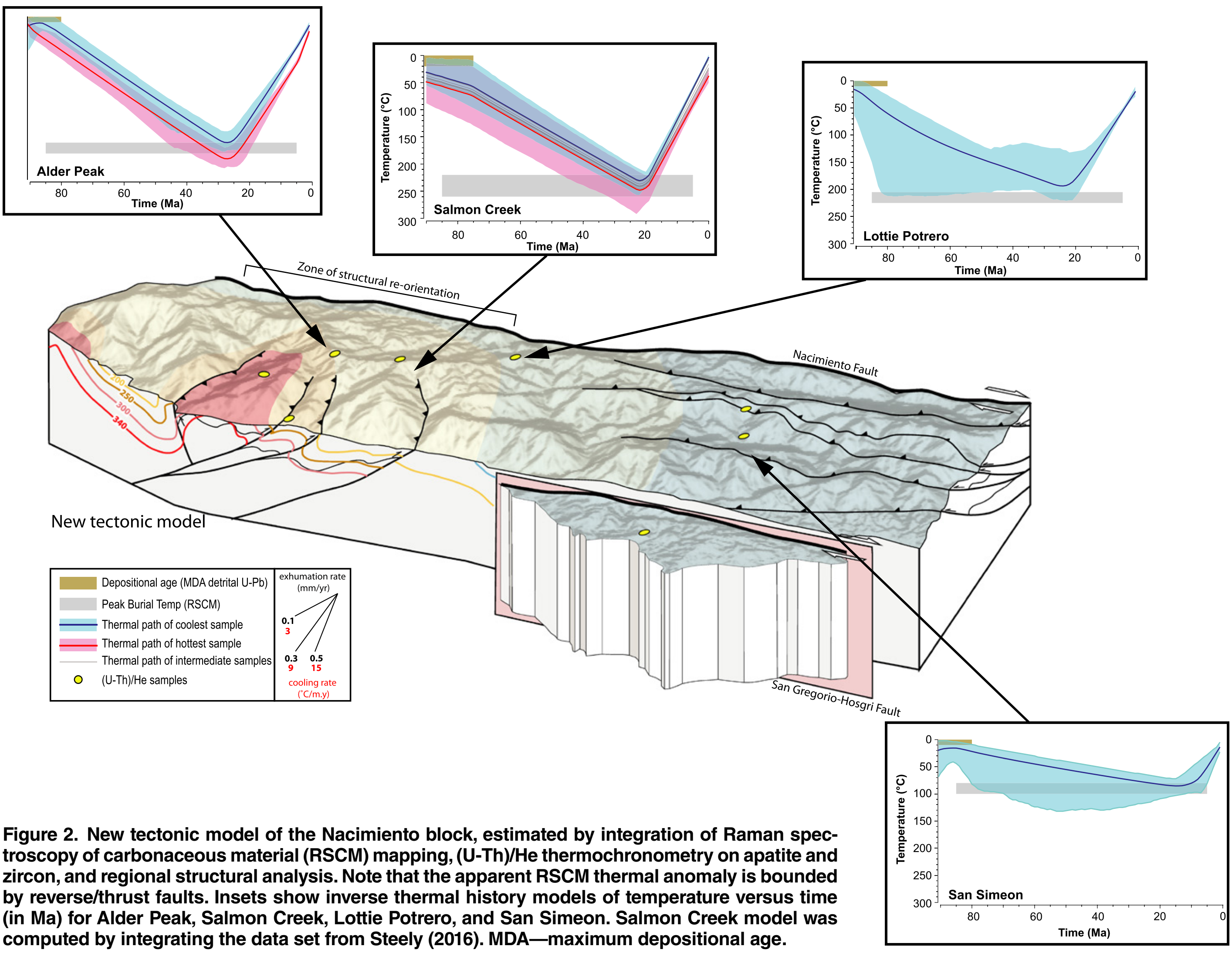

Figure 2. New tectonic model of the Nacimiento block, estimated by integration of Raman spectroscopy of carbonaceous material (RSCM) mapping, (U-Th)/He thermochronometry on apatite and zircon, and regional structural analysis. Note that the apparent RSCM thermal anomaly is bounded by reverse/thrust faults. Insets show inverse thermal history models of temperature versus time (in Ma) for Alder Peak, Salmon Creek, Lottie Potrero, and San Simeon. Salmon Creek model was computed by integrating the data set from Steely (2016). MDA—maximum depositional age.

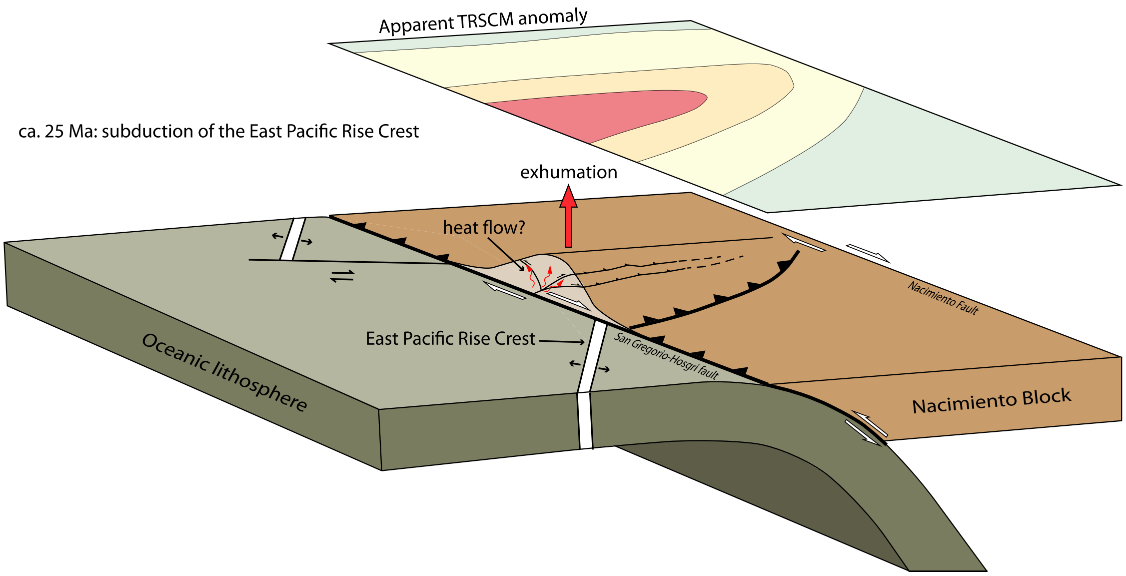

Figure 3. Schematic diagram of oblique subduction of the Mendocino Triple Junction migration beneath the Nacimiento block at ca. 25 Ma. Oblique subduction of the spreading rise produced ridge-parallel shortening that caused the erosion of the restraining bend forming the observed thermal anomaly. Note that some of the required Neogene heating of the Nacimiento block may be attributable to slab-window passage. TRSCM—Temperature Raman spectroscopy of carbonaceous material.

data were supplemented with two other data sets from the Nacimiento block (Table S4; Lori, 2016; Steely, 2016). Inverse thermal models were guided by depositional age information for the samples (Chapman et al., 2016), peak temperatures for each sample derived from RSCM, and present-day surface temperatures.

The inverse thermal models reveal a suite of time-temperature histories along the Nacimiento block that are consistent with protracted subduction-related burial throughout the Late Cretaceous and early Cenozoic, followed by a late Oligocene–early Miocene (ca. 20 Ma) onset of exhumation (Fig. 2). The ages of initiation of the exhumation are robust and, according to our forward models testing a range of burial scenarios, insensitive to burial conditions (see the Supplemental Material). Peak temperatures prior to exhumation decrease southward from ~250 °C at Alder Peak to ~225 °C at Salmon Creek and ~200 °C at Lottie Potrero (Fig. 2). The southernmost sample (San Simeon) reveals a much lower peak temperature (~80 °C) and later onset of exhumation (10–15 Ma) but should be treated cautiously, as this history is constrained by a single AHe age and a RSCM peak temperature below the calibrated range. The calculated cooling rate of the three northernmost samples is ~10 °C/m.y. (~0.3 mm/yr exhumation rate for a 30 °C/km geothermal gradient).

EVIDENCE OF TRANSPRESSIONAL DEFORMATION

The paleothermal anomaly recorded between Cape San Martin and Alder Peak is hypothesized to be the product of a post-metamorphic heating event (Underwood et al., 1995). However, structural analysis of the area shows that most of the fold orientations measured within and near the paleothermal anomaly (at 250°) contrast with the regional accretion-related fabrics (generally oriented 315–350°; Fig. 1C; Graymer et al., 2014; Johnson et al., 2018, Lacroix et al., 2020), suggesting a counterclockwise rotation of ~50–75°. We infer that this structural rotation highlights the presence of an undocumented local restraining bend that accommodates vertical uplift between the San Gregorio Hosgri and Nacimiento faults during dextral movement (Figs. 2 and 3). In active strike-slip settings, motion can be accommodated by local vertical-axis rotation and subsequent transpressional ridge formation (e.g., Spotila et al., 1998). Transpressional uplift and the associated development of folds are well-documented along the southern offshore extension of the San Gregorio Hosgri fault (Sorlien et al., 1999), as well as along other portions of the San Andreas fault system; e.g., the San Bernardino Mountains (Spotila et al., 2001; Niemi and Clark, 2018).

The existence of transpressional deformation is supported by our RSCM temperature distribution map (Fig. 1C), which shows the presence of an apparent thermal anomaly exposing rocks as hot as 336 °C in the area of Cape San Martin–Alder Peak (Figs. 1C and 2). Importantly, this apparent anomaly is spatially and geometrically correlated with the reorientation of the regional subduction-related structures. Additionally, this anomaly is bounded by a series of deeply incised valleys interpreted as thrust/reverse faults (Graymer et al., 2014; Fig. 2). Similar evidence of transpression has been documented by Johnston et al. (2019) along the McWay fault, a well-documented south-vergent thrust fault that marks the northern limit of the apparent thermal anomaly ~20 km north of Lopez Point.

A post-metamorphic heating event associated with local magmatism and hydrothermal gold deposits (e.g., Underwood et al., 1995) predicts a paleothermal anomaly with decreasing thermochronometric ages toward its center, though it fails to explain the structural reorientation discussed above. Indeed, samples collected at the contact of a small magmatic intrusion (sample BG16-70, see the Supplemental Material) and within the Los Burros deposit (Lacroix et al., 2020) did not record high RSCM temperatures (< 280 °C). Instead, we attribute the combination of (1) the apparent temperature anomaly, (2) the structural reorientation, and (3) the young (U-Th)/He thermochronometric ages to the presence of a previously undocumented east-west–trending transpressive zone that developed between the San Gregorio Hosgri and Nacimiento faults (Fig. 1C). Whereas the role of a post-metamorphic heating event cannot be fully excluded, and indeed we suggest here the existence of upwelling material due to impingement of the Mendocino Triple Junction with the California margin, the present-day exposure of a paleothermal anomaly is principally produced by transpressional deformation generating significant uplift in the vicinity of Cape San Martin/Alder Peak relative to the rest of the Nacimiento block to accommodate the shear activities of both the San Gregorio Hosgri and Nacimiento faults.

GEODYNAMIC INTERPRETATION

Thermochronometric ages of Franciscan terrigenous rocks from the Cape San Martin–Alder Peak area are significantly younger than Ar-Ar metamorphic ages (93–38 Ma; Ernst 1980, Underwood et al., 1995) and maximum detrital zircon depositional ages (98–82 Ma; Chapman et al., 2016). We suggest that the paleothermal anomaly area identified by RSCM was generated by significant transpressional exhumation over the past 25 Ma related to shear movement associated with the Pacific–North American plate boundary (Ducea et al., 2003).

Igneous geochronology and offshore magnetic anomaly patterns document the migration of the Mendocino Triple Junction beneath California and the transition of the continental margin from convergent to transform motion (Atwater, 1970; Dickinson, 1997; Atwater and Stock, 1998). Tectonic reconstructions suggest that impingement of the East Pacific Rise crest with the Nacimiento block occurred between 28.5 Ma and 20 Ma, which overlaps with the onset of exhumation as constrained by thermal models (Fig. 2). This similarity between our thermal models and collision of the East Pacific Rise crest suggests that the Mendocino Triple Junction migration may be responsible for both the local uplift and the apparent thermal anomaly (Fig. 3). Considering the angle of convergence between the ridge-transform fault system and the trench, the relative motion between the continental and oceanic plates had a significant dextral strike-slip component to initiate the observed transpressive deformation (Kuiper and Wakabayashi, 2018; Fig. 3). Additionally, development of a slab window in the subducting plate may have caused heating and fluid-flow that enhanced the local thermal overprint (Thorkelson, 1996; Underwood et al., 1999; Kuiper and Wakabayashi, 2018) and emplacement of the Los Burros gold deposit (Underwood et al., 1995; Lacroix et al., 2020).

We suggest that the apparent thermal anomaly recorded within the study area corresponds to one of the earliest expressions of transpressional deformation within the Coast Range of California and formed during the incipient stage of ridge subduction (Fig. 3). Other thermal anomalies have been reported within the Coast Range of California; e.g., the King Range and Point San Luis (Underwood et al., 1999; Underwood and Laughland, 2001). These authors propose alternatives to explain the presence of such anomalies involving either slab window heating or out-of-sequence thrust faults. Interestingly, the anomaly of Point San Luis is spatially correlated to structural grain, suggesting that localized and unsuspected transpressive zones may be common in the Franciscan Complex.

CONCLUSIONS

Tandem use of RSCM and (U-Th)/He thermochronometry permits mapping of the peak temperature distribution of the Nacimiento block, revealing an apparent post-subduction thermal anomaly. Structural data support the development of an apparent thermal anomaly through localized transpressive uplift and potentially heating, both of which are associated with ca. 25 Ma impingement of the East Pacific Rise crest with the Nacimiento block. Thermochronological data and thermal inverse modeling suggest that the area studied corresponds to one of the earliest expressions of transpressional deformation and associated exhumation (~0.3 mm/yr vertical exhumation rate) in the past 25 m.y. caused by the subduction of an ocean ridge.

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