



Limited underthrusting of India below Tibet: $^3\text{He}/^4\text{He}$ analysis of thermal springs locates the mantle suture in continental collision

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During continent–continent collision, does the downgoing continental plate underplate far inboard of the collisional boundary or does it subduct steeply into the mantle, and how is this geometry manifested in the mantle flow field? We test conflicting models for these questions for Earth's archetypal continental collision forming the Himalaya and Tibetan Plateau. Air-corrected helium isotope data ($^3\text{He}/^4\text{He}$) from 225 geothermal springs (196 from our group, 29 from the literature) delineate a boundary separating a Himalayan domain of only crustal helium from a Tibetan domain with significant mantle helium. This 1,000-km-long boundary is located close to the Yarlung-Zangbo Suture (YZS) in southern Tibet from 80 to 92°E and is interpreted to overlie the “mantle suture” where cold underplated Indian lithosphere is juxtaposed at >80 km depth against a sub-Tibetan incipiently molten asthenospheric mantle wedge. In southeastern Tibet, the mantle suture lies 100 km south of the YZS, implying delamination of the mantle lithosphere from the Indian crust. This helium-isotopic boundary helps resolve multiple, mutually conflicting seismological interpretations. Our synthesis of the combined data locates the northern limit of Indian underplating beneath Tibet, where the Indian plate bends to steeper dips or breaks off beneath a (likely thin) asthenospheric wedge below Tibetan crust, thereby defining limited underthrusting for the Tibetan continental collision.

continental collision | Tibetan plateau | mantle helium | structural seismology | Indian lithosphere

One long-standing seismologically driven model of the Himalaya–Tibet orogen—and by implication other continental collisions—is that the Indian plate underplates (underthrusts) much or all of the Tibetan Plateau, implying the lithospheric mantle below Tibet is cratonic Indian mantle (1, 2) (Fig. 1*A*). In an alternative model and description of mountain building, also seismologically driven, India plunges steeply into the mantle (subducts) beneath southernmost Tibet, implying the mantle beneath most of Tibet is “orogenic” and hot (3, 4) (Fig. 1*B*). An essential difference is whether there is an asthenospheric mantle wedge between the Tibetan crust and the downgoing Indian plate (Fig. 1*B*). Here we show with helium isotope data that India subducts beneath an asthenospheric wedge that underlies three-quarters of the Tibetan Plateau.

In Tibet, numerous seismological studies offer conflicting locations of the “mantle suture” [southern limit of orogenic or asthenospheric mantle at the Moho (5)] and hence the extent of incorporation of Indian continental lithosphere into the Tibetan Plateau (1–7) (Fig. 1*A* and *B*). Seismic wavespeed in the mantle is largely a proxy for temperature (8), and some interpret a south-to-north P-wavespeed decrease beneath southern Tibet as marking the northern leading edge of Indian subduction and the mantle suture (3) (red line, Fig. 1*C*), whereas others focus on the continuity from northern India to northern Tibet of surface-wave velocities down to >200-km depth that are consistent with a lithospheric mantle lid (2) (blue line, Fig. 1*C*).

Here we use helium-isotope ratios ($^3\text{He}/^4\text{He}$) measured in all accessible warm and hot springs in Tibet collected across diverse geologic settings such as suture zones, rifts, different host rocks, and different proximity to crustal intrusions. Our data explore the deep structure of the Himalaya and Tibet crucial to understanding the development of the world's largest mountain belt. Our hypothesis is that a “mantle suture” between cold Indian mantle and a hot orogenic Tibetan mantle wedge (Fig. 1*B*) should be identifiable by a boundary or transition at Earth's surface between groundwaters containing entirely crustal $^3\text{He}/^4\text{He}$ ratios and a domain with resolvable primordial mantle ^3He that has ascended from the mantle wedge. We build on similar studies in the Andes that also used helium isotopes from hot springs above a subducting plate to delineate a boundary between crustal-derived and mantle-derived helium domains (9). An

Significance

Our regional-scale geochemical dataset ($^3\text{He}/^4\text{He}$) resolves the geometry of the continental collision between India and Asia. Geophysical images have led to contradictory interpretations that India directly underthrusts Tibet as a horizontal plate or India subducts steeply into the mantle. Helium transits from mantle depths to the surface within a few millennia, such that the ratio of mantle-derived ^3He to dominantly crust-derived ^4He provides a snapshot of the subsurface. $^3\text{He}/^4\text{He}$ data from 225 geothermal springs across a >1,000-km-wide region of southern Tibet define a sharp boundary subparallel to the surface suture between India and Asia, just north of the Himalaya, delineating the northern limit of India at ~80-km depth. The India–Asia collision resembles oceanic subduction with an asthenospheric mantle wedge.

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The authors declare no competing interest.

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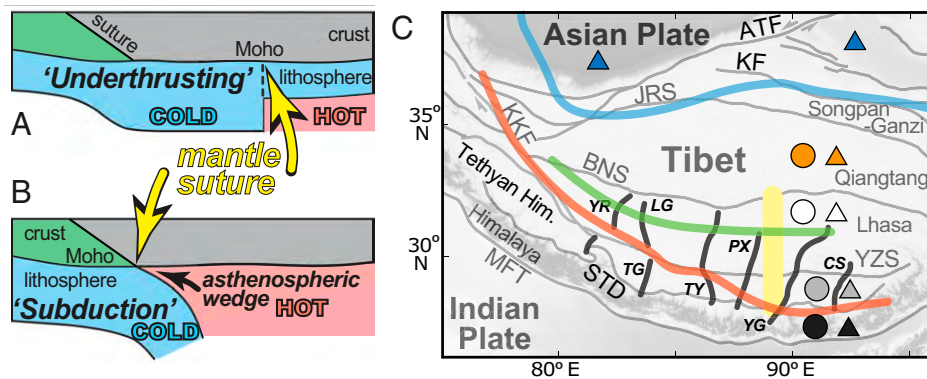


Fig. 1. Alternative geometries of continental collision, and location map. (A and B) Cartoons defining “underthrusting,” “subduction,” and “mantle suture” [boundary of Indian lithosphere with (A) Tibetan lithosphere or (B) asthenosphere]. Blue: cratonic lithosphere (cold); red: asthenosphere (hot). (C) Map (same area as Fig. 3) locating cross-section in Fig. 4 (yellow swath) and previous seismic interpretations: red: mantle suture from body-wave tomography (3); green: crustal front from receiver-functions (7); blue: northern limit of 240-km-thick Indian lithosphere produced by pure-shear shortening (2) intended to reproduce lithospheric thickness mapped by Rayleigh-wave tomography (8). Thin gray lines: sutures/major faults, south to north. MFT, Main Frontal Thrust; STD, South Tibet Detachment; YZS, Yarlung-Zangbo Suture; BNS, Banggong-Nujiang Suture; JRS Jinsha River Suture and major strike-slip faults ATF (Altyn Tagh), KF (Kunlun), and KKF (Karakoram). Thick gray lines: active rifts: YR, Yare; TG, Thakkola graben; LG, Lunggar graben; TY, Tangra-Yumco; PX, Pumco-Xainza; YG, Yadong-Gulu; CS, Cona-Sangri. Colored circles and triangles correspond to geologic terranes and match symbols in Fig. 2 and *SI Appendix, Figs. S2 and S5*.

equivalent surface boundary has also been found in Japan, above the subducting Pacific and Philippine Sea plates (10), that bounds a region of high mantle ^3He correlated with low seismic wavespeeds in the mantle (10). We build on earlier helium-isotope mapping in Tibet (11, 12) but with an order-of-magnitude more data across more diverse geologic settings to allow a continuous and more precise delineation of isotopic boundaries. Our broad geographic coverage spanning 1,500 km demonstrates that different helium domains are not associated with local geology or crustal terrane boundaries, thereby showing that measured ^3He does not represent the modern release of ^3He preserved within the crust from an earlier geologic period. Our database includes 86 springs from which samples air-corrected using ^{20}Ne unequivocally show the presence of mantle-derived helium (*SI Appendix, Table S1*).

The result is a geochemically constrained sharp boundary between a Himalayan domain of only crustal helium to the south and a Tibetan domain with mantle helium to the north. This boundary parallels the geologically defined suture zone for over 1,000 km across Tibet and resolves competing geophysical interpretations for the location of the mantle suture. Our boundary agrees best with tomographic images utilizing body waves (3, 6) and coincides with and helps explain both the northern limit of >65-km-deep earthquakes in the Indian plate (13) and the change in seismicity from dominantly normal faulting in southern Tibet to dominantly strike-slip faulting in central Tibet (14).

Results

New $^3\text{He}/^4\text{He}$ Data in Tibet. Tibet forms one of Earth’s great geothermal provinces, with over 700 warm, hot, and boiling springs (15). In Tibet, local topography drives advective flow to depths of 2 to 5 km (16, 17) so that even the hottest springs require no heat source beyond topographically driven penetration into a crust of average continental heat flux 60 to 90 $\text{mW}\cdot\text{m}^{-2}$ (17). Thus, spring temperatures largely represent depth of groundwater circulation and the extent of mixing between meteoric (shallow) and deeply sourced groundwaters. We systematically sampled 196 distinct spring systems (*Materials and Methods*), some not previously known to science, at elevations up to 5,630 m and temperatures of 6 to 93 °C spanning

1,500 km along- and 500 km across-strike (*SI Appendix, Fig. S1*). We measured $^3\text{He}/^4\text{He}$ of >280 distinct samples from these 196 springs (*Dataset S1*) plus numerous replicates, providing data exceeding our stringent quality criteria (*Materials and Methods*) for 168 spring systems. We supplement our own measurements with previously published data from 29 additional sites, mostly further south (Nepal/India) or north (Tarim/Qaidam).

We measured the $^3\text{He}/^4\text{He}$ ratio (R) of each sample and ratioed it to that in air ($R_A = 1.384 \times 10^{-6}$), giving R/R_A (Fig. 2). We correct for atmospheric contributions using the He/Ne of

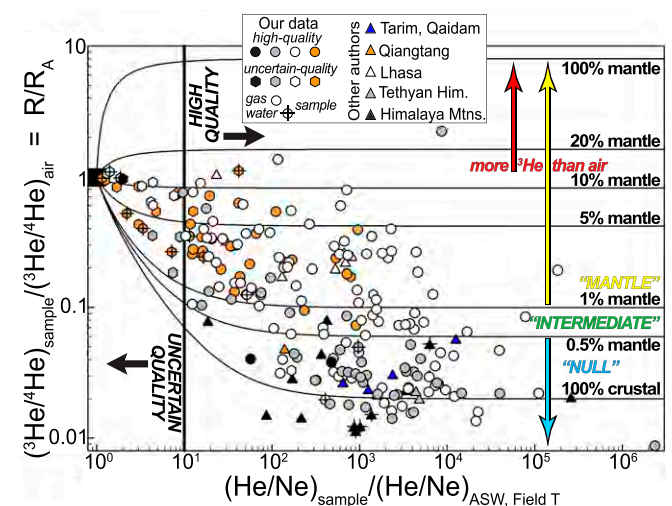


Fig. 2. Isotopic data by Tibetan terrane. R/R_A plotted against $(\text{He}/\text{Ne})_{\text{sample}}/(\text{He}/\text{Ne})_{\text{ASW, Field T}}$. Circles: our “high-quality” data separated by a vertical line at $(\text{He}/\text{Ne})_{\text{sample}}/(\text{He}/\text{Ne})_{\text{ASW, Field T}} = 10$ from hexagons: our “uncertain-quality” data; triangles: all “high-quality” data from other authors. Locations: blue: Tarim and Qaidam Basins; orange: Qiangtang terrane (includes one Songpan-Ganzi spring); white: Lhasa terrane; gray: Tethyan Himalaya; black: Greater, Lesser, and Sub-Himalaya; crosses indicate water samples. Data are superimposed on mixing curves of three end-member components [$\text{mantle} = 8R_A$ and $10^5(\text{He}/\text{Ne})_{\text{ASW}}$, $\text{crust} = 0.02R_A$, $10^5(\text{He}/\text{Ne})_{\text{ASW}}$, and $\text{ASW} = 0.985R_A$ (black square)]. Our “null,” “intermediate,” and “mantle” designations are separated at 0.5% and 1% mantle contributions (corresponding to $R/R_A = 0.06$ and 0.1 at high He/Ne values); red, yellow, blue, and green arrows and lettering correspond to colors in Fig. 3. *SI Appendix, Fig. S2* shows these data after air correction (plotting R_c/R_A instead of R/R_A). All plotted data are listed in *Dataset S1* but only “high-quality” points are plotted in Fig. 3.

air-saturated water (ASW) at the actual temperature, elevation, and salinity of each spring [hereafter $(\text{He}/\text{Ne})_{\text{ASW, Field T}}$], giving R_C/R_A (9, 18) (Fig. 3 and *SI Appendix, Fig. S2*). The mid-ocean ridge basalt mantle end-member is $8 \pm 1R_A$ (18–21), so samples with $R_C > 0.1R_A$ have $>1\%$ of their helium derived from the mantle. Samples with $R_C > 0.1R_A$, despite their continuous dilution by radiogenic ^4He during transport or storage (22, 23), indicate the unambiguous, recent addition of mantle volatiles (18–22) and are here called “mantle” samples. We only report samples as “mantle” if $R_C > 0.1R_A$ and if $(\text{He}/\text{Ne})_{\text{sample}}/(\text{He}/\text{Ne})_{\text{ASW, Field T}} > 10$ and if $[\text{O}_2] < 1\%$ (Fig. 2 and *Dataset S1*). R_C values $\leq 0.1R_A$ are considered ambiguous. The $^3\text{He}/^4\text{He}$ production ratio in Earth’s crust varies from 0.01 to $0.05R_A$ (18–22) but is canonically $0.02R_A$ (18–20), implying that any sample with $R_C > 0.02R_A$ must contain a lithogenic, tritiogenic, or mantle component. Our null hypothesis is that there should be no mantle helium component at the surface of Earth’s thickest crust. In order to essentially preclude false positives (false identification of samples as “mantle”) at the expense of accepting some false negatives (failing to recognize actual “mantle” samples), we term samples with $0.06R_A < R_C \leq 0.1R_A$ “intermediate” and samples with $R_C \leq 0.06R_A$ as “null,” or of crustal composition. Any cutoff value is arbitrary, but our choice of $0.06R_A$ and $0.1R_A$ is supported by the bimodal distribution of sample values (Fig. 3C and *SI Appendix, Fig. S3*) and is consistent with previous helium studies in Tibet and surrounding regions (11, 12, 20, 23). Our helium boundary is robust to different assumptions: Halving or doubling the cutoff values between categories does not materially affect our interpretations (*SI Appendix, Fig. S3B*).

Regional release of primordial ^3He from the mantle across large tectonic provinces requires incipient partial melting (11, 12, 19) and/or a flux of metasomatic fluids (21, 24, 25) and may be enhanced by pervasive strain (19, 20, 25) that assists fluid segregation (26). Less than 0.5% of metasomatic water is needed to lower the mantle solidus to 850°C at 75- to 100-km depth (27). Melt interconnection and melt mobility should prevail down to the coldest temperatures of $(\text{CO}_2 + \text{H}_2\text{O})$ -assisted melting, certainly down to 0.1 vol % melt (28). Even trace melting ($\sim 0.01\%$) very efficiently extracts ^3He from mantle minerals because of its strong incompatibility (partition coefficient $\sim 10^{-4}$) (29). Helium also partitions into metasomatic aqueous fluids to which the upper mantle is permeable at $\geq 800^\circ\text{C}$ if the fluids are even slightly saline (1% NaCl) (30).

Both temperature and age make Indian lithosphere an implausible source for mantle degassing. Indian crust now subducting beneath the Himalaya or underplating beneath Tibet is cold (Fig. 1A and B), with Moho temperature of ~ 420 to 520°C (13, 31) beneath the Himalayan front. Warming during underthrusting is so slow that the Indian Moho temperature would only reach 650 to 700°C beneath the Banggong-Nujiang Suture (13), temperatures sufficient for dehydration and decarbonation reactions but still too low to release helium from mantle minerals. Moreover, Indian lithosphere is Paleoproterozoic to Archaean in age (13, 31) so should exhibit highly elevated $[\text{He}]$ and helium isotopic values consistent with canonical crustal production rates (i.e., $\sim 0.02R_A$).

In contrast, Tibetan mantle is hot and has a Tertiary tectonothermal age as shown by mantle-sourced potassic and ultrapotassic volcanism spanning the Tibetan Plateau (32). Active volcanism in the northern Qiangtang and Songpan-Ganzi terranes (Fig. 3) suggests Moho temperatures $\geq 1,150^\circ\text{C}$ (33). Tibetan mantle has also been metasomatized by CO_2 and H_2O first from the subduction of Tethyan oceanic crust then from

India’s carbonate-rich passive continental margin and the Indian crustal basement with $\sim 1\%$ water (31), as shown by the isotopic contributions from the Indian lithosphere to Neogene volcanics (32). The hot, metasomatized Tibetan mantle wedge above and north of Indian lithosphere is a viable source of ^3He enrichment. Hence, the surface trace of the mantle suture should be marked by a transition between a region of “null” values (i.e., $\leq 0.06R_A$) above old, cold ($< 700^\circ\text{C}$) Indian lithosphere (whether crust or mantle) and a region with widespread “mantle” samples (i.e., $> 0.1R_A$) above the hotter ($> \sim 850^\circ\text{C}$), H_2O - and CO_2 -enriched, incipiently molten Tibetan mantle wedge.

Mapping the Mantle Suture. Fig. 3 includes 86 springs spanning 1,200 km that have unequivocal recent input of primordial ^3He from the upper mantle ($\geq 0.1R_A$) (*SI Appendix, Table S1*). At the scale of the entire orogen (at least 80° to 92°E) we can draw a sharp boundary line between these “mantle” springs to the north and 90 “null” springs to the south. This preferred boundary includes offsets beneath surface rifts and cleanly separates two distinct populations of samples (Fig. 3C and *SI Appendix, Fig. S2A*), lying as it does south of 99% (all but one) of the “mantle” samples and north of 94% (all but five) of the “null” samples from the Himalaya and Tibet plateau. It also cross-cuts surface geological features including crustal terrane boundaries, thereby implying the bimodality arises in the mantle. Alternative interpretations of the data that we considered included a straight-line transition zone more than one crustal-thickness ($> 75\text{-km}$) wide that can achieve an equally good separation of “mantle” from “null” samples only if it encompasses, hence fails to honor, $> 20\%$ of the individual springs (Fig. 3). Alternate boundaries, for example drawn strictly parallel to the Yarlung-Zangbo Suture (YZS) (11, 12), also honor many fewer high-confidence data points (*SI Appendix, Fig. S7*).

In contrast to the clear spatial organization of R_C/R_A values (Fig. 3) there is little geographical organization that would suggest control by other physicochemical parameters (*SI Appendix, Fig. S4*). We see no spatial control on pH, conductance, $[\text{CO}_2]$, or $[\text{CO}_2]/[^3\text{He}]$. The scarcity of high-temperature springs in northern Tibet may suggest the lower topographic relief there does not drive surface fluids to significant depths. A tendency toward higher $[\text{He}]$ content in southern Tibet may correlate with young radiogenic rocks such as the Gangdese batholith and Indian shelf/slope sedimentary rocks and basement in that region. Although high- $[\text{He}]$ fluids require a larger $[\text{He}]$ inventory in order to be recorded as “mantle” samples, the production ratio of $[\text{He}]$ to $[\text{He}]$ in crustal helium ($\sim 0.02R_A$) is independent of $[\text{U}]$ and only weakly dependent on $[\text{U}/\text{Th}]$. Thus, fluids with high absolute concentration of $[\text{He}]$ also have high $[\text{He}]$, and hence $[\text{He}]/[\text{He}]$ (R/R_A) only varies over two orders of magnitude (Fig. 2) despite $[\text{He}]$ and $[\text{He}]$ each varying by greater than four orders of magnitude (Fig. 3C). The consequent strong correlation of $[\text{He}]$ with $[\text{He}]$ (Fig. 3C) and the minimal correlation of R_C/R_A with $[\text{He}]$ ($r^2 = 0.06$) or spring temperature or other physicochemical spring parameters (*SI Appendix, Fig. S5*) show that neither spring characteristics, nor carrier gases, nor high strain rates, nor proximity to Quaternary volcanic sites (*SI Appendix, Fig. S5*) can explain the geographical organization of $^3\text{He}/^4\text{He}$ values (Fig. 3). We conclude that the plateau-wide helium boundary separates distinct mantle provinces.

This helium boundary places the surface expression of the mantle suture as subparallel to and variably 0 to 170 km north of the YZS from 79 to 91°E and up to 100 km south of the YZS from 91 to 93°E . Given that upward transport of mantle

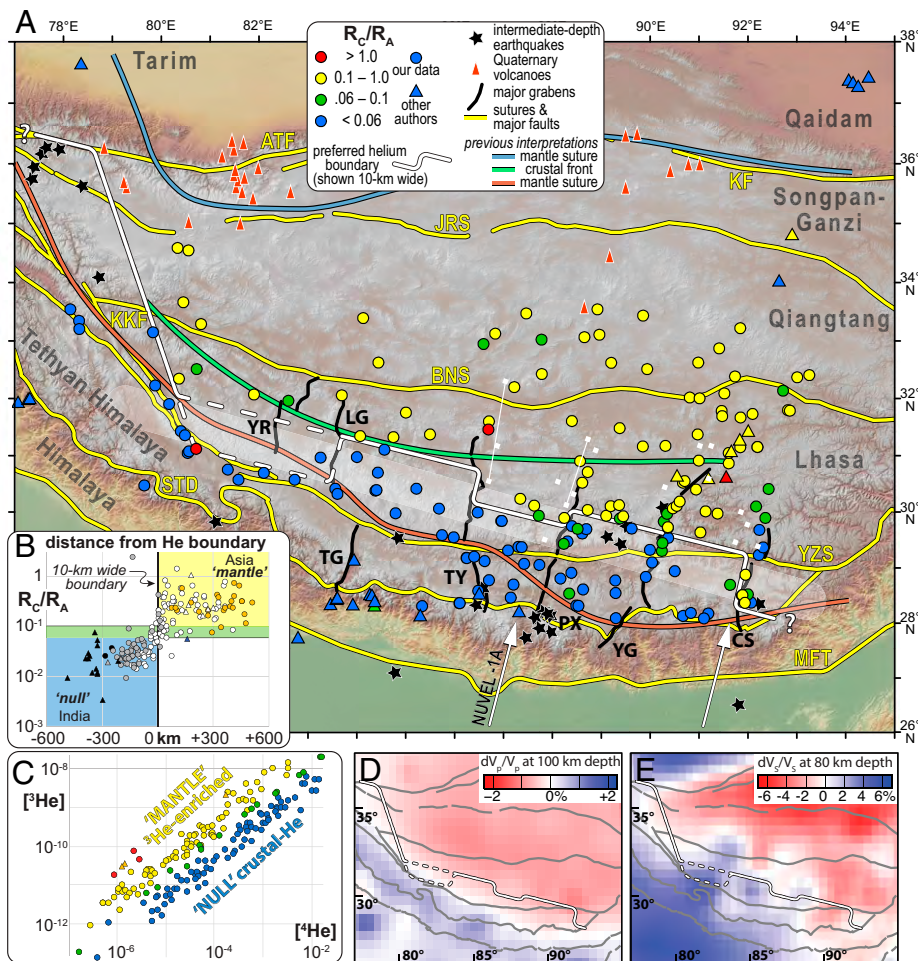


Fig. 3. Distribution of “mantle” and “null” samples. (A) $^3\text{He}/^4\text{He}$ isotope data (R_c/R_a); circles and triangles as in Fig. 2, now color-coded red “mantle” samples $>1R_a$; yellow “mantle” samples $>0.1R_a$; green “intermediate” samples $>0.06R_a$; blue “null” samples $\leq 0.06R_a$. Mantle suture: preferred: thin solid white line shows 10-km-wide helium boundary that 1) separates 99% of “mantle” samples from 96% of “null” samples, dashed where data are sparse, 2) separates 65-to-100-km deep earthquakes (black stars) from Quaternary volcanoes (narrow red triangles), and 3) is further constrained to trend 105° orthogonal to plate-convergence vector (white arrows) and be offset only at active rifts (heavy black lines). Alternate interpretation of helium transition shown as 75-km-wide transparent white line. Small white squares: seismic observations of Moho offsets and abrupt upper-mantle velocity transitions (lines linking squares). Yellow lines: sutures/major faults; black lines: normal faults; blue/green/red geophysical boundaries as in Fig. 1C. (B) R_c/R_a as a function of distance from the preferred 10-km-wide helium boundary (using northern dashed line in A and color-coded by terrane affinity as in Figs. 1C and 2). All samples in the blue “India” null quadrant, yellow “Asia” mantle quadrant, or green intermediate band fit our preferred model. (C) Measured abundance of ^3He vs. ^4He color-coded as in main map, showing clear bimodality (two parallel but clearly separated trend-lines). (D) Seismic body-wave tomography, dV_p/V_p at 100 km depth (3), same area as A, overlain by preferred helium boundary (white line). (E) As in D but showing adjoint tomography, dV_s/V_s at 80 km depth (6). For additional data sources see [SI Appendix, Fig. S7](#).

helium through the lithosphere is within a carrier fluid (18, 19) (carbonic, aqueous, or magmatic) by buoyant, hence subvertical, ascent (9, 23, 34), this surface expression lies above the actual mantle suture. Fig. 3 also plots all earthquakes with hypocentral depths at 65 to 100 km, thereby including events both close above and below expected Tibetan Moho depth. Brittle-failure earthquakes generally require temperatures at ~ 70 -km depth of $\sim 600^\circ\text{C}$ (13) and hence mark the presence of cold Indian lithospheric mantle south of the mantle suture (35), though higher strain rates expected near the transition from underplating to subduction may allow earthquakes near the mantle suture to occur at temperatures up to at least 700°C (36). In contrast, all Quaternary volcanoes in Tibet (Fig. 3)—that suggest higher temperatures, hence the absence of Indian lithosphere, directly below the Tibetan Moho—lie north of our mantle suture. This orogen-scale result requires incipiently melting and/or fluid-fluxed mantle north of the helium boundary and requires that Indian lithosphere does not directly underplate most of Tibet (Fig. 4).

Our preferred helium boundary shown in Fig. 3 (white line) has a location uncertainty ± 5 to 75 km ([SI Appendix, Fig. S3C](#)) due to the irregular availability of springs for sampling, but our preferred abrupt boundary segmented at several rifts that parallel the plate-convergence direction separates 99% of “mantle” samples from 96% of “null” samples. Our abundant “mantle” samples in Tangra-Yumco (TY), Pumco-Xainza (PX), and Yadong-Gulu (YG) rifts north of the YZS are consistent with the Moho offsets and slab tears or fragmentation previously claimed beneath these rifts from seismological evidence (Fig. 3A and [SI Appendix, Fig. S7](#)). An alternative interpretation to our preferred inference of slab tearing beneath the Cona-Sangri (CS) rift would be that these “mantle” samples reflect ~ 100 -km horizontal transport within the crust along the discontinuous normal faults that bound the segmented rift (Fig. 3).

The helium boundary that we associate with the mantle suture is only locally geographically coincident with the Indian crustal front (Fig. 4). The “ 31°N discontinuity” interpreted as the Indian crustal front (7) (green line, Fig. 3, cf. Fig. 1B) is

strongest gas (bubble) flows within the highest-temperature water of highest conductivity. Gas and water samples were collected in refrigeration-grade copper tubes flushed in-line with >50 volumes of sample fluid prior to sealing with stainless steel clamps (44).

Some geothermal springs are single outlets (*SI Appendix, Fig. S1 E, F, G, and I*); others have many tens of spring vents spread continuously over hundreds of meters (*SI Appendix, Fig. S1 A–D and H and Table S1*). We report all outlets within 1 km as a single spring unless they lie in different drainages or have clearly distinct field parameters (e.g., temperature, conductance, pH). Samples >1 km apart, even when along a single fault or river valley, are reported separately. Spring temperatures ranged from 6 to 93 °C (*SI Appendix, Fig. S5A*), plus one fumarole, and two well-head samples at 105 °C and 195 °C (#34 ZGR08 and #100 ZDX14). We collected samples at elevations from 1,934 to 5,634 m above sea level (data from other authors extends down to 307 m above sea level in the Subhimalaya) (*SI Appendix, Fig. S5H*). pH ranges from 6.2 to 9.9 (or as low as 6.0 for data from other authors) and conductance from 0.14 to 14 mS (*SI Appendix, Fig. S5 B and C*). All high-quality “mantle” samples separated by >25 km are listed in *SI Appendix, Table S1*, and complete data are listed in *Dataset S1*.

Laboratory Methods. Fluid samples were extracted from the copper tube on a vacuum line and sonicated for ~30 min to ensure complete transfer of dissolved gases from the extraction vessel to the sample inlet line (45). Major gas components (CO₂, N₂, O₂, Ar, CH₄) were measured at Ohio State University using an SRS Residual Gas Analyzer 300 AMU quadrupole mass spectrometer and a Thermo Fisher Trace 1310 gas chromatograph equipped with a thermal conductivity detector and flame ionization detector (44, 46). Average precision values for each analyte, based on repeated measurements of the Lake Erie Air and DCG Partnership and Praxair natural-gas reference materials, are as follows: [N₂] ±1.91%, [CO₂] ±2.07%, [Ar] ±2.38%, and [CH₄] ±2.56%. Noble-gas elemental and isotopic compositions were measured and corrected (47) using a Thermo Fisher Helix SFT noble-gas mass spectrometer (44, 48). [⁴He], [²²Ne], and [³⁶Ar] concentrations were determined by comparison to monometrically calibrated aliquots of the internal but cross-referenced (49) Lake Erie Air reference material. Average external precision for noble-gas isotope concentrations based on known-unknown standards were ⁴He 1.26%, ²²Ne 1.93%, and ³⁶Ar 0.96%. Helium isotopic values were determined by comparison to Lake Erie Air and the Scripps Institution of Oceanography MM gas reference materials. Average isotopic errors for helium were approximately ±0.0096 times the ratio of air for ³He/⁴He (or 1.330 × 10^{−8}). Helium and neon isotope ratios were corrected for HD⁺, ²⁰NeH⁺, ⁴⁰Ar²⁺, and CO₂²⁺ interferences (47, 50). The average isotopic errors are ²⁰Ne/²²Ne <±0.49%, ²¹Ne/²²Ne <±0.96%, ³⁸Ar/³⁶Ar <±0.89%, and

⁴⁰Ar/³⁶Ar <±0.56%. One hundred seventy-six of the noble-gas data reported from our 196 distinct springs were analyzed at Ohio State University; the remaining 20 samples were analyzed elsewhere (*Dataset S1*) using substantially similar methods.

Atmospheric Corrections. Atmospheric ³He is accounted for and corrected by measuring the atmospheric abundances of air-saturated noble gases (e.g., ²⁰Ne) in crustal fluids and calculating R_c/R_a, which is the ratio of the measured value of ³He/⁴He to the equivalent ratio in air (R_a, 1.384 × 10^{−6}) after correction using the solubility of ⁴He/²⁰Ne in ASW calculated using the field-measured parameters spring temperature, salinity, and elevation. These R_c/R_a values are on average 0.001R_a lower than (R_c/R_a)_{Static T} calculated with a static ASW composition assuming 45 °C, salinity = 0.01 per mil and elevation 4,700 m. Similarly, (He/Ne)_{ASW, Field T} values are on average 0.06 log₁₀ units lower than (He/Ne)_{ASW, Static T}. Our approach is similar to the X-factor (9, 20, 21) but is a more conservative correction, mostly reducing (He/Ne)_{ASW, Static T} values, and excluding data points with (He/Ne)_{sample}/(He/Ne)_{ASW, Field T} ≤ 10 using the geologically more reasonable choice of ASW, rather than air, contamination.

Data Availability. All study data are included in the article and/or supporting information.

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SI Appendix

Limited underthrusting of India below Tibet: $^3\text{He}/^4\text{He}$ analysis of thermal springs locates the mantle suture in continental collision

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This file includes:

Supplementary Text, Figures and Table

1. Quality control, choice of cut-off values and precision of location of the helium boundary or transition.

Fig. S1. Example thermal springs in Tibet.

Fig. S2. Isotopic data by Tibetan terrane, R_c/R_A vs. $(\text{He}/\text{Ne})_{\text{sample}}/(\text{He}/\text{Ne})_{\text{ASW}}$, Field T.

Fig. S3. Tests and effects of different cut-off values for 'null' and 'mantle' samples.

Fig. S4. Spatial variability of physical and chemical parameters of thermal springs.

Fig. S5. Cross-plots of R_c/R_A and physico-chemical data of springs

Table S1. Summary physical/chemical/isotopic data for high-quality 'mantle' samples, R_c/R_A

2. Quantifying spatial and temporal association of the mantle suture with the helium transition.

3. Correlation of the helium boundary with seismological measurements.

Spatial correlations of the helium boundary with seismological measurements.

Seismological constraints on depth of origin of ^3He recorded in surface springs.

Fig. S6. Inferred mantle suture overlain on published seismic models.

4. Possible alternate tectonic associations of the helium transition.

Association with active rifts

Association with Yarlung Zangbo Suture (YZS)

Association with slab rollback in SE Tibet and slab underthrusting in NW Tibet.

Fig. S7. Alternate helium transition parallel to YZS.

Supplementary References All citations in the Supplementary Text and in the Dataset are to these Supplementary References, not to the references in the main article or Methods section, which if necessary are repeated here with the appropriate (different) number.

Caption for Dataset

Other Supplementary Materials for this manuscript include the following:

Klemperer.HeliumMantleSutureTibet.PNAS.2022.Dataset.xlsx contains physical locations, elevations, field data, gas concentrations and isotopic data for samples plotted in Figs. 2 & 3.

The Dataset lists 225 distinct thermal springs (and wells) of which 196 were sampled and analyzed by the authors, and 29 are literature analyses that (to the extent we can tell) meet our quality criteria. The samples span ~1500 km WNW–ESE and ~1200 km SSE–NNW, encompassing ~1,000,000 km².

1. Quality control, choice of cut-off values and precision of location of the helium boundary or transition

We use helium '*boundary*' to mean our preferred interpretation of a sharp (10-km wide) discontinuity that separates 99% of our '*mantle*' values from '*null*' values and we use helium '*transition*' to mean an alternate smooth 75-km-wide zone that separates ~75% of our values.

Data quality control

In contrast to most studies of mantle helium signatures that routinely focus on samples with $\sim 2 < R_C/R_A < 50$, e.g. from hotspots¹, magmatic arcs²⁻⁴, and rifts⁶, 98% of our high-quality samples from Himalaya-Tibet have $R_C/R_A < 1$. We therefore carry out far more stringent quality control than used in most studies of helium isotopes, including previous studies in Tibet, to remove essentially all false positives associated with contamination by air or air dissolved in water, or with analytic uncertainties associated with tiny samples ($\sim 10^{-16}$ – 10^{-18} moles ^3He). We define as 'high-quality' those 168 of our 196 samples which have $(\text{He}/\text{Ne})_{\text{sample}}/(\text{He}/\text{Ne})_{\text{ASW, Field T}} > 10$ and also $< 1\%$ oxygen; and we include in our study the 29 distinct literature samples we found with $(\text{He}/\text{Ne})_{\text{sample}}/(\text{He}/\text{Ne})_{\text{ASW, Field T}} > 10$, even though $[\text{O}_2]$ was not reported for 25 of these literature samples.

We did not measure tritium levels in our water samples (tritium produces helium by the decay $^3\text{H}(\beta^-)^3\text{He}$), but five previously published samples in our Dataset (#212, 213, 215–217) lacked detectable tritium and were thereby shown to have $< 10\%$ tritiogenic ^3He (ref. 6). Very variable tritium levels in groundwater and springs in the Himalaya (sampled 1977-1980)⁷ and Tibet (analyzed 2011)⁸ show strong negative correlations between ^3He and spring temperature⁷ and between ^3He and chlorine content⁸ implying mixing between cold shallow groundwater with thermonuclear tritium and a hot deeper source that is 'tritium-free'. The shallow groundwater component must have isolation times from the atmosphere of only one to two ^3H half-lives (12–25 years), consistent with expectation that re-charge and discharge are balanced⁹, and implying that today, nearly five half-lives since the peak in thermonuclear tritium, little or no excess ^3H should be present in our spring samples. Our focus on the hottest springs with highest conductivity, and our designation of samples as high-quality only if they have $< 1\%$ oxygen and $(\text{He}/\text{Ne})_{\text{sample}}/(\text{He}/\text{Ne})_{\text{ASW, Field T}} > 10$, both mitigate against inclusion in our database of samples exposed to atmospheric tritium.

As described in the main text, we use $R_C/R_A > 0.1R_A$ as our test for a '*mantle*' contribution to our sample (Figs. 2, S3)¹⁰. Analytic uncertainties are sufficiently low that all our samples with $R_C/R_A > 0.1R_A$ also have $[R_C/R_A - 2\sigma] > 0.1R_A$ and all our samples with $(\text{He}/\text{Ne})_{\text{sample}}/(\text{He}/\text{Ne})_{\text{ASW, Field T}} > 10$ also have $[(\text{He}/\text{Ne})_{\text{sample}}/(\text{He}/\text{Ne})_{\text{ASW, Field T}} - 2\sigma] > 10$. If we had used $(\text{He}/\text{Ne})_{\text{ASW, StaticT}}$ values, i.e. uncorrected for actual field parameters, a single additional spring (Table Data #201 Sample ID ZCNA01) would meet our quality criteria and be plotted as a '*mantle*' value without affecting the helium boundary; no springs would thereby fail to meet our quality criteria.

Where possible we collected multiple independent samples from the same spring system – as many as three additional independent samples for 70 springs plotted in Fig. 2 (indicated in the Dataset as '# extra anal.'; repeat measurements on the same sample tube are not included because we do not regard them as independent). Because all samples have their ^3He component diluted by radiogenic-rich near-surface crustal fluids – the cause of the

general upper left-to-lower right trend in Figs. 2 and S3 – it is common to assume the sample with the highest R_C/R_A contains the most representative sample of deeply sourced $^3\text{He}/^4\text{He}$. Instead, to minimize the number of false positives, for springs for which we analyzed multiple independent samples we select and plot the sample with highest $(\text{He}/\text{Ne})_{\text{sample}}/(\text{He}/\text{Ne})_{\text{ASW, Field T}}$ (i.e., least mixing with air or air-saturated water), as opposed to the sample with the highest R_C/R_A . This extra precaution of using the highest $(\text{He}/\text{Ne})_{\text{sample}}/(\text{He}/\text{Ne})_{\text{ASW, Field T}}$ changes the categorization of two of the 70 springs for which we analyzed multiple independent samples (Dataset, lines 173 and 174). These two springs are north of our preferred helium boundary and are here characterized as ‘*intermediate*’, but would be regarded as very clearly ‘*mantle*’ springs if we had not analyzed separate samples with even higher $(\text{He}/\text{Ne})_{\text{sample}}/(\text{He}/\text{Ne})_{\text{ASW, Field T}}$ but somewhat lower R_C/R_A .

For all springs for which we analyzed multiple ‘splits’ from the same sample tube all R_C/R_A values and $(\text{He}/\text{Ne})_{\text{sample}}/(\text{He}/\text{Ne})_{\text{ASW, Field T}}$ values lie within the same category (‘*mantle*’, ‘*intermediate*’, or ‘*null*’; ‘*high-quality*’ or ‘*uncertain quality*’). For 28 springs all our analyses have either $(\text{He}/\text{Ne})_{\text{sample}}/(\text{He}/\text{Ne})_{\text{ASW, Field T}} \leq 10$ or $\text{O}_2 \geq 1\%$; these samples are listed in Dataset lines 176–203 and plotted in Fig. 2 as ‘*uncertain-quality*’ data. For three springs all our analyses have $(\text{He}/\text{Ne})_{\text{sample}}/(\text{He}/\text{Ne})_{\text{ASW, Field T}} \leq 2$ and $\text{O}_2 \geq 10\%$; these samples are so contaminated with air that we do not list them or plot them.

Our review of published literature found just 29 additional sample analyses to extend our dataset, three that meet our ‘*high-quality*’ standard, and 26 of presumptive high-quality (oxygen content not reported) (see Dataset lines 205–233). These 29 analyses comprise data from nine springs in Tibet that we did not sample, one that we sampled but from which we did not obtain high-quality data, five hydrocarbon-well samples north of Tibet (Tarim and Qaidam basins), and 14 spring samples south of Tibet (India and Nepal). All other published analyses either do not meet our quality-control standards or have been superseded by our own measurements that have higher $(\text{He}/\text{Ne})_{\text{sample}}/(\text{He}/\text{Ne})_{\text{ASW, Field T}}$ from the same spring.

Choice of cut-off values

Samples with $R_C > 0.1R_A$ (five times the canonical $^3\text{He}/^4\text{He}$ crustal production ratio of $0.02R_A$) are conventionally considered to include an unambiguous contribution of ^3He from the mantle¹⁰ (our ‘*mantle*’ samples, Figs. 2, S3). This standard classification is geologically very conservative because mantle fluids become rapidly diluted with volumetrically more abundant crustal helium during transport through or residence in the crust¹¹. Similar rapid dilution applies to any ^3He contributions from ^3H or ^6Li , or geologically-old mantle-sourced ^3He trapped in the crust^{12–14}. Our samples show a bimodal distribution when binned logarithmically by R_C/R_A as is appropriate for these ratios that span three orders of magnitude (Fig. S2a) consistent with two separate populations (visually, of approximately normal distribution) clustered around representative values of $R_C = 0.025R_A$ and $R_C = 0.25R_A$. A cross-plot of $[^3\text{He}]$ vs. $[^4\text{He}]$ shows the same clear bi-modal distribution, with ‘*mantle*’ samples having R/R_A values an order-of-magnitude larger than ‘*null*’ samples (Fig. 3c). This bimodality suggests the ‘*intermediate*’ values (green, Figs. 3, S2a) may represent mixing of fluids from our two geographically separated ‘*crustal*’ and ‘*mantle-influenced*’ populations (e.g. within the helium transition) and/or variable mixing of different groundwaters in any location. The $R_C = 0.1R_A$ value we use to define the presence of an unequivocal mantle helium contribution north of the helium boundary is an arbitrary cut-off, but one that is

appropriate to describe the bimodality of our data and the value used ubiquitously in other modern continental helium studies¹²¹⁴. Twenty samples with R_C values below our assumed crustal end-member of $0.02R_A$ (Figs. 2, S2a) suggest there are locations where the appropriate crustal end-member has $R_C < 0.02R_A$ and our cut-off value of $R_C = 0.1R_A$ there exceeds five times the crustal end-member. Plotting our data as a function of distance from the helium boundary (Fig. 3b) shows the transition from ‘null’ to ‘mantle’ domains is close to a step-function, again corroborating our choice of cut-off. Our choice of $0.06R_A$ as the boundary between ‘null’ and ‘intermediate’ is supported by the data distribution (Fig. S2a), but inevitable remaining uncertainty in the appropriate boundaries between categories is irrelevant to our interpretations: halving the cut-off value defining ‘nulls’ to 0.03 (blue samples, Fig. S2b), and doubling the cut-off value defining ‘mantle’ samples to 0.2 (yellow) increases the population of ‘intermediate’ samples (green) but does not change the location of the helium transition or our tectonic conclusions.

Limits on precision of location of the helium transition.

The geothermal springs studied here have a wide range of physical characteristics (Fig. S1), but there is no correlation of R_C/R_A with spring flow rate or temperature. Despite their variable character we can draw a sharp boundary (Fig. 3) separating 99% of ‘mantle’ samples (Table S1) from 94% of ‘nulls’. But how well constrained is this line? Here we show that non-uniform spring distribution (Fig. S2c), choice of R_C/R_A value to define the transition (Figs. S2b, S3), and possible correlations of R_C/R_A with physicochemical character of the springs and basement geology (Figs. S4, S5) only introduce an average ± 30 km uncertainty in locating the helium transition.

Our ability to map a helium boundary is entirely dependent on the availability of geothermal waters to sample. In Fig. S2c (using the same R_C/R_A cut-off values as Fig. 3) we ignore all prior geological information, and we draw black lines linking the southernmost ‘mantle’ samples (northernmost possible location of the helium boundary) and linking the northernmost ‘nulls’ (dashed where needed to include spatial outliers at 81°E and 92°E). These two lines, marking respectively the northernmost and southernmost possible locations of the helium boundary, vary in separation from 10–150 km (mean ~ 60 km from 80–92°E). Thus if our only uncertainty was due to sample distribution, we could typically locate the helium boundary to ± 30 km. Under our additional assumption that the helium boundary is perpendicular to plate convergence, offset only along active rifts, the boundary is constrained to within 10 km from the Lunggar graben to the Cona-Sangri rift, 83.5–92°E, even for a broad range of interpretations of what constitutes a mantle signature (Fig. S2b).

Figure S4 tests possible controls of other parameters that may influence the $^3\text{He}/^4\text{He}$ values of springs and hence influence the proposed helium boundary. For ‘high-quality’ samples (Table S1) there is a weak spatial pattern in spring temperature (Fig. S4a) and [He] (Fig. S4b), but no visible spatial pattern in pH, conductance, [CO₂], or CO₂/ ^3He (Fig. S4c–f) or clear correlation of R_C/R_A with these latter four parameters (Fig. S5b–e). For example, several notably-high R_C/R_A values occur in samples with the highest conductance (Fig. S5b) and high [CO₂] (Fig. S5d), reflecting low degrees of mixing with relatively young surface waters, but there are also many counter-examples of ‘mantle’ springs with low conductance and low [CO₂]. Spring temperatures are typically higher in the Lhasa block where deep penetration of fluids is enabled by the most active normal faults in Tibet and driven by the

highest local topography on the Plateau (Fig. S4a), but R_C/R_A is uncorrelated with spring temperature ($r^2 = 0.01$, Fig. S5a). Although some high-temperature geysers and high-flux springs provide ‘*null*’ samples (Fig. S1a,b), others exhibit ‘*mantle*’ R_C/R_A (Fig. S1d,h), while some cold seeps or trickles carry strong mantle signals (Fig. S1e,i). Springs associated with rifts or grabens may yield either nulls (Fig. S1a) or mantle samples (Fig. S1f), as can springs above granite batholiths (Fig. S1a: null; Fig. S1c: mantle). $[^4\text{He}]$ shows the clearest spatial pattern (Fig. S4f) likely due to variations in thickness and age of the radiogenic crust, with highest $[^4\text{He}]$ values ($>0.1\%$) seen largely in the southern Lhasa block that includes the thickest crust in Tibet (locally 90 km^{15}) and that hosts the youngest granitic batholith, the Cretaceous Gangdese batholith¹⁶. However, the very weak and negative correlation between R_C/R_A and $[^4\text{He}]$ ($r^2 = 0.06$, Fig. S5g) reinforces our conclusion that the helium transition is not a consequence of spatially varying $[^4\text{He}]$. The very strong correlation between $[^3\text{He}]$ and $[^4\text{He}]$ (Fig. 3c) is expected because the $[^3\text{He}]/[^4\text{He}]$ crustal production rate is independent of $[\text{U}]$ (see Methods). More important than the correlation of $[^3\text{He}]$ with $[^4\text{He}]$ is the bimodal distribution of their ratio (Fig. S2a), as also shown by the two parallel trend lines in Fig. 3c.

The parameter with which R_C/R_A most strongly correlates is distance from the helium boundary, i.e. the principal discovery of this paper, which can be characterized as an order-of-magnitude step increase across a narrow boundary from almost-exclusively ‘*null*’ values in the south to almost-exclusively ‘*mantle*’ values in the north (Fig. 3b). This correlation in turn causes the weak positive correlations of R_C/R_A with elevation ($r^2 = 0.17$, Fig. S5h, because all sample elevations below 3500 m are from Himalayan terranes or the Tarim and Qaidam basins), with distance from the YZS ($r^2 = 0.23$, Fig. S5k, because the helium transition is sub-parallel to the YZS), and even with longitude ($r^2 = 0.17$, Fig. S5j, because the helium transition crudely trends ESE). Similarly the strong correlation of R_C/R_A with distance from the helium boundary causes weak negative correlations of R_C/R_A with strain rate ($r^2 = 0.08$, Fig. S5i, because the highest strain rates are south of the boundary line in the Himalaya), and with distance from Quaternary volcanic outcrop ($r^2 = 0.27$, Fig. S5l, because all these volcanics are north of the boundary line, in or north of the Qiangtang terrane).

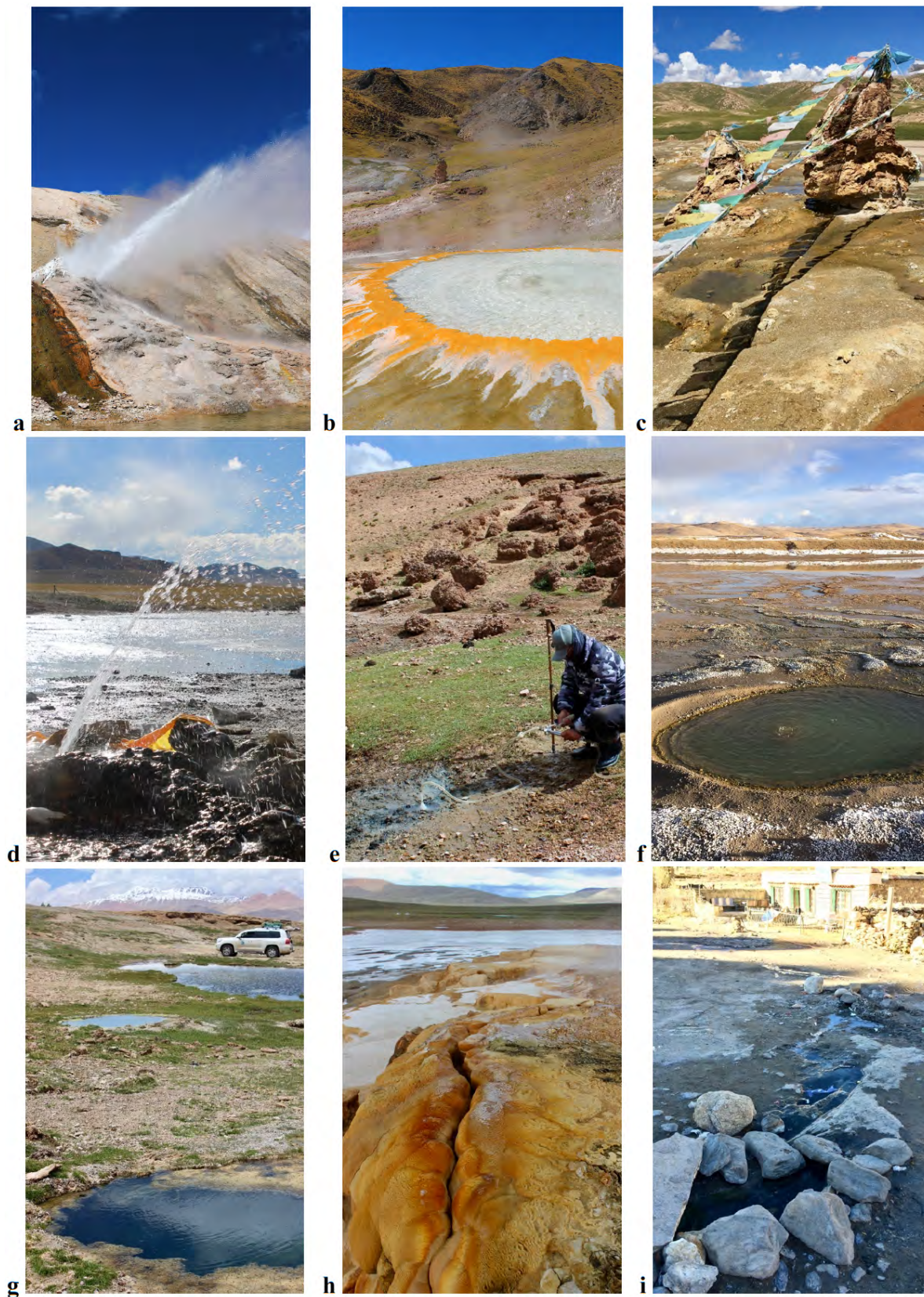


Figure S1. Examples of thermal springs in Tibet

Figure S1. Examples of thermal springs in Tibet.

Springs shown in **a** and **b** are ‘nulls’; those in **c** thru **i** display ‘mantle’ signatures, $R_C > 0.1R_A$).

a, Tibet’s most famous geyser, Dagejia, #57 ZNR01 (spring IDs from Table S1 and Dataset) in the Daggyai Co graben (Co=lake) 25 km north of the YZS, spouts 84°C water (boiling temperature at local elevation of +5.1 km) through Cretaceous and Paleogene clastics at the south margin of the Late Cretaceous Gangdese batholith, forming extensive siliceous sinters and degassing CO₂ at ~10⁷ kg/yr¹⁷. Sampling has spanned two decades^{12,18–20}, but has only ever yielded ‘null’ samples, here $R_C/R_A = 0.013$, the lowest value we recorded in Tibet.

b, Mangra, #89 ZNML12, is a field of a dozen continuously spouting travertine cauldrons (77°C) spanning ~4.10⁴ m², and at +4.7km is midway between (~250 m above and below) the valley floor and local ridgelines. Despite its vigor, it yields $R_C/R_A = 0.047$ (‘null’), defining the location of the helium boundary in the southern Lhasa block.

c, #90 ZBG03 in the central Lhasa terrane is a 10⁴ m² field of travertine and bubbling pools up to 78°C, with clear ‘mantle’ ³He/⁴He, $R_C = 0.319R_A$ despite forming on the flanks of the mid-Cretaceous Bangoin granite batholith that likely extends to >15 km depth²¹ and is an obvious source of ⁴He to lower the ³He/⁴He of geothermal waters.

d, #86 ZBG02 includes 58°C artesian springs with ‘mantle’ ³He/⁴He, $R_C = 0.255R_A$ located 20 km SE of Siling Co, close to that lake’s likely Late Pleistocene shoreline and considerably above the estimated Holocene highstand²², perhaps suggesting a >0.1Ma lifetime for this spring.

e, #75 ZXZ01 is in the northernmost Lhasa terrane, <50 km from the Banggong-Nujiang suture, and the modern 40°C seep with ‘mantle’ ³He/⁴He, $R_C = 0.194R_A$, is remnant of a formerly vigorous system as evidenced by spectacular crystalline travertine growths extending for ~0.3 km. This site is < 20 km SW of Siling Co, at the same 4.61 km elevation as ZBG02 (also a ‘mantle’ spring; photo c) that is 85-km distant from ZXZ01.

f, #114 ZAD13 is a warm spring (22°C) with ‘mantle’ ³He/⁴He, $R_C = 0.621R_A$ at the northern margin of the Lhasa terrane on the shore and close to the lake level of Cona Co that lies in a poorly-developed half-graben.

g, #6 ZRT03 at the extreme NW of our survey area, 5 km SE of Longmu Co on its highest visible paleo-shoreline shows a quiet bubble stream into the near pool yielding ‘mantle’ ³He/⁴He, $R_C = 0.255R_A$; the distant pool is standing water. This site is in the northernmost Qiangtang ~35 km south of the Jinsha suture / Longmu Co-Gozha strike-slip fault, and just 50 km south of Pleistocene potassic volcanic outcroppings¹⁶.

h, #23 ZAD28 is a Qiangtang spring not previously known to science (~50 km from the nearest permanent dwelling), emitting copious 63°C water from numerous vents and fissures carrying gas with ‘mantle’ ³He/⁴He, $R_C = 0.696R_A$, at the NE end of a 850-m long travertine ridge. The ridge sits close to base elevation in a modern >500 km² internally drained basin, but at the northeastern corner of the hypothesized last-interglacial ‘East Qiangtang Lake’²² centered on Siling Co.

i, #167 ZND01 is a cold-water (8°C) trickle with ‘mantle’ ³He/⁴He, $R_C = 0.405R_A$, 70 km south of the YZS in the Tethyan Himalaya within Proterozoic gneisses (Greater Himalayan crystallines) of the Miocene Yardoi North Himalayan gneiss dome²³, at the southeastern extent of our sampling.

Photo credits a and b, PZ; c, d, e, g, h, SLK; and f, i, TL.

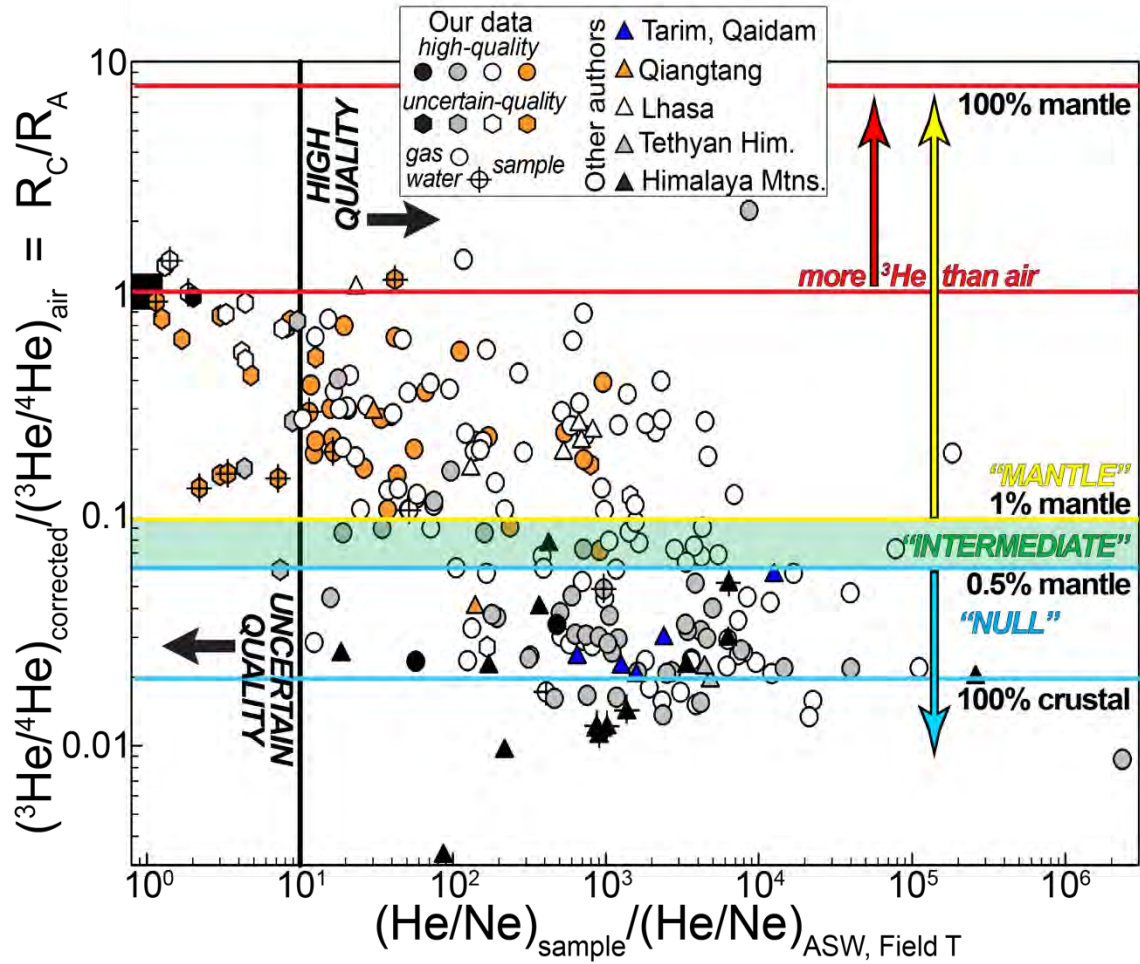


Figure S2. Isotopic data by Tibetan terrane. R_C/R_A plotted against $(\text{He}/\text{Ne})_{\text{sample}}/(\text{He}/\text{Ne})_{\text{ASW, Field T}}$ (i.e. with all corrections made assuming atmospheric contributions are sourced from ASW at the field conditions measured in the relevant spring). All annotation as in Fig. 2: *circles*: our ‘high-quality’ data, separated by a vertical line at 10 times the ASW value from *hexagons*: our ‘uncertain-quality’ data; *triangles*: all putative ‘high-quality’ data from other authors. Locations: *blue*: Tarim and Qaidam Basins; *orange*: Qiangtang terrane (includes one Songpan-Ganzi spring); *white*: Lhasa terrane; *grey*: Tethyan Himalaya; *black*: Greater, Lesser and Sub-Himalaya; *crosses* indicate water samples. Data are divided into ‘null’, ‘intermediate’ and ‘mantle’ designations at 0.5% and 1% nominal mantle contributions (corresponding to $R_C/R_A = 0.06$ and 0.1); red, yellow, blue and green arrows and lettering represent colors in Fig. 3. All plotted data are listed in the Dataset but only ‘high-quality’ points are plotted in Figs. 3 & S3,4,5,7.

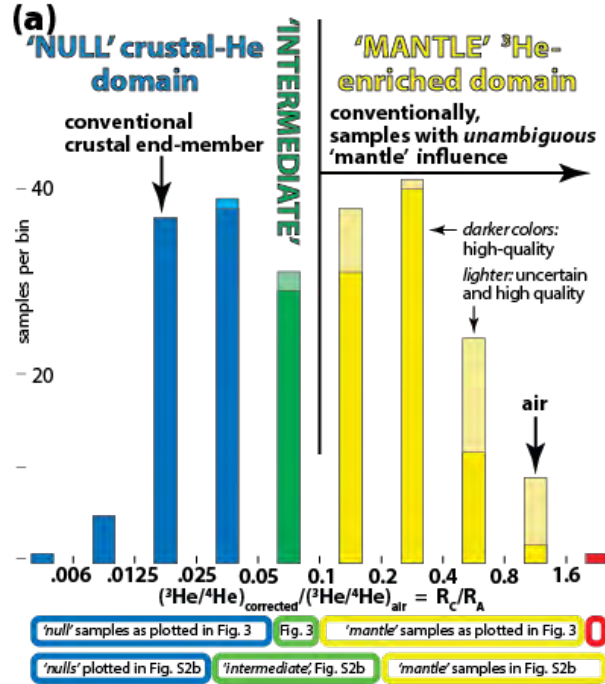
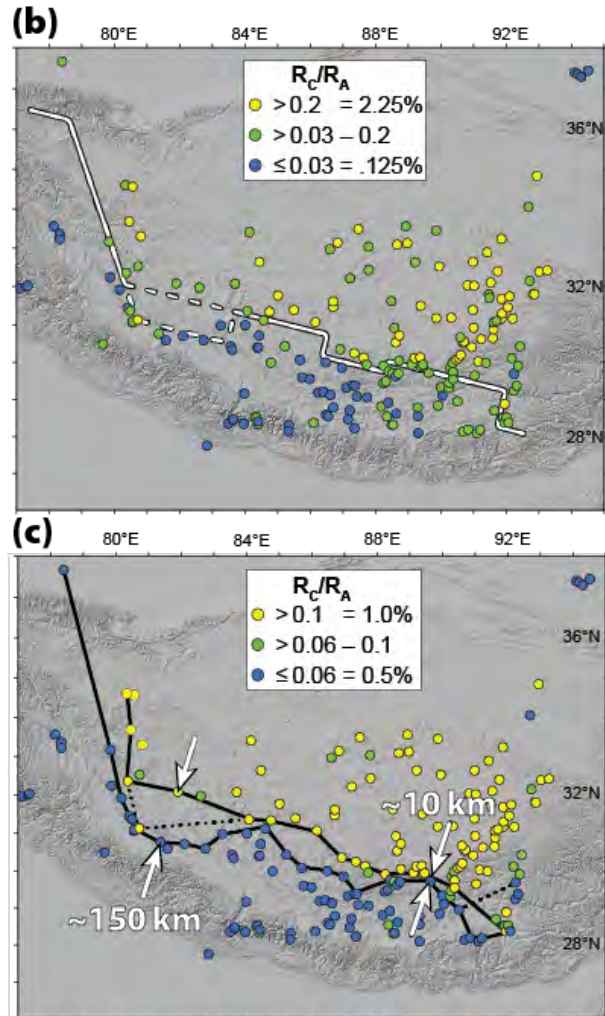


Figure S3. Tests of appropriate cut-off values for 'null' and 'mantle' samples, and robustness of helium-boundary location.

a. Histogram of R_C/R_A values to show their bimodal distribution; bins are defined by successive doublings of R_C/R_A (i.e. equi-spaced in logarithmic space as is appropriate for ratios conventionally plotted logarithmically). Blue, green, yellow and red colors are as in Fig. 3; dark colors represent all high-quality samples shown in Fig. 3; light colors additionally include all samples shown in Fig. 2.



b. Map distribution of high-quality data with 'null' samples re-defined as $R_C \leq 0.03 R_A$ and 'mantle' samples re-defined as $R_C \geq 0.2 R_A$ (respectively half and double the values used in Fig. 3; all other conventions as in Fig. 3) to show robustness of location of helium transition to changed cut-off values. % values in the legend are the percentage mantle contribution of [He] to the sample implied by each R_C/R_A value assuming the mantle reservoir is $8 R_A$ and the crustal reservoir is $0.02 R_A$. White helium boundary is drawn 10-km wide.

c. same as Fig. 3, now with black lines marking the northernmost and southernmost possible locations of the helium transition showing uncertainty ranging from ± 5 km to ± 75 km due to availability of springs to sample.

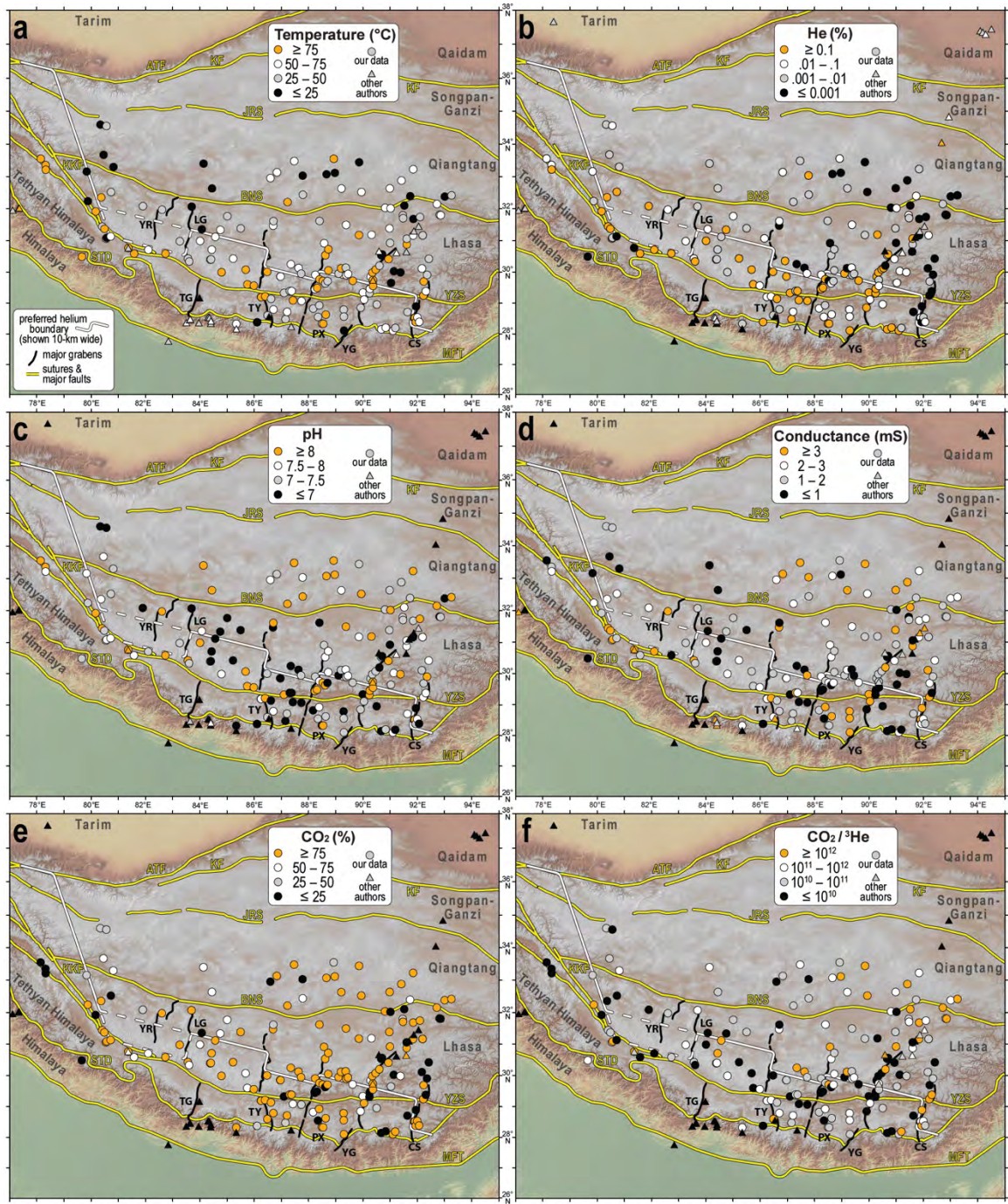


Figure S4. Spatial variability of physical and chemical parameters of thermal springs. Each panel shows points plotted in Fig. 3 color-coded by parameter values to show the *de minimis* spatial correlation in **a**, Spring temperature (°C) and **b**, [^4He] (%); and the lack of spatial correlation **c**, pH; **d**, Conductance (mS); **e**, [CO_2] (%); and **f**, $\text{CO}_2/{}^3\text{He}$. Helium boundary and all other annotation as in Fig. 3. All sample values are listed in the Dataset.

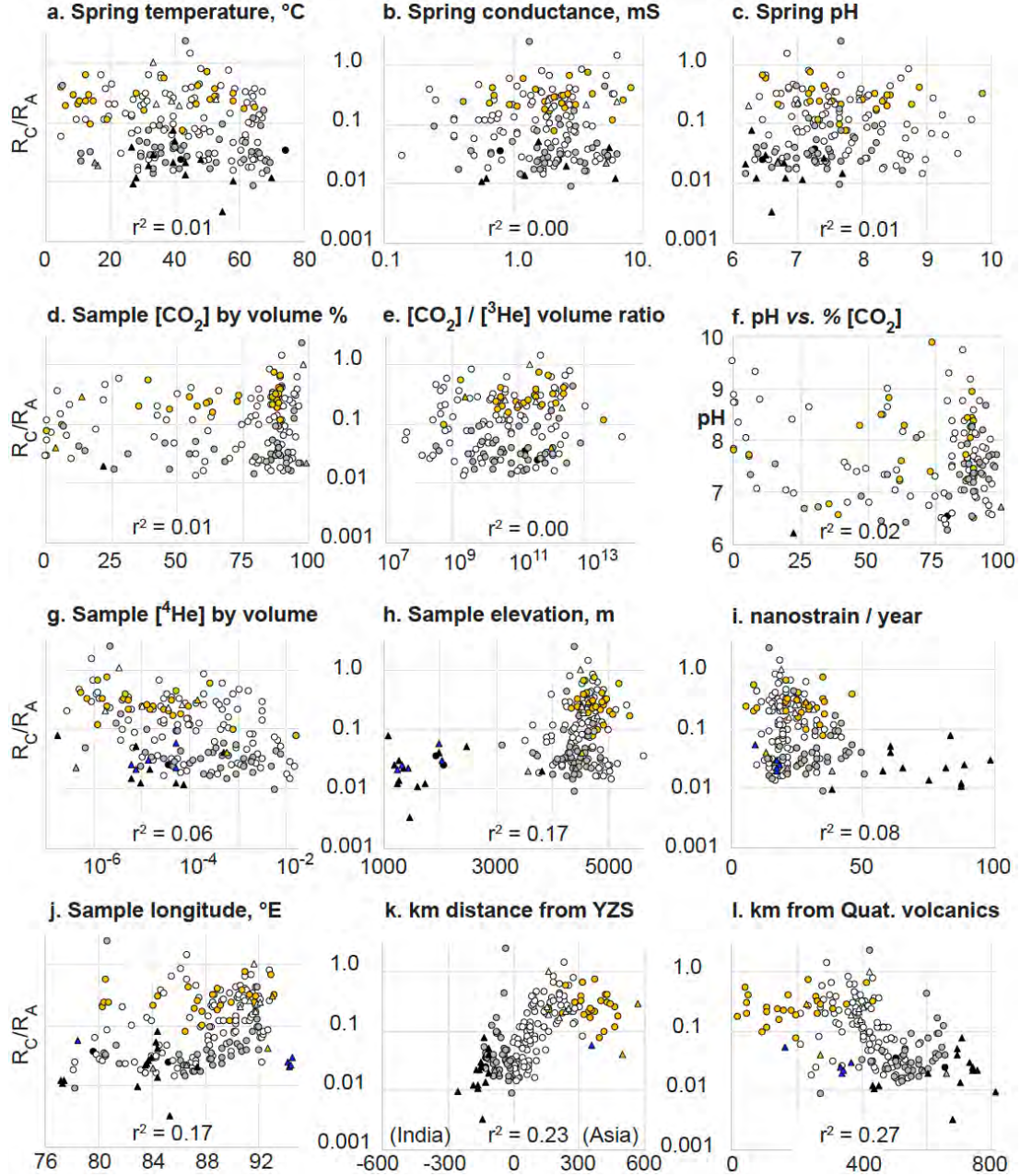


Figure S5. Cross-plots of high-quality R_C/R_A and physico-chemical data of springs color-coded by terrane (as in Figs. 2, S2). R_C/R_A lacks meaningful correlation with **a** Temperature, **b** Conductance, **c** pH, **d** $[CO_2]$ (%), and **e** $CO_2/{}^3He$. **f**: pH is not correlated with $[CO_2]$. **g**: R_C/R_A is slightly correlated to $[{}^4He]$ but this is entirely explained by the strong (bimodal) correlation of $[{}^3He]$ with $[{}^4He]$ (Fig. S3b). **h**, R_C/R_A is correlated with elevation and **i**, inversely correlated with the absolute magnitude of the strain²⁴ but in both cases the causative effect is distance from the lower-elevation, higher-strain-rate Himalaya; R_C/R_A is slightly correlated with **j**, longitude, with **k**, R_C/R_A distance from the YSZ and (negatively) with **l**, distance from the closest Quaternary volcanics but in each case the causative effect is distance from the helium transition on which R_C/R_A shows a much stronger dependence (Fig. 3b). In some plots a very few points with extreme values are omitted to allow presentation at a suitable scale; all sample values are listed in the Dataset.

Table S1. Summary physical/chemical/isotopic data for high-quality ‘mantle’ samples, $R_C/R_A > 0.1$ (excluding 17 samples < 25 km from the adjacent sample), ordered by terrane, then by longitude.

ID number*	Sample ID *	Terrane	Latitude °N	Long. °E	Elevation (km)	Temp. (°C)	CO ₂ % STP	⁴ He $\mu\text{cc/cc}$	R/R _A	R _C /R _A	†‡	(He/Ne) _{sample} / (He/Ne) _{ASW Field T} †	CO ₂ / ³ He
S1g	5	ZRT05	Qiangtang	33.681	80.454	4.47	19	62	17	0.269	0.222	16.21	9.553E+10
	6	ZRT03	Qiangtang	34.564	80.562	5.19	46	39	268	0.540	0.535	110.75	1.960E+09
	7	ZRT09	Qiangtang	33.304	80.815	4.36	16	62	11	0.277	0.216	12.60	1.515E+11
	8	ZGZ11A	Qiangtang	33.408	84.135	4.54	13	58	15	0.243	0.195	16.55	1.128E+11
	9	ZGZ15	Qiangtang	32.640	84.444	4.73	11	55	42	0.298	0.280	39.31	3.144E+10
	11	ZNMA26B	Qiangtang	33.140	86.832	4.63	60	89	55	0.392	0.391	954.33	3.013E+10
	12	ZNMA18	Qiangtang	32.216	87.226	4.65	82	88	36	0.181	0.180	716.31	9.760E+10
	13	ZSH28	Qiangtang	33.490	87.470	4.93	64	88	13	0.237	0.236	537.84	2.108E+11
	15	ZSH14	Qiangtang	32.442	87.791	5.38	39	64	47	0.173	0.154	43.14	5.614E+10
	16	ZSH24	Qiangtang	33.082	88.661	4.96	17	74	4	0.350	0.290	11.47	3.478E+11
S1h	17	ZSH21	Qiangtang	33.559	88.926	5.10	77	47	66	0.196	0.165	26.17	2.656E+10
	18	ZSH07	Qiangtang	33.121	88.969	4.89	7	88	1	0.433	0.381	11.76	2.696E+12
	19	ZSH08	Qiangtang	32.639	89.208	4.88	59	86	5	0.214	0.200	55.82	5.509E+11
	20	ZSH15	Qiangtang	33.450	89.857	4.93	24	89	1	0.132	0.109	37.47	3.982E+13
	21	ZSH16	Qiangtang	32.527	89.943	4.73	73	89	2	0.222	0.216	139.16	1.524E+12
	22	ZAD5B	Qiangtang	32.036	90.814	4.58	66	89	5	0.367	0.357	66.11	3.866E+11
	23	ZAD28	Qiangtang	32.643	90.988	4.77	63	87	2	0.711	0.696	19.48	4.443E+11
	24	ZAD07	Qiangtang	32.886	91.418	4.97	73	88	1	0.344	0.301	15.77	2.625E+12
	25	ZAD11	Qiangtang	32.402	91.744	4.80	14	73	100	0.231	0.226	169.77	2.296E+10
	26	Qinghai-QH1	Qiangtang	33.236	91.850	4.90	66	87	5	0.293	0.272	33.87	3.899E+11
S1a	27	ZNYR11	Qiangtang	32.388	93.012	4.58	16	89	1	0.627	0.618	41.70	3.856E+11
	34	ZGR08 Zh02 9903	Lhasa	32.361	80.363	4.51	105	81	1003	0.192	0.192	183197.41	n.r.
	37	ZGG04	Lhasa	32.088	81.897	4.58	37	43	3488	0.186	0.186	4641.63	4.733E+08
	44	ZGZ08	Lhasa	32.075	83.697	4.50	25	78	25	0.137	0.122	57.71	1.625E+11
	46	ZZB09	Lhasa	31.360	84.071	4.43	16	1	100	0.144	0.109	24.95	2.670E+08
	51	ZCQ01	Lhasa	31.339	84.751	4.66	74	66	833	0.349	0.348	1377.98	1.634E+09
	53	ZGZ20	Lhasa	31.767	85.011	4.96	47	50	61	0.339	0.306	20.40	1.753E+10
	55	ZCQ04	Lhasa	31.388	85.501	4.83	45	89	23	0.597	0.597	606.64	4.715E+10
	57	ZNR01	Lhasa	29.605	85.746	5.07	84	57	13039	0.013	0.013	21358.20	2.363E+09
	59	ZCQ06	Lhasa	31.067	86.162	4.74	60	85	202	0.789	0.789	712.87	3.870E+09
S1e	61	ZNMA23	Lhasa	31.471	86.698	4.66	57	90	1	1.354	1.357	116.89	5.322E+11
	63	ZNR09	Lhasa	30.351	86.917	4.90	34	63	3324	0.126	0.126	6894.38	1.088E+09
	67	ZXTM01	Lhasa	30.249	87.346	4.82	60	90	1	0.453	0.422	21.24	2.743E+12
	69	ZXTM23	Lhasa	30.129	87.633	4.48	67	89	1	0.351	0.271	10.36	1.976E+12
	72	ZXTM08	Lhasa	29.911	88.249	4.70	72	88	96	0.136	0.135	939.47	4.877E+10
	75	ZXZ01	Lhasa	31.623	88.483	4.61	39	90	17	0.197	0.194	288.35	1.897E+11
	77	ZXZ05	Lhasa	30.917	88.573	4.78	56	97	0	0.219	0.185	23.11	1.103E+13
	81	ZXZ09	Lhasa	30.721	88.728	4.75	80	95	30	0.293	0.292	514.60	7.814E+10
	82	ZXTM16	Lhasa	30.050	88.728	4.54	81	90	6	0.201	0.196	137.09	5.030E+11
	83	ZNML03	Lhasa	29.948	89.107	4.24	45	77	513	0.109	0.108	975.35	9.987E+09
S1d	85	ZNML01	Lhasa	30.136	89.367	5.33	34	93	195	0.238	0.238	2118.30	1.437E+10
	86	ZBG02	Lhasa	31.499	89.379	4.65	58	88	82	0.255	0.255	1206.04	3.039E+10
	88	ZNML05	Lhasa	29.941	89.452	4.55	62	89	30	0.125	0.113	74.66	1.700E+11
	89	ZNML12	Lhasa	29.721	89.626	4.74	77	49	8468	0.047	0.047	39548.66	8.931E+08
	90	ZBG03	Lhasa	31.175	89.856	4.76	78	87	44	0.320	0.319	670.90	4.467E+10
	95	ZBG09	Lhasa	31.185	90.317	4.71	68	56	1698	0.397	0.397	2291.13	5.965E+08
	97	ZDX17 middle	Lhasa	29.733	90.367	4.76	85	90	164	0.115	0.114	1549.33	3.448E+10
	101	ZDX13	Lhasa	30.124	90.544	4.33	38	78	606	0.264	0.264	4444.01	3.540E+09
	104	ZDX18	Lhasa	30.564	90.706	4.93	26	23	1144	0.432	0.430	267.88	3.313E+08
	105	ZDX06	Lhasa	30.412	90.943	4.24	81	86	354	0.269	0.268	2318.58	6.493E+09
S1f	106	ZBG13	Lhasa	31.385	90.979	4.61	55	81	35	0.372	0.366	94.88	4.546E+10
	107	ZDX01	Lhasa	30.924	91.000	4.74	40	96	1	0.613	0.605	46.74	1.106E+12
	108	ZAD30D	Lhasa	32.023	91.017	4.60	57	22	430	0.241	0.235	120.52	1.547E+09
	109	ZDD03	Lhasa	29.653	91.032	3.65	12	46	96	0.126	0.109	51.12	2.753E+10
	110	ZLHZ01	Lhasa	30.027	91.140	3.98	24	5	204	0.366	0.353	50.79	4.733E+08
	113	ZAD31	Lhasa	31.709	91.481	4.64	50	87	5	0.141	0.127	58.22	8.292E+11
	114	ZAD13	Lhasa	32.104	91.526	4.60	22	n.r.	n.r.	0.760	0.621	12.57	2.970E+12
	117	ZNQ08B	Lhasa	31.163	91.848	4.68	57	90	1	0.396	0.387	71.18	1.304E+12
	119	ZNYR01	Lhasa	31.743	92.100	4.64	49	88	4	0.303	0.286	40.50	5.202E+11
	121	ZNQ13	Lhasa	31.164	92.199	4.58	50	82	135	0.254	0.253	590.18	1.719E+10
S1i	128	ZBRU01	Lhasa	31.813	92.825	4.26	40	n.r.	n.r.	0.250	0.229	732.98	2.600E+10
	134	ZGR13 Zh02 9910	Tethyan Him.	31.131	80.719	4.40	55	98	2	2.225	2.225	8663.44	n.r.
	165	ZLNZ04	Tethyan Him.	28.386	91.942	4.74	81	95	3	0.130	0.118	75.31	1.807E+12
	166	ZND01	Tethyan Him.	28.891	91.952	4.28	7	n.r.	n.r.	0.570	0.405	17.80	4.640E+12

* ID number and name as in Dataset; samples labelled S1a thru' S1i are shown in Figure S1; samples labelled Zh02 from ref. 20. † plotted in Fig. 2. ‡ plotted in Fig. 3. n.r. = not reported.

2. Quantifying spatial and temporal association of the mantle suture with the helium boundary or transition.

Upward transport of mantle helium through the lithosphere is by buoyant hence sub-vertical ascent within a carrier fluid (carbonic, magmatic, or aqueous) as shown by the correlation of helium anomalies with tectonic boundaries²⁻⁴, and of elevated $^3\text{He}/^4\text{He}$ ratios with low-wavespeed mantle^{2,4,25,26}, in other parts of the world. In principle, topographic loads could drive fluids substantial distances in unfaulted, near-horizontal sedimentary strata²⁷, thereby obfuscating the relationship between the surface sample of primordial ^3He and its mantle source. In Tibet, groundwater flow is driven by local topographic gradients and sustained by recharge at high elevations, but ridges and valleys serve as groundwater divides so that the volumetrically dominant flows only travel laterally up to half the topographic wavelength⁹. The only syn-orogenic basins are in the active NNE-trending rift valleys (Fig. 3) that dominate the internal topography of the Tibetan Plateau, but these are formed by along-strike linkage of much-smaller half-grabens, typically <20 km wide, leading to small, chemically distinct groundwater domains³⁰. Thus, lateral spreading of the $^3\text{He}/^4\text{He}$ isotopic signal is both hydrodynamically unlikely in Tibet, and geochemically infeasible given that long-term, long-distance migration would maximize mixing with ^4He -rich crustal fluids²⁹.

Much of the Tibetan Plateau lies within the internally drained 'Qiangtang Basin'³⁰ (Fig. S7) but the boundary between internal and external drainage does not correlate well with the helium transition. The proposal³⁰ that km³/yr of water leak from the Qiangtang Basin southwards along the NNE-trending rift valleys is not supported by any evidence of increased numbers or higher temperatures of springs in the southern prolongations of these rift valleys beyond the Qiangtang Basin (Figs. S4a, S7). A global assessment³¹ that compressional faults are rarely associated with fluid discharge is consistent with the lack of springs along the trace of the subduction megathrust (Main Himalayan Thrust, the only active sub-horizontal fault) (Fig. 3) suggesting that it is not a particularly active conduit for fluid flow. In contrast, active normal and strike-slip faults are globally linked to gas discharges³¹ and in Tibet manifestly channel warm groundwater to springs¹³ (Fig. 3). These normal and strike-slip faults have dips $\geq 60^\circ$ ³² and thus provide <15 km lateral transport between the brittle-ductile transition at c. 20 km³³ and the surface.

Hence, the springs we sampled likely receive their primordial ^3He from within $\sim \pm 20$ km laterally of their mantle source, corresponding to ascent within 15° of the vertical averaged across a 75-km-thick crust. Coupled with our typical ± 30 km uncertainty in locating the helium transition, we suggest the helium transition and the surface trace of the mantle suture are separated by < $\sim$ half the crustal thickness in southern Tibet.

The primordial fluids we sample also likely represent geologically instantaneous snapshots of the mantle, as temporal correlation of increased $^3\text{He}/^4\text{He}$ ratios at the surface with preceding fluid-induced earthquake swarms that propagate vertically upwards from the Moho shows that vertical transport of fluid through the whole crust can occur at tens of km/yr^{34,35}. Even absent crack propagation, theoretical and experimental data on interfacial energy-driven infiltration imply ascent rates of 20–50 m/yr³⁶ (a few thousand years to reach the surface from 100-km depth) comparable to lateral groundwater flow velocities up to 10 m/yr in Tibet when modelled as driven by topographic variations⁹. Vertical flow velocities that exceed or at least match lateral transport velocities also support our claim that the observed helium transition locates the mantle suture within approximately half the crustal thickness.

3. Correlation of the helium boundary with seismological measurements

Spatial correlations of the helium boundary with seismological measurements

Our observation of the helium transition and our presumption that it lies vertically above the mantle suture are entirely independent of the vast seismological literature on Tibet; but the seismological data (though not necessarily their interpretations!) are all consistent with our helium transition and mantle-suture interpretation (Fig. S6). There is reasonably good agreement of the helium transition with a regional transition from higher P-wave velocity to the southwest and lower P-wave velocity to the northeast detected by travel-time body-wave tomography³⁷ (Figs. 3d, S6a) as well as with the presumably equivalent S-wavespeed transition detected by adjoint tomography that seeks to match the full waveform³⁸ (Figs. S3e, S6b). Note that the boundary between blue and red regions of these maps is simply the average wavespeed at that depth rather than any specific seismic velocity associated with a particular mantle temperature or onset of melting.

2D Pn tomography³⁹ (Pn is the P-wave traveling along the topmost mantle as the result of the sudden velocity increase at the Moho discontinuity) also images a boundary between high Pn velocity to the south and low Pn velocity to the north that is in reasonable agreement with the helium transition east of 82°E (Fig. S6c). Apparent alignments of lower wavespeed in this Pn velocity map have further been interpreted as “tears in the Indian mantle lithosphere”³⁹ that we do not see (Fig. 3). The eastern lower-wavespeed alignment beneath the YGR is corroborated by a more recent depth-dependent Pn tomography⁴⁰ and could be indicated in our data by intermediate R_c/R_A measurements there (Figs. 3, S2b). In contrast the hypothesized west-Tibet and central-Tibet tears³⁹ are not seen in the depth-dependent Pn tomography⁴⁰ or in other models derived from local arrays (e.g. refs. 41,42) and are highly oblique to both the active rifts and the NUVEL-1A convergence vector⁴³, so lack any obvious explanation beyond an *ad hoc* “pre-existing structure”. In contrast, all the tears of the subducting slab we suggest in Figure 3 are collinear with active rifts where local seismic arrays have identified Moho offsets^{15,42,44-45} (Fig. S7; note that no equivalent seismic data exists for the Lunggar Rift).

Seismic attenuation, as measured by efficiency of propagation of Sn in the uppermost mantle (Sn is a shear-wave travelling close beneath the Moho) has been used to map a zone of inefficient propagation in the Qiangtang and Songpan-Ganzi terrane^{48,49} (Fig. S6d), significantly further north than the helium transition. However, the mean Sn amplitude-to-Pg coda amplitude ratio (Pg coda is multiply-scattered upper-crustal P waves) in the 1–5 Hz bandwidth smoothed by a Gaussian filter with a radius of 150 km⁵⁰ shows good agreement from 83–92° between the helium transition and southernmost limit of enhanced Sn attenuation (Fig. S6d).

In Fig. S6e we compare previous suggestions of the northern limit of Indian underthrusting of Tibet based on the location of near-Moho earthquakes⁵¹, that agrees well with the helium transition west of 79° and east of 85°E: there are no deep earthquakes from 79–85°E so no basis for interpretation of the northern limit of Indian underthrusting from such earthquakes. Also in Fig. S6e we show the helium boundary bracketed between observations of a ‘sharp hinge’ in gravity measurements⁵² and a mapped transition in SXS (teleseismic core-reflected S phases) splitting from negligible split times in the southern Lhasa terrane to significant split times further north⁵³. The ~150-km separation between the gravity- and the SKS-

interpretations is likely because the gravity field nominally maps the exact mantle suture whereas large SKS split times can only be accumulated over tens of km-thickness of anisotropic mantle, whereas the helium transition may mark just a few km thickness of mantle wedge. Fig. S6e also shows focal mechanisms of moderate earthquakes distinguishing normal-fault, strike-slip fault and thrust-fault earthquakes. The helium transition matches the gradual northward evolution from dominantly normal-fault to dominantly strike-slip mechanisms, previously inferred to mark the northern limit of rigid Indian crust beneath Tibet⁵⁴.

Finally, in Fig. S6f there is no agreement between the helium transition and lithospheric thickness⁵⁵ estimated from a shear-wavespeed model⁵⁶ based only on long-period surface waves, with lateral and vertical correlation lengths of ~250 km and ~50 km respectively. We suggest that the very thick lithosphere^{55,56} interpreted from this long-period surface-wave model (extending to the blue line in Figs. 1c, 3) may represent the combined Tibetan crust, the asthenospheric mantle wedge, *and* underlying shallowly-subducting Indian cratonic lithosphere (Fig. 4). The asthenospheric mantle wedge is clearly visible in a 125-km deep horizontal section and in vertical sections⁵¹ through this shear-wavespeed model^{55,56} as low wavespeeds north of (approximately) the Bangong-Nujiang suture from 100-km depth (shallowest level shown) to ~130 km. In contrast to this surface-wave tomography, receiver-function CCP profiles⁵⁷ (green line, Figs. 1c, 3) image the Indian crustal front, and body-wave tomography³⁷ (Fig. S6a,b; red line, Figs. 1c, 3) images a proxy for the mantle suture.

Depth constraints

Our isotopic data carry no information about the dip of Indian subduction, hence whether the Tibetan mantle wedge is thick above a steeply dipping India or thin above a gently-dipping India. However, gently-dipping subduction beneath only a thin layer of Tibetan mantle (Fig. 4) is more consistent with absolute wavespeeds at ~200 km depth beneath northern Tibet typically indicative of stable lithosphere^{55,56} (Fig. S6f). Low-, not high-, angle subduction is also suggested by efficient S_n propagation across the Lhasa and western Qiangtang terranes that implies cold (therefore Indian) mantle lithosphere at depth⁵⁸. However, the region of efficient S_n propagation extends progressively further south at increasingly high frequencies⁵⁰ (Fig. S6d) demonstrating the existence of at least a thin highly attenuating or negative wavespeed-gradient zone close below the Tibetan Moho in eastern Tibet as far south as the YYS. Such a zone would be characteristic of the incipiently melting or fluid-rich asthenospheric mantle implied by our helium measurements north of the helium transition. Recent 2D numerical thermomechanical models of continental collision include the possibility of continental crust underthrust sub-horizontally ~200 km beneath an overlying continental crust, separated by an intervening thin layer of partially melting mantle just 10–20 km thick⁵⁹. This may be the situation today in the ‘flat-slab’ segments of Andean subduction⁶⁰ and also in Tibet, giving rise to the helium transition we have mapped.

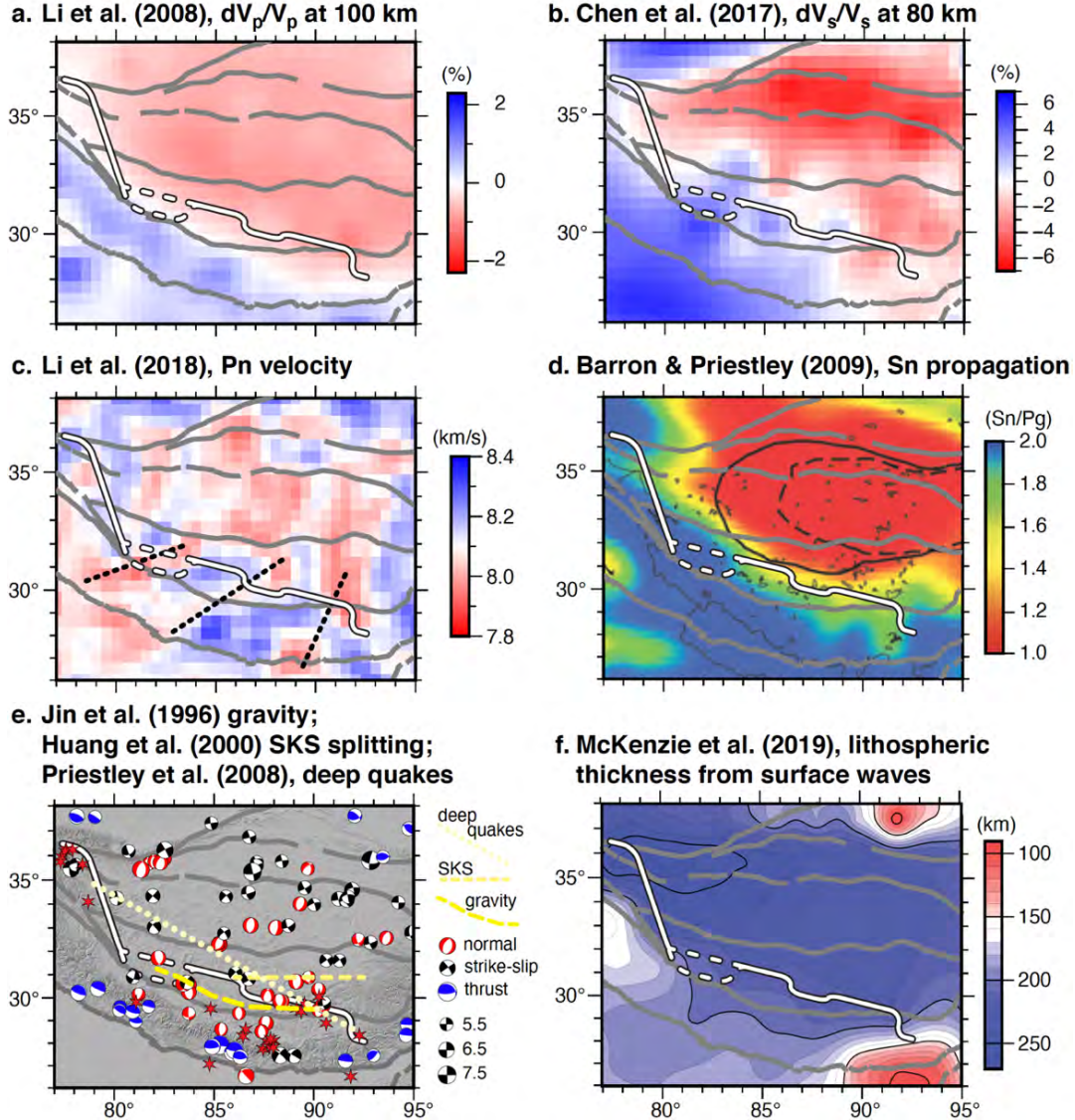


Figure S6. Inferred mantle suture overlain on published seismic models. Helium boundary (white) and major faults/sutures (grey), as in Fig. 3. **a**, P-wavespeed (% deviation from local mean) at 100 km depth from 3D travel-time tomography (figure 10a of ref. 37) re-plotted from their digital model³⁶. **b**, S-wavespeed (% deviation from local mean) at 80-km depth obtained from adjoint 3D tomography (figure 2a of ref. 37) re-plotted from digital model EARA201³⁸ downloaded from chenseismolab.org/resources/. **c**, Pn-wavespeed in km/s from 2D Pn tomography (figure 2 of ref. 39 re-plotted from data provided by the authors) overlain by their interpretations³⁹ of “tears in the Indian mantle lithosphere”. **d**, Propagation efficiency of Sn (from figure 7c of ref. 50) overlain by inefficient propagation regions (dashed black outline⁴⁸ and solid black outline⁴⁹). **e**, “northern limit of the Indian Shield as a strong entity”⁵⁰ (pale-yellow dotted line) as interpreted from deep earthquakes⁵¹ and the northern limit of weak shear-wave (SKS) splitting^{51,53} (medium-yellow short-dash), and mantle suture from gravity analysis⁵² (dark yellow long-dash) in the region of “the contrast in tectonic regime between primarily strike-slip faulting in northern Tibet and dominantly normal faulting in southern Tibet”⁵⁴ (focal mechanisms⁶¹ from earthquakes magnitude ≥ 5.5 , depth ≤ 50 km). **f**, Lithospheric thickness (figure 7b of ref. 55) updated from thicknesses⁵⁶ derived from temperature estimates obtained from their surface-wave (global multi-mode Rayleigh-wave) S-wavespeed model PM_v2_2012.

4. Possible alternate geologic / tectonic associations of the helium boundary or transition

Association with active rifts

Our preferred helium boundary from 80–93°E is drawn orthogonal to the relative plate convergence of India with respect to Asia⁴³, formed of four (northern dashed line) (or five – southern dashed segment) linear segments offset at three (or four) rifts. It separates 99% (or 100%) of ‘mantle’ and 94% (or 93%) of ‘null’ samples to be respectively north and south of the boundary, as expected if the helium boundary lies vertically above the mantle suture. The three eastern rifts across which we show jogs in our preferred helium boundary all have geophysical indicators of Moho offsets (Figs. 3, S7) at the same latitude, that we speculate also mark tears in subducting Indian lithosphere at the transition across the mantle suture from underplating (south of the boundary) to subduction (further north). Local Pn tomography⁴² defines abrupt rift-parallel uppermost-mantle velocity changes along the TY and PX rifts. P-receiver function images show Moho offsets beneath the PX¹⁵, YG^{44,47} and CS^{15,47} rifts. A virtual deep-seismic sounding (VDSS) study⁴⁵ reported Moho offsets beneath PX and YG, and shear-wave splitting⁴⁶ suggests offsets beneath the TY, PX and YG rifts (Figs. 3, S7). Equivalent array data are not available for LG. Our preferred helium transition also lies north and east of all but two earthquakes reliably reported to have source depths 65–100 km and $m_b \geq 3.7$ ^{51,62-66}, and south and west of all Quaternary volcanoes^{16, 67,68} (Fig. S7).

Association with Yarlung Zangbo Suture (YZS)

Our preferred helium boundary does not follow surface litho-tectonic boundaries such as the YZS¹². As shown in Fig. 3 a broad linear transition with no obvious geologic significance can also be made to satisfy most of the data outside the broad transition zone. Alternatively, a smooth and sinuous helium transition parallel to and 50-km north of the YZS (Fig. S7) appropriately separates 89% of ‘mantle’ and ‘null’ samples to be respectively north and south of the transition. This is a less-good fit to the isotopic data and triples the number of ‘mantle’ and ‘null’ samples respectively south and north of the transition. A smooth transition 50-km north of the YZS also lies far southwest of the northwest-Tibet sub-Moho earthquakes (Fig. S7). Perhaps most important, a simple transition parallel to the YZS, even if broadened to a 75-km (crustal-thickness) wide transition (Fig. S7), fails to explain the group of clear ‘mantle’ samples up to 100-km south of the YZS spanning 70 km along the CS rift⁶⁹, the easternmost of the N-to-NNE-trending normal-fault systems that cut across the Tethyan Himalaya and Lhasa Terrane (Figs. 1c, S7). We cannot exclude these samples as representing fluids flowing south along upper-crustal rift-bounding faults from a mantle suture significantly further north; or asthenospheric fluids derived from asthenosphere migrating south beneath the Moho along the rift axis, but neither possibility is consistent with mantle fluids appearing south of the YZS only in the CS rift and not in the YG, PX or TY rifts that each record significantly more total extension than the CS rift⁷⁰ and are all still tectonically active at present³².

If indeed it were possible for mantle-sourced fluids to travel south for considerable distances in the crust along the NNE-trending active rift structures in the CS graben, then one could further imagine that the mantle suture lies as far north as the Banggong-Nujiang suture (BNS

in Fig. 3) that is the northern limit of the best-developed rifts. In this case all our ‘mantle’ samples could be sourced exclusively from lateral flow in the crust of fluids sourced within the rifts. We reject this idea because of the numerous ‘mantle’ samples south of the BNS and outside the rifts (up to 80 km distant), because this would require flow for 80 km through the Gangdese granite batholith that is intrinsically less likely to allow lateral flow than the north-south basins in which lateral flow seems to be restricted to the basin width typically <20 km.

Although thus far we have no spring samples east of CS (Fig. 3) so alternative interpretations are possible, we prefer the concept that the CS ‘mantle’ samples are representative of regionally extensive asthenospheric mantle above the Indian slab that is rolling back to the southwest as it approaches the Eastern Himalayan Syntaxis (EHS)^{47,71}. We predict that our planned sampling further east will identify additional ‘mantle’ samples east of the CS rift.

Association with slab rollback in SE Tibet and slab underthrusting in NW Tibet.

Seismic data from SE Tibet have been interpreted in terms of a west-to-east transition from shallow to steep subduction of the Indian plate, via slab rollback southwest of the EHS^{47,71}. The CS rift is ~300-km west of the EHS, and only ~300 km north of the north-south-striking Indo-Burman foreland fold-and-thrust belt that links to east-dipping subduction of continental Indian plate beneath the Quaternary Burma volcanic arc^{37,72}. The ~200-km Indian lithospheric thickness⁵⁵ means that the tightest possible bending radius is ~350 km⁷³, approximately the radius defined by the MFT (surficial India-Asia plate boundary) due south of the CSR and the northern part of the Sagaing fault that accommodates most motion across the India-Asia (or Sunda) plate boundary in Myanmar⁷⁴. We propose that, as the YZS approaches the EHS, the Indian underplating slab is rolling back (delaminating) to the southwest, bringing the mantle suture southwest with it, and causing tearing or fragmentation of the Indian plate in the region of the EHS^{15,71,75}. Slab roll-back and tearing together permit asthenospheric mantle to upwell and source the observed ³He-enriched springs^{15,47}.

As in eastern Tibet east of 92°E, so in western Tibet west of 80°W our sampling grows sparse, and different interpretations of the helium transition and the mantle suture are possible. Two previously reported ‘mantle’ samples¹³ at ~35°N, 77.5°E (that were interpreted as showing the mantle suture at the Karakoram Fault or following the YZS¹³) have associated uncertainties that fail to meet the more-stringent quality-control criteria used in this paper. Our westernmost samples that are unequivocally ³He-enriched, at ~80°E (Fig. 3), encourage our interpretation that the helium transition trends NNW west of 80°E, east of a cluster of deep earthquakes^{51,63,6} where the Jinsha River suture and the Altyn Tagh fault approach the Hindu Kush, but west of the Quaternary volcanoes of the western Kunlun Mountains^{16,68}. This NNW trend of the mantle suture in western Tibet likely reflects the widely recognized northward prolongation of Indian lithosphere beneath the Western Himalayan syntaxis to meet the Pamir subduction zone⁷⁶.

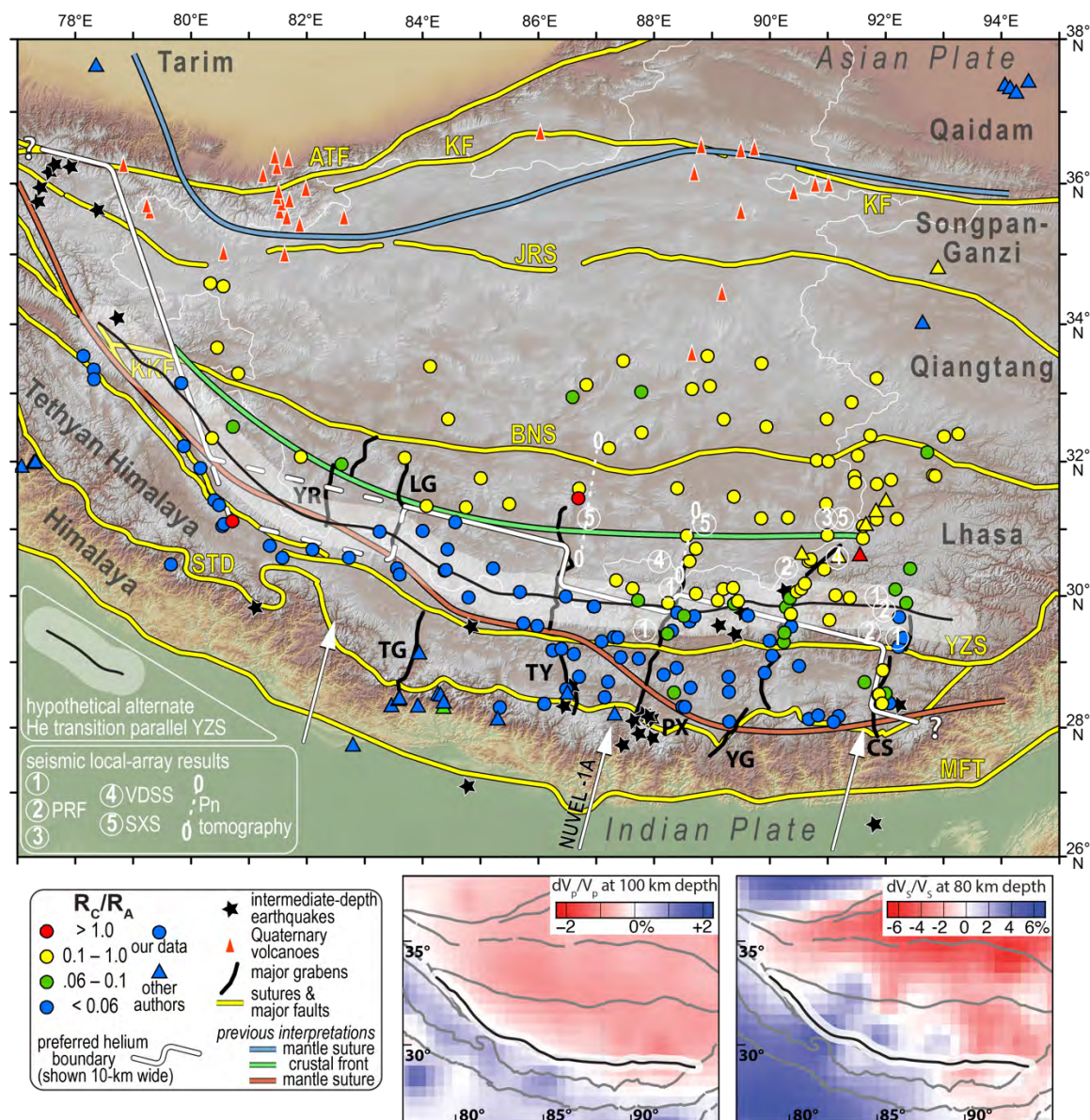


Figure S7. Alternate helium transition parallel to YZS, and details of Moho offsets reported beneath Tibet. Fig. 3 of the main text, with our preferred mantle suture (narrow white line) overlain by a conceptually simpler 75-km wide helium transition (broad transparent white line) constrained to be parallel to and 50 km NNE of the YZS (thin black line). Also shown are fine white line: boundary between interior and external drainage; white numbers: seismic observations from local arrays within Tibet of abrupt upper-mantle velocity transitions (lines separating 0s parallel TYR and PXR)⁴² and Moho offsets from receiver functions (points 1, 2, 3)^{15,44,47}, virtual deep-seismic sounding (points 4)⁴⁵ and shear-wave splitting (5)⁴⁶. All other symbols as Fig. 3, including white arrows: plate convergence vector⁴³, black stars: near-Moho earthquakes with hypocentral depths 65–100 km from waveform studies^{51,62–66}, and narrow red triangles: Quaternary volcanoes^{16,67,68}. Faults and sutures after refs. 77 & 78.

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Caption for “Dataset”

(see the separate file *Klemperer.HeliumMantleSutureTibet.PNAS.2022.Dataset.xlsx* that is also repeated immediately following as a flat image within this Supporting Information, for the convenience of readers)

Physical locations, elevations, field data, gas concentrations and isotopic data for:

- (1)** Our ‘*high-quality*’ data: 168 data-points (circles) on Figs. 2 & 3 representing 168 distinct spring systems (separated by >1km) with $(\text{He/Ne})_{\text{sample}}/(\text{He/Ne})_{\text{ASW, Field T}} > 10$ and $\text{O}_2 < 1\%$;
- (2)** Our ‘*high-quality*’ analyses that have lower $(\text{He/Ne})_{\text{sample}}/(\text{He/Ne})_{\text{ASW, Field T}}$ but sufficiently higher R_c/R_a as to place them in the ‘*mantle*’ category: 2 data-points (hexagons) on Fig. 2, not plotted on Fig. 3;
- (3)** Our ‘*uncertain-quality*’ data: 28 data-points (hexagons) on Fig. 2, not plotted on Fig. 3 representing 28 additional distinct springs with $(\text{He/Ne})_{\text{sample}}/(\text{He/Ne})_{\text{ASW, Field T}} \leq 10$ or $\text{O}_2 > 1\%$ (italicized values);
- (4)** Previously published data (other authors) likely of ‘*high-quality*’: 29 data-points (triangles) plotted on Figs. 2 and 3: 28 additional springs we did not sample, and one spring we sampled but with air contamination (only three of these 29 analyses include $[\text{O}_2]$ without which we cannot confidently call these data ‘*high-quality*’, and a fourth sample has $\text{N}_2 + \text{CO}_2 > 99\%$);

appended by footnotes #1–23.

[illegible]

Index #	Lab. #	data source	Foot- notes	# extra analys	Sample ID	Terrore	Lat., °N	Long., °E	Elevation (m)	Water Temp. (°C)	Water Cond. (µm/cm)	Sample type	OH ₄ % STP	N ₂ % STP	CO ₂ % STP	³ He % STP	¹⁸ O	²⁰ Ne	³⁶ Ar	⁴⁰ Ar	R ₁ /R ₂	R ₃ /R ₄	R ₅ /R ₆	R ₇ /R ₈	R ₉ /R ₁₀	R ₁₁ /R ₁₂	R ₁₃ /R ₁₄	R ₁₅ /R ₁₆	R ₁₇ /R ₁₈	R ₁₉ /R ₂₀	R ₂₁ /R ₂₂	R ₂₃ /R ₂₄	R ₂₅ /R ₂₆	R ₂₇ /R ₂₈	R ₂₉ /R ₃₀	R ₃₁ /R ₃₂	R ₃₃ /R ₃₄	R ₃₅ /R ₃₆	R ₃₇ /R ₃₈	R ₃₉ /R ₄₀	R ₄₁ /R ₄₂	R ₄₃ /R ₄₄	R ₄₅ /R ₄₆	R ₄₇ /R ₄₈	R ₄₉ /R ₅₀	R ₅₁ /R ₅₂	R ₅₃ /R ₅₄	R ₅₅ /R ₅₆	R ₅₇ /R ₅₈	R ₅₉ /R ₆₀	R ₆₁ /R ₆₂	R ₆₃ /R ₆₄	R ₆₅ /R ₆₆	R ₆₇ /R ₆₈	R ₆₉ /R ₇₀	R ₇₁ /R ₇₂	R ₇₃ /R ₇₄	R ₇₅ /R ₇₆	R ₇₇ /R ₇₈	R ₇₉ /R ₈₀	R ₈₁ /R ₈₂	R ₈₃ /R ₈₄	R ₈₅ /R ₈₆	R ₈₇ /R ₈₈	R ₈₉ /R ₉₀	R ₉₁ /R ₉₂	R ₉₃ /R ₉₄	R ₉₅ /R ₉₆	R ₉₇ /R ₉₈	R ₉₉ /R ₁₀₀	R ₁₀₁ /R ₁₀₂	R ₁₀₃ /R ₁₀₄	R ₁₀₅ /R ₁₀₆	R ₁₀₇ /R ₁₀₈	R ₁₀₉ /R ₁₁₀	R ₁₁₁ /R ₁₁₂	R ₁₁₃ /R ₁₁₄	R ₁₁₅ /R ₁₁₆	R ₁₁₇ /R ₁₁₈	R ₁₁₉ /R ₁₂₀	R ₁₂₁ /R ₁₂₂	R ₁₂₃ /R ₁₂₄	R ₁₂₅ /R ₁₂₆	R ₁₂₇ /R ₁₂₈	R ₁₂₉ /R ₁₃₀	R ₁₃₁ /R ₁₃₂	R ₁₃₃ /R ₁₃₄	R ₁₃₅ /R ₁₃₆	R ₁₃₇ /R ₁₃₈	R ₁₃₉ /R ₁₄₀	R ₁₄₁ /R ₁₄₂	R ₁₄₃ /R ₁₄₄	R ₁₄₅ /R ₁₄₆	R ₁₄₇ /R ₁₄₈	R ₁₄₉ /R ₁₅₀	R ₁₅₁ /R ₁₅₂	R ₁₅₃ /R ₁₅₄	R ₁₅₅ /R ₁₅₆	R ₁₅₇ /R ₁₅₈	R ₁₅₉ /R ₁₆₀	R ₁₆₁ /R ₁₆₂	R ₁₆₃ /R ₁₆₄	R ₁₆₅ /R ₁₆₆	R ₁₆₇ /R ₁₆₈	R ₁₆₉ /R ₁₇₀	R ₁₇₁ /R ₁₇₂	R ₁₇₃ /R ₁₇₄	R ₁₇₅ /R ₁₇₆	R ₁₇₇ /R ₁₇₈	R ₁₇₉ /R ₁₈₀	R ₁₈₁ /R ₁₈₂	R ₁₈₃ /R ₁₈₄	R ₁₈₅ /R ₁₈₆	R ₁₈₇ /R ₁₈₈	R ₁₈₉ /R ₁₉₀	R ₁₉₁ /R ₁₉₂	R ₁₉₃ /R ₁₉₄	R ₁₉₅ /R ₁₉₆	R ₁₉₇ /R ₁₉₈	R ₁₉₉ /R ₂₀₀	R ₂₀₁ /R ₂₀₂	R ₂₀₃ /R ₂₀₄	R ₂₀₅ /R ₂₀₆	R ₂₀₇ /R ₂₀₈	R ₂₀₉ /R ₂₁₀	R ₂₁₁ /R ₂₁₂	R ₂₁₃ /R ₂₁₄	R ₂₁₅ /R ₂₁₆	R ₂₁₇ /R ₂₁₈	R ₂₁₉ /R ₂₂₀	R ₂₂₁ /R ₂₂₂	R ₂₂₃ /R ₂₂₄	R ₂₂₅ /R ₂₂₆	R ₂₂₇ /R ₂₂₈	R ₂₂₉ /R ₂₃₀	R ₂₃₁ /R ₂₃₂	R ₂₃₃ /R ₂₃₄	R ₂₃₅ /R ₂₃₆	R ₂₃₇ /R ₂₃₈	R ₂₃₉ /R ₂₄₀	R ₂₄₁ /R ₂₄₂	R ₂₄₃ /R ₂₄₄	R ₂₄₅ /R ₂₄₆	R ₂₄₇ /R ₂₄₈	R ₂₄₉ /R ₂₅₀	R ₂₅₁ /R ₂₅₂	R ₂₅₃ /R ₂₅₄	R ₂₅₅ /R ₂₅₆	R ₂₅₇ /R ₂₅₈	R ₂₅₉ /R ₂₆₀	R ₂₆₁ /R ₂₆₂	R ₂₆₃ /R ₂₆₄	R ₂₆₅ /R ₂₆₆	R ₂₆₇ /R ₂₆₈	R ₂₆₉ /R ₂₇₀	R ₂₇₁ /R ₂₇₂	R ₂₇₃ /R ₂₇₄	R ₂₇₅ /R ₂₇₆	R ₂₇₇ /R ₂₇₈	R ₂₇₉ /R ₂₈₀	R ₂₈₁ /R ₂₈₂	R ₂₈₃ /R ₂₈₄	R ₂₈₅ /R ₂₈₆	R ₂₈₇ /R ₂₈₈	R ₂₈₉ /R ₂₉₀	R ₂₉₁ /R ₂₉₂	R ₂₉₃ /R ₂₉₄	R ₂₉₅ /R ₂₉₆	R ₂₉₇ /R ₂₉₈	R ₂₉₉ /R ₃₀₀	R ₃₀₁ /R ₃₀₂	R ₃₀₃ /R ₃₀₄	R ₃₀₅ /R ₃₀₆	R ₃₀₇ /R ₃₀₈	R ₃₀₉ /R ₃₁₀	R ₃₁₁ /R ₃₁₂	R ₃₁₃ /R ₃₁₄	R ₃₁₅ /R ₃₁₆	R ₃₁₇ /R ₃₁₈	R ₃₁₉ /R ₃₂₀	R ₃₂₁ /R ₃₂₂	R ₃₂₃ /R ₃₂₄	R ₃₂₅ /R ₃₂₆	R ₃₂₇ /R ₃₂₈	R ₃₂₉ /R ₃₃₀	R ₃₃₁ /R ₃₃₂	R ₃₃₃ /R ₃₃₄	R ₃₃₅ /R ₃₃₆	R ₃₃₇ /R ₃₃₈	R ₃₃₉ /R ₃₄₀	R ₃₄₁ /R ₃₄₂	R ₃₄₃ /R ₃₄₄	R ₃₄₅ /R ₃₄₆	R ₃₄₇ /R ₃₄₈	R ₃₄₉ /R ₃₅₀	R ₃₅₁ /R ₃₅₂	R ₃₅₃ /R ₃₅₄	R ₃₅₅ /R ₃₅₆	R ₃₅₇ /R ₃₅₈	R ₃₅₉ /R ₃₆₀	R ₃₆₁ /R ₃₆₂	R ₃₆₃ /R ₃₆₄	R ₃₆₅ /R ₃₆₆	R ₃₆₇ /R ₃₆₈	R ₃₆₉ /R ₃₇₀	R ₃₇₁ /R ₃₇₂	R ₃₇₃ /R ₃₇₄	R ₃₇₅ /R ₃₇₆	R ₃₇₇ /R ₃₇₈	R ₃₇₉ /R ₃₈₀	R ₃₈₁ /R ₃₈₂	R ₃₈₃ /R ₃₈₄	R ₃₈₅ /R ₃₈₆	R ₃₈₇ /R ₃₈₈	R ₃₈₉ /R ₃₉₀	R ₃₉₁ /R ₃₉₂	R ₃₉₃ /R ₃₉₄	R ₃₉₅ /R ₃₉₆	R ₃₉₇ /R ₃₉₈	R ₃₉₉ /R ₄₀₀	R ₄₀₁ /R ₄₀₂	R ₄₀₃ /R ₄₀₄	R ₄₀₅ /R ₄₀₆	R ₄₀₇ /R ₄₀₈	R ₄₀₉ /R ₄₁₀	R ₄₁₁ /R ₄₁₂	R ₄₁₃ /R ₄₁₄	R ₄₁₅ /R ₄₁₆	R ₄₁₇ /R ₄₁₈	R ₄₁₉ /R ₄₂₀	R ₄₂₁ /R ₄₂₂	R ₄₂₃ /R ₄₂₄	R ₄₂₅ /R ₄₂₆	R ₄₂₇ /R ₄₂₈	R ₄₂₉ /R ₄₃₀	R ₄₃₁ /R ₄₃₂	R ₄₃₃ /R ₄₃₄	R ₄₃₅ /R ₄₃₆	R ₄₃₇ /R ₄₃₈	R ₄₃₉ /R ₄₄₀	R ₄₄₁ /R ₄₄₂	R ₄₄₃ /R ₄₄₄	R ₄₄₅ /R ₄₄₆	R ₄₄₇ /R ₄₄₈	R ₄₄₉ /R ₄₅₀	R ₄₅₁ /R ₄₅₂	R ₄₅₃ /R ₄₅₄	R ₄₅₅ /R ₄₅₆	R ₄₅₇ /R ₄₅₈	R ₄₅₉ /R ₄₆₀	R ₄₆₁ /R ₄₆₂	R ₄₆₃ /R ₄₆₄	R ₄₆₅ /R ₄₆₆	R ₄₆₇ /R ₄₆₈	R ₄₆₉ /R ₄₇₀	R ₄₇₁ /R ₄₇₂	R ₄₇₃ /R ₄₇₄	R ₄₇₅ /R ₄₇₆	R ₄₇₇ /R ₄₇₈	R ₄₇₉ /R ₄₈₀	R ₄₈₁ /R ₄₈₂	R ₄₈₃ /R ₄₈₄	R ₄₈₅ /R ₄₈₆	R ₄₈₇ /R ₄₈₈	R ₄₈₉ /R ₄₉₀	R ₄₉₁ /R ₄₉₂	R ₄₉₃ /R ₄₉₄	R ₄₉₅ /R ₄₉₆	R ₄₉₇ /R ₄₉₈	R ₄₉₉ /R ₅₀₀	R ₅₀₁ /R ₅₀₂	R ₅₀₃ /R ₅₀₄	R ₅₀₅ /R ₅₀₆	R ₅₀₇ /R ₅₀₈	R ₅₀₉ /R ₅₁₀	R ₅₁₁ /R ₅₁₂	R ₅₁₃ /R ₅₁₄	R ₅₁₅ /R ₅₁₆	R ₅₁₇ /R ₅₁₈	R ₅₁₉ /R ₅₂₀	R ₅₂₁ /R ₅₂₂	R ₅₂₃ /R ₅₂₄	R ₅₂₅ /R ₅₂₆	R ₅₂₇ /R ₅₂₈	R ₅₂₉ /R ₅₃₀	R ₅₃₁ /R ₅₃₂	R ₅₃₃ /R ₅₃₄	R ₅₃₅ /R ₅₃₆	R ₅₃₇ /R ₅₃₈	R ₅₃₉ /R ₅₄₀	R ₅₄₁ /R ₅₄₂	R ₅₄₃ /R ₅₄₄	R ₅₄₅ /R ₅₄₆	R ₅₄₇ /R ₅₄₈	R ₅₄₉ /R ₅₅₀	R ₅₅₁ /R ₅₅₂	R ₅₅₃ /R ₅₅₄	R ₅₅₅ /R ₅₅₆	R ₅₅₇ /R ₅₅₈	R ₅₅₉ /R ₅₆₀	R ₅₆₁ /R ₅₆₂	R ₅₆₃ /R ₅₆₄	R ₅₆₅ /R ₅₆₆	R ₅₆₇ /R ₅₆₈	R ₅₆₉ /R ₅₇₀	R ₅₇₁ /R ₅₇₂	R ₅₇₃ /R ₅₇₄	R ₅₇₅ /R ₅₇₆	R ₅₇₇ /R ₅₇₈	R ₅₇₉ /R ₅₈₀	R ₅₈₁ /R ₅₈₂	R ₅₈₃ /R ₅₈₄	R ₅₈₅ /R ₅₈₆	R ₅₈₇ /R ₅₈₈	R ₅₈₉ /R ₅₉₀	R ₅₉₁ /R ₅₉₂	R ₅₉₃ /R ₅₉₄	R ₅₉₅ /R ₅₉₆	R ₅₉₇ /R ₅₉₈	R ₅₉₉ /R ₆₀₀	R ₆₀₁ /R ₆₀₂	R ₆₀₃ /R ₆₀₄	R ₆₀₅ /R ₆₀₆	R ₆₀₇ /R ₆₀₈	R ₆₀₉ /R ₆₁₀	R ₆₁₁ /R ₆₁₂	R ₆₁₃ /R ₆₁₄	R ₆₁₅ /R ₆₁₆	R ₆₁₇ /R ₆₁₈	R ₆₁₉ /R ₆₂₀	R ₆₂₁ /R ₆₂₂	R ₆₂₃ /R ₆₂₄	R ₆₂₅ /R ₆₂₆	R ₆₂₇ /R ₆₂₈	R ₆₂₉ /R ₆₃₀	R ₆₃₁ /R ₆₃₂	R ₆₃₃ /R ₆₃₄	R ₆₃₅ /R ₆₃₆	R ₆₃₇ /R ₆₃₈	R ₆₃₉ /R ₆₄₀	R ₆₄₁ /R ₆₄₂	R ₆₄₃ /R ₆₄₄	R ₆₄₅ /R ₆₄₆	R ₆₄₇ /R ₆₄₈	R ₆₄₉ /R ₆₅₀	R ₆₅₁ /R ₆₅₂	R ₆₅₃ /R ₆₅₄	R ₆₅₅ /R ₆₅₆	R ₆₅₇ /R ₆₅₈	R ₆₅₉ /R ₆₆₀	R ₆₆₁ /R ₆₆₂	R ₆₆₃ /R ₆₆₄	R ₆₆₅ /R ₆₆₆	R ₆₆₇ /R ₆₆₈	R ₆₆₉ /R ₆₇₀	R ₆₇₁ /R ₆₇₂	R ₆₇₃ /R ₆₇₄	R ₆₇₅ /R ₆₇₆	R ₆₇₇ /R ₆₇₈	R ₆₇₉ /R ₆₈₀	R ₆₈₁ /R ₆₈₂	R ₆₈₃ /R ₆₈₄	R ₆₈₅ /R ₆₈₆	R ₆₈₇ /R ₆₈₈	R ₆₈₉ /R ₆₉₀	R ₆₉₁ /R ₆₉₂	R ₆₉₃ /R ₆₉₄	R ₆₉₅ /R ₆₉₆	R ₆₉₇ /R ₆₉₈	R ₆₉₉ /R ₇₀₀	R ₇₀₁ /R ₇₀₂	R ₇₀₃ /R ₇₀₄	R ₇₀₅ /R ₇₀₆	R ₇₀₇ /R ₇₀₈	R ₇₀₉ /R ₇₁₀	R ₇₁₁ /R ₇₁₂	R ₇₁₃ /R ₇₁₄	R ₇₁₅ /R ₇₁₆	R ₇₁₇ /R ₇₁₈	R ₇₁₉ /R ₇₂₀	R ₇₂₁ /R ₇₂₂	R ₇₂₃ /R ₇₂₄	R ₇₂₅ /R ₇₂₆	R ₇₂₇ /R ₇₂₈	R ₇₂₉ /R ₇₃₀	R ₇₃₁ /R ₇₃₂	R ₇₃₃ /R ₇₃₄	R ₇₃₅ /R ₇₃₆	R ₇₃₇ /R ₇₃₈	R ₇₃₉ /R ₇₄₀	R ₇₄₁ /R ₇₄₂	R ₇₄₃ /R ₇₄₄	R ₇₄₅ /R ₇₄₆	R ₇₄₇ /R ₇₄₈	R ₇₄₉ /R ₇₅₀	R ₇₅₁ /R ₇₅₂	R ₇₅₃ /R ₇₅₄	R ₇₅₅ /R ₇₅₆	R ₇₅₇ /R ₇₅₈	R ₇₅₉ /R ₇₆₀	R ₇₆₁ /R ₇₆₂	R ₇₆₃ /R ₇₆₄	R ₇₆₅ /R ₇₆₆	R ₇₆₇ /R ₇₆₈	R ₇₆₉ /R ₇₇₀	R ₇₇₁ /R ₇₇₂	R ₇₇₃ /R ₇₇₄	R ₇₇₅ /R ₇₇₆	R ₇₇₇ /R ₇₇₈	R ₇₇₉ /R ₇₈₀	R ₇₈₁ /R ₇₈₂	R ₇₈₃ /R ₇₈₄	R ₇₈₅ /R ₇₈₆	R ₇₈₇ /R ₇₈₈	R ₇₈₉ /R ₇₉₀	R ₇₉₁ /R ₇₉₂	R ₇₉₃ /R ₇₉₄	R ₇₉₅ /R ₇₉₆	R ₇₉₇ /R ₇₉₈	R ₇₉₉ /R ₈₀₀	R ₈₀₁ /R ₈₀₂	R ₈₀₃ /R ₈₀₄	R ₈₀₅ /R ₈₀₆	R ₈₀₇ /R ₈₀₈	R ₈₀₉ /R ₈₁₀	R ₈₁₁ /R ₈₁₂	R ₈₁₃ /R ₈₁₄	R ₈₁₅ /R ₈₁₆	R ₈₁₇ /R ₈₁₈	R ₈₁₉ /R ₈₂₀	R ₈₂₁ /R ₈₂₂	R ₈₂₃ /R ₈₂₄	R ₈₂₅ /R ₈₂₆	R ₈₂₇ /R ₈₂₈	R ₈₂₉ /R ₈₃₀	R ₈₃₁ /R ₈₃₂	R ₈₃₃ /R ₈₃₄	R ₈₃₅ /R ₈₃₆	R ₈₃₇ /R ₈₃₈	R ₈₃₉ /R ₈₄₀	R ₈₄₁ /R ₈₄₂	R ₈₄₃ /R ₈₄₄	R ₈₄₅ /R ₈₄₆	R ₈₄₇ /R ₈₄₈	R ₈₄₉ /R ₈₅₀	R ₈₅₁ /R ₈₅₂	R ₈₅₃ /R ₈₅₄	R ₈₅₅ /R ₈₅₆	R ₈₅₇ /R ₈₅₈	R ₈₅₉ /R ₈₆₀	R ₈₆₁ /R ₈₆₂	R ₈₆₃ /R ₈₆₄	R ₈₆₅ /R ₈₆₆	R ₈₆₇ /R ₈₆₈	R ₈₆₉ /R ₈₇₀	R ₈₇₁ /R ₈₇₂	R ₈₇₃ /R ₈₇₄	R ₈₇₅ /R ₈₇₆	R ₈₇₇ /R ₈₇₈	R ₈₇₉ /R ₈₈₀	R ₈₈₁ /R ₈₈₂	R ₈₈₃ /R ₈₈₄	R ₈₈₅ /R ₈₈₆	R ₈₈₇ /R ₈₈₈	R ₈₈₉ /R ₈₉₀	R ₈₉₁ /R ₈₉₂	R ₈₉₃ /R ₈₉₄	R ₈₉₅ /R ₈₉₆	R ₈₉₇ /R ₈₉₈	R ₈₉₉ /R ₉₀₀	R ₉₀₁ /R ₉₀₂	R ₉₀₃ /R ₉₀₄	R ₉₀₅ /R ₉₀₆	R ₉₀₇ /R ₉₀₈	R ₉₀₉ /R ₉₁₀	R ₉₁₁ /R ₉₁₂	R ₉₁₃ /R ₉₁₄	R ₉₁₅ /R ₉₁₆	R ₉₁₇ /R ₉₁₈	R ₉₁₉ /R ₉₂₀	R ₉₂₁ /R ₉₂₂	R ₉₂₃ /R ₉₂₄	R ₉₂₅ /R ₉₂₆	R ₉₂₇ /R ₉₂₈	R ₉₂₉ /R ₉₃₀	R ₉₃₁ /R ₉₃₂	R ₉₃₃ /R ₉₃₄	R ₉₃₅ /R ₉₃₆	R ₉₃₇ /R ₉₃₈	R ₉₃₉ /R ₉₄₀	R ₉₄₁ /R ₉₄₂	R ₉₄₃ /R ₉₄₄	R ₉₄₅ /R ₉₄₆	R ₉₄₇ /R ₉₄₈	R ₉₄₉ /R ₉₅₀	R ₉₅₁ /R ₉₅₂	R ₉₅₃ /R ₉₅₄	R ₉₅₅ /R ₉₅₆	R ₉₅₇ /R ₉₅₈	R ₉₅₉ /R ₉₆₀	R ₉₆₁ /R ₉₆₂	R ₉₆₃ /R ₉₆₄	R ₉₆₅ /R ₉₆₆	R ₉₆₇ /R ₉₆₈	R ₉₆₉ /R ₉₇₀	R ₉₇₁ /R ₉₇₂	R ₉₇₃ /R ₉₇₄	R ₉₇₅ /R ₉₇₆	R ₉₇₇ /R ₉₇₈	R ₉₇₉ /R ₉₈₀	R ₉₈₁ /R ₉₈₂	R ₉₈₃ /R ₉₈₄	R ₉₈₅ /R ₉₈₆	R ₉₈₇ /R ₉₈₈	R ₉₈₉ /R ₉₉₀	R ₉₉₁ /R ₉₉₂	R ₉₉₃ /R ₉₉₄	R ₉₉₅ /R ₉₉₆	R ₉₉₇ /R ₉₉₈	R ₉₉₉ /R ₁₀₀₀	R ₁₀₀₁ /R ₁₀₀₂	R ₁₀₀₃ /R ₁₀₀₄	R ₁₀₀₅ /R ₁₀₀₆	R ₁₀₀₇ /R ₁₀₀₈	R ₁₀₀₉ /R ₁₀₁₀	R ₁₀₁₁ /R ₁₀₁₂	R ₁₀₁₃ /R ₁₀₁₄	R ₁₀₁₅ /R ₁₀₁₆	R ₁₀₁₇ /R ₁₀₁₈	R ₁₀₁₉ /R ₁₀₂₀	R ₁₀₂₁ /R ₁₀₂₂	R ₁₀₂₃ /R ₁₀₂₄	R ₁₀₂₅ /R ₁₀₂₆	R ₁₀₂₇ /R ₁₀₂₈	R ₁₀₂₉ /R ₁₀₃₀	R ₁₀₃₁ /R ₁₀₃₂	R ₁₀₃₃ /R ₁₀₃₄	R ₁₀₃₅ /R ₁₀₃₆	R ₁₀₃₇ /R ₁₀₃₈	R ₁₀₃₉ /R ₁₀₄₀	R ₁₀₄₁ /R ₁₀₄₂	R ₁₀₄₃ /R ₁₀₄₄	R ₁₀₄₅ /R ₁₀₄₆	R ₁₀₄₇ /R ₁₀₄₈	R ₁₀₄₉ /R ₁₀₅₀	R ₁₀₅₁ /R ₁₀₅₂	R ₁₀₅₃ /R ₁₀₅₄	R ₁₀₅₅ /R ₁₀₅₆	R ₁₀₅₇ /R ₁₀₅₈	R ₁₀₅₉ /R
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