Research Article

Heat Flow Data in an Area of the Eastern Southern Basin and Range in Arizona Contribute to an Analysis of Neogene Lithosphere Thinning Greater than 100 Km

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Heat flow data and thermochronologic derived paleotemperature gradient data are examined to calculate heat flow ~25 Ma and, at present, for a southern Basin and Range location north of Tucson, Arizona. An increase in the surface heat flow is estimated from ~25 Ma to the present; changing from ~47 to ~83 mW m⁻². Steady-state conduction temperature vs. depth profiles provide estimates of lithosphere thicknesses both for the present and for ~25 Ma. Different heat transfer models for present heat flow predict present LAB depth that agrees with seismic studies. From these temperature profiles, lithosphere thinning from ~184 km to ~70 km is suggested during the Neogene. Mantle lithosphere thinning caused by thermal phenomena is likely a fundamental driving force for southern Basin and Range extension. Because the mantle lithosphere has likely thinned much more than the crust, it is shown that additional vertical advection, such as an asthenosphere plume, delaminating part of the mantle lithosphere, convection cells, and rising magmas along conduits, add to the vertical advection component of upper mantle lithosphere extension. Interestingly, values of heat flow 25 Ma, lithosphere thicknesses 25 Ma, and Neogene lithosphere thinning are somewhat similar for the Four Corners area of the Colorado Plateau and the southern Basin and Range, even though Neogene tectonic development was quite different, i.e., no Neogene extension in the Colorado Plateau vs. ~57% in the southern Basin and Range. Neogene lithosphere thinning phenomena are likely different in the two regions.

1. Introduction

Obtaining data-driven estimates of lithosphere thickness ~25 Ma and Neogene lithosphere thinning in different geological provinces of the western United States may provide valuable boundary conditions for geologic models of Neogene tectonics. Geothermal information providing subsurface temperature estimates relevant to a past geologic time can be considered with present heat flow data to estimate the related past lithosphere thickness as well as lithosphere thinning over the corresponding geologic interval. For example, mineralogy and heat flow studies were used to estimate heat flow ~25 Ma for the Four Corners Area of the Colorado Plateau [1, 2] and to suggest Neogene lithosphere thinning of ~100 km for the area. A heat flow-temperature-depth expression, the same as in this study, was used to match upper mantle depth-temperature estimates at ~25 Ma consistent with the mineralogy data relevant at ~70 and ~140 km depth [1, 2]. From this analysis, a heat flow estimate of ~47 mW m⁻² for 25 Ma was possible, and therefore, an estimate of lithosphere thickness could be made [1]. Heat flow analyses also provided estimates of present lithosphere thickness from the present heat flow data for the Colorado Plateau, which was consistent with seismic studies [1]. Lithosphere thinning as proposed for the Colorado Plateau results from a mantle delaminating process or upper mantle layer separation [1, 3]. Interestingly, Axen et al. [4] present a very different mechanism for Laramide tectonics in which flat-slab subduction plows off 20-50 km of lower continental lithosphere across large regions of the western United States.

In the present study, I employ thermochronologic derived near-surface geothermal gradients relative to the
beginning of extension at a location in the southern Basin and Range ~87 km north of Tucson, Arizona (the Grayback normal fault block in the Tortilla Mountains; [5, 6]; Figure 1). Extension is thought to have begun ~25 Ma or 25-20 Ma [5, 6]. This location is quite unique in that more than a dozen present-day heat flow measurements are also available in the area. Differing from the study in the Four Corners area, near-surface paleogeothermal gradients combined with appropriate thermal conductivity data (from [7, 8]) allow preextension heat flow to be estimated at the study location in the southern Basin and Range. Using the derived heat flow estimate for ~25 Ma, the cotemporal lithosphere thickness is calculated. From present-day heat flow data over the study area, the present lithosphere thickness is also calculated, which agrees with seismic studies of lithosphere depth. These calculations show that a significant increase in heat flow over the past ~25 Myr is likely coupled with a major decrease in lithosphere thickness.

The present study area in the southern Basin and Range has experienced considerable Neogene extension and crustal thinning whereas the Four Corners area of the Colorado Plateau has not experienced Neogene extension [9, 10]. In this study, it will be shown that these two very different geologic regions have comparable pre-Neogene (25 Ma) heat flow and rather similar pre-Neogene (25 Ma) lithosphere thickness, as well as a large amount of Neogene lithosphere thinning. Lithosphere separation is proposed as the Neogene lithosphere thinning process in the Four Corners region and may have occurred in the southern Basin and Range as well. However, additional advective mechanisms such as a primary thermal plume, convection cells, and magma migration along conduits are likely present for southern Basin and Range development [11, 12]. Crustal and mantle lithosphere extensions are considered to show the necessity of upper mantle asthenosphere and lithosphere advection in the southern Basin and Range. The present study will develop numerical estimates for southern Basin and Range Neogene lithosphere thinning in Arizona.

2. Data Presentation and Site Relevance

Near-surface geothermal gradients, determined by thermochronologic methods, relating to pre-Neogene (just before crustal extension began ~25 Ma) in the study area (Figure 1) are rather low (17 ± 5°C km⁻¹, [5]; 14 ± 7°C km⁻¹, [6]). The two values average 15.5 ± 2.1 ± 1.5°C km⁻¹ (average ± standard deviation ± standard error of the mean; more study values may provide a more certain mean and reduce the mean uncertainty). Although the study location has undergone a high degree of extension, the location is not within a metamorphic core complex [6, 13]. The present crustal thickness at the study area is ~28.5 km, almost the same as the characteristic thin crust of 28.2 ± 0.5 km for the southern Basin and Range in Arizona [10]. The location is amagmatic,
as opposed to two other paleogeotherm temperature gradient study sites (with higher calculated temperature gradients) located in the lower Colorado River area in a region of major extension [5, 14]. It is suggested therefore that the study locale is a rather representative location of Neogene geologic development occurring in many areas of the southern Basin and Range of Arizona.

Sixteen present-day heat flow measurements at sites within ~50 km of the study locale yield a mean value of 83.1 ± 14.4 ± 3.7 mW m⁻² [7, 8, 13]. Including values within the 99.9% confidence range, the mean of thirteen heat flow values is 84.5 ± 7.7 ± 2.2 mW m⁻² (Figure 1). This value happens to be very similar to the average of seven heat flow values taken over much of the southern Basin and Range in Arizona in plutonic rocks to depths greater than 500 m (84.5 ± 6.1 ± 2.5 mW m⁻²; [7, 8]; Figure 1; deeper tests in plutonic rocks typically allow longer conductive temperature gradient intervals to be observed). Neogene erosion of ~1 km is suggested for the study locale but is also questioned [15]. The present heat flow value for the study area is therefore reduced by about 0.3% (calculated after [16]), giving a heat flow of ~83 mW m⁻². This value is quite similar to the average of a large number of values across the southern Basin and Range (82 mW m⁻²; [13; 157 values]). Therefore, the study location may also be rather representative of geothermal evolution over the past 25 Myr in many areas of the southern Basin and Range in Arizona.

Although the mean thermal conductivity for the thirteen heat flow sites in various rock types for the study area is 3.26 ± 0.30 ± 0.10 W m⁻¹ C⁻¹ (giving a present-day heat flow of 83 mW m⁻²), the thermochronologic study site is located specifically in plutonic-granitic rocks [6]. As such, it is suggested that the mean thermal conductivity value for the seven deep tests greater than 500 m in plutonic rocks across the southern Basin and Range in Arizona best estimates the thermal conductivity at the thermochronologic study location (discussed above). The mean thermal conductivity value for the seven plutonic rock heat flow sites is 3.04 ± 0.44 ± 0.17 W m⁻¹ C⁻¹. It follows the pre-Neogene heat flow is ~47 ± 5 mW m⁻² using the statistical calculation for (15.5 ± 1.5°C k m⁻¹ × 3.04 ± 0.17 W m⁻¹ C⁻¹). Therefore, it is proposed that the near-surface heat flow at the study site in the southern Basin and Range has changed from ~47 to ~83 mW m⁻² over the past ~25 Myr; the change in the heat flow at the Four Corners area over the same time interval is ~47 to ~64 mW m⁻² [1].

3. Temperature-Depth Calculations

The expression used to arrive at first-order approximations to lithosphere temperatures is the steady-state one-dimensional heat flow equation (from equation 4, [17]):

$$T(z) = 1/K((q - DA_o)z + D^2A_o(1 - \exp(-(z/D))))$$ \hspace{1cm} (1)

where $K$ is thermal conductivity, $T(z)$ is temperature at depth $z$, $q$ is near-surface heat flow, $A_o$ is radiogenic heat production at the top of a granitic crustal radiogenic layer where radioactive heat production theoretically decreases exponentially with depth, and $D$ equals 10 km ($D$ is the depth above which all but 1/10^6 of radioactivity occurs). The values presently calculated for $A_o$ in the southern Basin and Range of Arizona is 2.6 ± 1.9 ± 0.8 μW m⁻³ (average for six granite and granodiorite sample values from boreholes ≥ 200 m depth, average depth 482 m) or 2.3 ± 0.8 ± 0.4 μW m⁻³ for four of the sites if values within the 99% confidence level are considered [7, 8]. Sass et al. [13] arrive at a somewhat lower value for radiogenic heat production from crystalline rock over the southern Basin and Range (2.1 μW m⁻³).

Using Equation (1) implies that lithosphere temperatures have been relatively constant for an extended geologic time, which may be hypothesized as a limiting approximation for the pre-Neogene (~25 Ma) initial time condition but will be further discussed for the present. As well as model considerations, the thermal conductivity and radiogenic distributions are always somewhat speculative. Sass et al. [13] discuss non-linear variability of radiogenic heat production $A_o$ vs. heat flow in the Basin and Range resulting from extension and magmatism. Many models of crustal radiogenic distribution (~500, [18]), as well as limited data, contribute to calculated lithosphere temperature uncertainty. The lithosphere thermal conductivity values in the present study are estimated to 200 km depth from average rock type values weighted by the appropriate interval length proportional to the total depth considered (rock type given and extrapolated from [10]; thermal conductivity values from [19]). Interestingly, temperature and pressure effects on mafic lithosphere rock thermal conductivity appear small compared to variation within rock type at room temperature [20].

4. Lithosphere Temperatures and the Lab (Lithosphere-Asthenosphere Boundary)

Figure 2 shows the calculated lithosphere temperatures (using Equation (1)) for heat flows of 47 and 83 mW m⁻². The temperatures related to 47 mW m⁻² estimate the initial temperature distribution proposed for the present study site at about 25 Ma or just before the start of extension. The LAB is suggested to occur at 1300°C or 1573 K [18, 21]. From Figure 2, the LAB appears to occur at ~184 km depth corresponding to near-surface heat flow of 47 mW m⁻².

As mentioned above, the calculated temperature distribution is sensitive to the near-surface radiogenic heat concentration ($A_o$ in Equation (1)). For example, a value of 2.6 μW m⁻³, instead of 2.3 μW m⁻³, would indicate 1300°C at about 210 km depth for a heat flow of 47 mW m⁻², instead of 184 km. In both cases, the preextension lithosphere is suggested to be quite deep, generally consistent with (and possibly the same as) estimates of LAB depths for early Proterozoic areas (200-220 km, [18]; the study site is located in a Paleo-Proterozoic area, [22]). If $A_o$ equals 2.1 μW m⁻³ [13] instead of 2.3 μW m⁻³ as used above, the lithosphere thickness using Equation (1) would still be quite deep for a heat flow of 47 mW m⁻², 170 km.

Figure 2 also shows the calculated present-day temperature-depth profile derived from Equation (1) for a
surface heat flow of 83 mW m$^{-2}$; the LAB at 1300°C is at ~70 km depth ($A_o = 2.3$ mW m$^{-2}$; for $A_o$ equal to 2.1 μW m$^{-3}$, the lithosphere thickness is ~68 km using Equation (1)). This estimate of the LAB is in quite good agreement with seismic study estimates of the LAB for the study location (~70-72 km; [23, 24]). Agreement of the LAB depth between several seismic studies and the steady-state conduction temperature model suggests that advection of heat is moving the temperature distribution much faster than conduction alone. Lachenbruch and Sass [17] also present a steady-state thermal model of lithosphere extension by mantle stretching and crustal intrusion; the predicted LAB is the same as above. Agreement of the LAB depth between the two thermal models likely results from different thermal conductivity and $A_o$ estimates. From these estimates of heat flow ~25 Ma and present day, considerable thinning of the lithosphere in the southern Basin and Range of Arizona over the past 25 Myr is suggested, >~100 km (~114 km = 184 – 70 km). This is somewhat larger than predicted for the Four Corners region in the Colorado Plateau (~100 km; [11]).

In an area of about 50 km in radius centered at 111°W and 32°N, just south of the study location, there are 19 heat flow values [7, 13]. Considering the data within a 99.9% confidence level and applying a small Neogene erosion correction as discussed above, the average heat flow is ~87 mW m$^{-2}$. The resulting LAB calculated as above is 65 km. From seismic studies, the LAB is also ~65 km [23, 24]. Although we have no preextension thermal gradient estimate at this second location, the elevated present-day heat flow data correlating with a relatively thin lithosphere supports the notion that thinning of the lithosphere relates to a thermal source which may be the fundamental cause for extensional tectonic development of the southern Basin and Range.

5. Geothermal Considerations of Lithosphere Thinning

Why the steady-state conduction thermal model (Equation (1)) appears to present accurate estimates of the present LAB depth is rather enigmatic (of course more study sites are needed). Lachenbruch et al. [25] suggest that various advection phenomena during southern Basin and Range extension followed by conductive cooling may be consistent with present heat flow in the southern Basin and Range. The 83 mW m$^{-2}$ temperature profile represents steady-state conduction (Figure 2). Advection processes in the asthenosphere and mantle lithosphere that would bring temperatures of 1300°C from ~184 km depth (25 Ma LAB estimate) to ~70 km depth (present LAB estimate, Figure 2) beginning ~25 Ma must be accompanied by additional advection processes in the mantle lithosphere which bring warmer temperatures closer to the earth’s surface than 70 km. This is because the conduction time constant for 70 km is ~39 Myr (the conduction time constant is the time it takes for the near-surface temperatures to reach within 1/e$^{th}$ of steady state assuming a step continuous temperature increase). If conduction were the sole means of heat transport from 70 km to the surface, while 1300°C was initiated and maintained at 70 km depth 25 Ma (possible maximum boundary conditions), the near-surface temperature (heat flow) would only have increased ~47% of the equilibrium increase in heat flow or about 17 mW m$^{-2}$ for the present case ($0.47 \times (83 - 47 \text{ mW m}^{-2})$).

From another perspective, it may be noted from Figure 2 that steady-state conduction temperatures at the base of the present crust (83 mW m$^{-2}$, ~28.5 km depth; [10]) are the same as those steady-state conduction temperatures at 82 km for heat flow of 47 mW m$^{-2}$ 25 Ma. This involves advection to establish Moho temperatures compatible with surface heat flow of 83 mW m$^{-2}$. Heat delivered and temperatures maintained at the base of the 28.5 km thick crust can provide near-surface almost steady-state temperatures after 25 Myr because the conduction time constant for 28.5 km is ~6.4 Myr resulting in a heat flow increase that is 98% of an equilibrium value.

6. Crustal and Mantle Lithosphere Thinning Calculation

Pre-Neogene (25 Ma) crustal thickness estimates depend on Neogene extension estimates and present crustal thickness. The characteristic crustal thickness for the southern Basin and Range of Arizona is 28.2 ± 0.5 km, at the study site I estimate ~28.5 km [10]. Extension over the entire southern Basin and Range from ~25 Ma (El Paso TX to the North American Plate margin) is ~57% (change in width/initial width; [9]); the ratio of the present width to the initial width is then 1.57. If the cross section area of the crust along cross section remains constant during extension ([10], suggest from seismic data a simple extension of the upper and lower crust),
then the crustal thickness ratio after and before extension is the inverse of the width ratio (or $d/28.2 = 1.57$, where the initial crustal thickness $d = 44.3$ km). If the crustal thickness at the study location is 28.5 km, then the initial crustal thickness is 44.7 km (I use an average of $44.5$ km). The crustal Neogene thinning is $\sim 36\%$ ($\sim 44.5-28.5/44.5$). This compares to lithosphere thinning of $\sim 62\%$ ($(184 - 70)/184$). The ratio of the pre-Neogene crustal thickness 25 Ma to the present crustal thickness is estimated to be $1.57 = a$, whereas the ratio of the pre-Neogene mantle lithosphere thickness 25 Ma to the present mantle lithosphere thickness is $3.4$ ($\beta = 184 - 44.5)/(70 - 28.5)$). Mantle lithosphere thinning would be about 70%. The results are comparable to rifted regions in the Salton Trough and in the Ethiopian Rift/Afar region ($\alpha \leq 2$, $\beta = 2$ to 3, [26]).

It is noted that large areas of the northern Basin and Range across Nevada have a greater crustal thickness and have experienced greater Neogene extension, than the southern Basin and Range ($\sim 37$ km vs. $\sim 28$ km and $\sim 100\%$ vs. $\sim 57\%$; [9, 27]). The preextension crustal thickness in these areas for the present model ($\sim 74$ km) would be quite large even compared with much of the present southern Rocky Mountains’ crustal thickness ($48 \sim 50$ km; [27]). This suggests that additional processes contributed to crustal thickness and crustal extension in these regions of the northern Basin and Range, e.g., possibly extensive crustal underplating and silt and dike formation.

The above calculations suggest much greater thinning in the mantle lithosphere than in the crust for the southern Basin and Range. If a given cross section area of the mantle lithosphere remains the same during the thinning process, then as the mantle lithosphere thins, it should extend much more than the crust extends; alternatively, additional vertical advection in the mantle lithosphere accompanies extension and contributes to its thinning.

7. Heat Input to the New Lithosphere and Crust as Heat Flow Increases from 47 to 83 mW m$^{-2}$

One may estimate the immense heat input to the lithosphere at 70 km accompanying the LAB change from 184 to 70 km depth and the heat flow increase from 47 to 83 mW m$^{-2}$ by subtracting the area under the 47 mW m$^{-2}$ temperature-depth curve, from the surface to 70 km, from the corresponding area under the 83 mW m$^{-2}$ curve (Figure 2); i.e., $\Delta Q$ (change in heat) = ($\Delta$ integrals of $T dz$ from 0 to 70 km) × $c \times \rho$, $c$ is specific heat and $\rho$ is density. Bashir et al. [10] suggest $V s/V P$ and $R$ data for the southern Basin and Range in Arizona, referenced to a typical cratonic region, indicate simple extension of both the upper and lower crusts ($R$ is amplitude of $P$ to $S$ converted wave). Therefore, as a first-order approximation allow the pre-Neogene ($\sim 25$ Ma) upper and lower crust thicknesses to have the same ratio as today (upper crust/lower crust $\sim 1.5$, but does vary along profile, [10]). With the pre-Neogene ($\sim 25$ Ma) thickness of 44.5 km (above), the upper and lower crustal thickness estimates are $\sim 26.7$ and 17.8 km. The three-layer model after Bashir et al. [10] is then adopted (the heat calculations depend mainly on the change in the upper mantle thickness). The pre-Neogene ($\sim 25$ Ma) structure to 70 km is then crust 44.5 km-26.7 km granitic-17.8 km basalti, and upper mantle-25.5 km peridotite; and present structure to 70 km is 17.2 km-granitic, 11.3 km-basaltic, and 41.5 km-peridotite (approximately after [10]). With densities of 2.75, 2.87, and 3.25 kg m$^{-3}$, respectively, and specific heats of 1000, 1100, and 1300 J kg$^{-1}$C$^{-1}$, respectively ([10]: [28]), the heat input to the LAB at 70 km is $\sim 11.2 \times 10^{13}$ m$^{-2}$.

To better illustrate the magnitude of this amount of heat, compare with a surface basalt flow of height “$z$”, the associated heat is $Q = \rho \times c \times T \times z + L \times \rho \times z$. Choosing density and specific heat as above, temperature $T = 1250^\circ$C, and latent heat of solidification $L = 4 \times 10^4$ J kg$^{-1}$ [29], the amount of heat per horizontal square meter in the basalt flow is $\sim 4.62 \times 10^9$ J m$^{-3}$ × $z$. Equating to the amount of heat input at 70 km when heat flow is increased from 47 to 83 mW m$^{-2}$, the estimate $z$ is $\sim 2.43 \times 10^4$ m, or 24.3 km, a remarkable height.

Proceeding as above, consider the heat input into the new crust at 28.5 km as heat flow changes from 47 to 83 mW m$^{-2}$. The calculated heat input at 28.5 km is $\sim 16.6 \times 10^{13}$ J m$^{-2}$, equivalent to $\sim 3.6$ km of basalt flow. As heat flow changes from 47 to 83 mW m$^{-2}$, heat input into the mantle lithosphere would be $\sim 9.54 \times 10^{13}$ J m$^{-2}$ (11.2 $\times 10^{13} - 1.66 \times 10^{13}$), or about 5.75 times the heat input into the crust.

8. Discussion

Heat flow and seismic data integrated with thermochronologic paleogeotemperature gradient data provide an estimate of considerable lithospheric thinning ($\sim 114$ km or $\sim 62\%$) over the past $\sim 25$ Myr at the study location in the eastern southern Basin and Range of Arizona. The difference between crustal thinning and mantle lithospheric thinning proposed from the above calculations, as well as the conduction time constants, suggests considerable vertical upward advective heat transfer to thin the mantle lithosphere. The study location is an amagmatic area with considerable extension, but not in a metamorphic core complex, has a heat flow almost the same as the southern Basin and Range average heat flow (83 vs. 82 mW m$^{-2}$), and a crustal thickness essentially the same as that characterizing the southern Basin and Range in Arizona (28.2 ± 0.5 vs. 28.5 km; [5, 10, 13]). The change from subduction to divergence between the North American and Pacific plate boundary is followed by the beginning of extension across the southern Basin and Range and at the study area as well [5, 6, 9, 30]. For these reasons, I suggest the study area as a potential location for first-order representation of geothermal and extensional processes in many areas over the southern Basin and Range of Arizona.

Figure 3 shows depth estimates from several studies for the Moho and LAB along 33°N across southern Arizona. The LAB shallows dramatically west of 114°W approaching the Salton Sea. East of 114°W, the LAB depth shallows gradually to 110°W and then deepens somewhat to 109°W. The depth of 70 km at 111°W (the study location) appears to be an approximate average depth east of 114°W, although the LAB depths do vary along the profile east of 114°W about...
To further examine lithosphere thinning in the southern Basin and Range, consider a model where mantle lithosphere extension across the southern Basin and Range is limited by the western boundary of the North American plate and the extension across the southern Basin and Range along 33°N latitude.LAB depth estimates from seismic studies ([23]—solid dots; [24]—open dots). Moho depth estimates from seismic studies ([33]—solid squares; [10]—solid inverted triangles; [34]—open inverted triangles).

10 to 16 km depending on the study. It is noted that the depth estimates are ± several km while interpolating the color-coded maps for LAB depth. Further study may better correlate heat flow with the LAB; this has been done in the present study for another site near 111°W and 32°N (above). The crustal depth estimates shallow approaching 115°W and are within several km of one another eastward to 111°W at which point depths appear to diverge going eastward. The study by Bashir et al. [10] shows only a couple km difference in crustal depths east of 114°W along 33°N; the map by Gilbert [27] shows rather uniform crustal thickness of about 28 km across the entire southern Basin and Range of Arizona.

To further examine lithosphere thinning in the southern Basin and Range, consider a model where mantle lithosphere extension across the southern Basin and Range is limited by the western boundary of the North American plate and the eastern boundary of the Pacific Plate and is therefore the same as the crustal extension. One may calculate potential thinning of mantle lithosphere due to extension or spreading for a straightforward geometric model versus separate vertically upward advection not explicitly a component of lithosphere extension (extension or spreading and thinning the mantle lithosphere transports heat both horizontally and vertically, see [17], their Figure 9-8). As before, allow the model cross sectional area along the cross section to remain constant during mantle lithosphere extension and the LAB temperature to also remain constant. In this model, the upward advection associated with mantle lithosphere spreading results from the LAB rising with mantle lithosphere thinning inversely proportional to extension. As mentioned before, overall east–west extension across the southern Basin and Range during the past ~30 to 25 Myr is ~57% (El Paso, TX to the North American plate margin; from [9]). Of course this is an average, but from Figure 3 and previous discussions, it would appear the crustal and LAB depths, as well as extension and heat flow, at the study site are reasonable average approximations across the southern Basin and Range in Arizona. If extension was 57%, the lithosphere thickness after extension may be calculated as the initial depth divided by final depth z: (184/z = 1.57) giving the LAB depth z as 117 km. This represents a first-order estimate, as per the present model, of the effect of vertical heat transport associated with mantle lithosphere extension and thinning. As such, in the present model, additional processes advecting heat vertically upward and involved with lithosphere thinning are necessary to account for the LAB at 1300°C to move an additional ~47 km upward from ~117 km to 70 km (Figure 2). Some of the fundamental advection mechanisms suggested are a rising primary mantle plume inducing convection cells, delaminating parts of the mantle with associated upward advection, and magma motion along conduits (a few references are, respectively, [3, 11, 12]).

The same basic geometric model can be applied to the crust and upper mantle lithosphere. If crustal extension and thinning occurred in such a manner as to preserve Moho temperatures, then preextension temperatures at ~44.5 km (429°C for 47 mW m⁻²) would be brought to ~28.5 km. However, the present heat flow suggests a temperature of ~656°C at 28.5 km; this requires additional heat transfer involving advection in the thinning mantle lithosphere (Figure 2).

Seismic studies of rifted regions in southern California suggest that mechanisms of lithosphere deformation and strain accommodation are unclear; however, a lack of systematic offset between the lower lithosphere and crustal surface deformation agrees with the notion of lithosphere symmetric extension [26]. Colocation of crustal surface rifting evidence and a flat and shallow LAB suggests that deep lithosphere extension and crustal extension are related [26].

Increased elevation and crustal thickness as well as lithosphere thinning can provide deviatoric stresses promoting southern Basin and Range extension; lithosphere thinning with asthenosphere replacement can also increase elevation [30]. Lithosphere thinning warms the remaining lithosphere which decreases its viscosity allowing for easier deformation. Thinning of lithosphere thickness by over 100 km at the study location should provide considerable deviatoric stresses and initially preextension elevation increase [30]. The change from a convergent to divergent plate boundary just beginning ~30 Ma [9] appears to have allowed deviatoric tension to proceed with extension.

Yuen and Fleitout [12] suggest that a primary thermal plume causes strong small-scale convection that thins the lithosphere and reduces viscosity. Their model predicts observed rapid rates of uplift and lithosphere thinning. Lachenbruch et al. [25] suggest that the history of extension in the southern Basin and Range (occurring mainly between 28 and 16 Ma; [30]) indicates advection rapidly changing
lithosphere and crustal temperatures to promote extension, whereas tectonic quiescence post 16 Ma and present relatively high heat flow suggest the absence of advection and gradual cooling by conduction. Van Wijk et al. [31] discuss small-scale convection at the boundary of Colorado Plateau and the Basin and Range driven by a lithosphere step between the two regions. Schmandt and Lin [32] show negative velocity perturbations (dVp/Vp and dVs/Vs) at 75 and 200 km depth over almost all of the southern Basin and Range, suggesting warmer temperatures at considerable depth over a very large region.

The above discussions indicate mantle lithosphere thinning results because of both mantle lithosphere extension and additional vertical heat advection; but mantle lithosphere extension is in turn dependent on lithosphere thinning. A thick crust and a thinning lithosphere result in a potential energy configuration most likely to develop deviatoric stresses [30]. Both the crust and the lithosphere in the southern Basin and Range of Arizona were much thicker ~30-~25 Ma (~44.5 km and ~184 km, respectively, as calculated before) when the Pacific and North American plates just began to diverge. Because a thick crust is conducive for deviatoric stress, it would seem reasonable that lithosphere thinning began with thermal erosion near the LAB caused by a large primary thermal source. The seismic data indicating warmer conditions to depths of at least 200 km under almost all of the southern Basin and Range suggest a very large thermal anomaly at depth ultimately associated with a primary thermal upwelling or plume, subsequent convection to contribute to lithosphere thinning as well as magma movement along conduits is also likely occur [11, 12, 32].

With the thick crust and divergent plate motion, the thinning mantle lithosphere may promote sufficient deviatoric stress to initiate extension. One may suggest that a feedback mechanism could have been operating in the southern Basin and Range. As the mantle lithosphere continues to thin, more extensional stress is generated. However, as the crust extends and thins, extensional stress is decreased. A decrease in thermal activity associated with mantle lithosphere thinning may have brought about a balance between decreasing stresses generated by crustal thinning and increasing stresses generated by mantle lithosphere thinning, arriving at a cessation in southern Basin and Range extension.

Processes that may produce the present lithosphere depth as well as the estimated Moho temperature (Equation (1)) would establish the present LAB by asthenosphere and mantle lithosphere advection and lithosphere extension; upward advection in the thinned mantle lithosphere would establish a new elevated shallower Moho temperature. The crustal temperatures could respond conductively rather quickly to the new Moho temperature (relatively short time constant as discussed above). The high thermal gradient just below the Moho caused by advection may supply heat conductively to maintain Moho temperature after advection and extension stop (after [25]). Crustal intrusion and sill formation have not presently been included. Temperatures shown in Figure 2 between the present Moho and LAB are probably not linear as shown but are instead convex upward as per temperature profiles showing upward fluid movement across a layer. Long-term thermal relaxation should approach temperatures shown in Figure 2 as long as the LAB remains at 70 km.

9. Conclusion

The increase in heat flow sometime during the past ~25 Myr as measured at the study site in the southern Basin and Range of Arizona identifies thinning of the lithosphere caused by thermal phenomena as a probable fundamental driving force of southern Basin and Range extension. The straightforward model presented above suggests lithosphere thinning may be accomplished by both extension and additional thermal advection, while extension is allowed by the change to divergent plate motion.

Data Availability

The data sources are all given in the references cited in the text and presented in the reference list. Several of the primary references are (1) Shearer, C.R., 1979, A regional terrestrial heat flow study in Arizona, (PhD Thesis): Socorro, New Mexico Institute of Mining and Technology. (2) Shearer C.R., and Reiter, M., 1981, Terrestrial heat flow in Arizona: Journal of Geophysical Research, v. 86, p. 6249-6260. (3) Reiter, M., 2014, Heat flow in the four corners area suggests Neogene crustal warming resulting from partial lithosphere replacement in the Colorado Plateau interior, southwest USA: GSA Bulletin, v. 124, no. 7/8, p. 1084-1092, doi: 10.1130/B30951.1. (4) Sass, J.H., et al., 1994, Thermal regime of the southern Basin and Range Heat flow data Province: 1. Heat flow data from the Arizona and the Mojave Desert of California and Nevada: Jour. Geophysical Research, v. 99, p. 22093-22119. (5) Wong, M.S, et al., 2015, Confirmation of a low pre-extensional geothermal gradient in the Grayback normal fault block, Arizona: Structure and AHe thermochronologic evidence: GSA Bulletin, v 127, no 1/2, p. 200-210, doi: 10.1130/B31033.1. (6) Howard, K.A., and Foster, D.A., 1996, Thermal and unroofing history of a thick, tilted Basin and Range crustal section in the Tortilla Mountains, Arizona: Jour. Geophysical Research, v. 1001, no. 81, p. 511-522.

Conflicts of Interest

There is no conflict of interest with respect to the present manuscript.

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