



Noble gases show highly localized mantle degassing during the development of a diffuse plate boundary (Betic Cordillera, SE Spain)

Bérénice CATELAND¹, Anne BATTANI¹, Frédéric MOUTHEREAU^{1,2,3}, Nicolas E. BEAUDOIN¹, Benjamin LEFEUVRE¹, Matthias S. BRENNWALD⁴, Jose BENAVENTE⁵, Laurent EMMANUEL⁶, Magali PUJOL⁷.

¹ *Laboratoire des Fluides Complexes et de leurs Réservoirs, Université de Pau et des Pays de l'Adour, CNRS, E2S UPPA, LFCR, Pau, France.*

² *Université de Toulouse III – Paul Sabatier, laboratoire Géosciences Environnement Toulouse, UMR 5563, F31400 Toulouse, France.*

³ *Institut Universitaire de France, 75005 Paris, France.*

⁴ *Department of Water Resources and Drinking Water, Eawag: Swiss Federal Institute of Aquatic Science and Technology, Ueberlandstrasse 133, CH-8600 Dübendorf, Switzerland.*

⁵ *Departamento de Geodinámica e Instituto de Investigación del Agua, Universidad de Granada, Granada, Spain.*

⁶ *Institut des Sciences de la Terre de Paris-ISTeP, UMR SU/CY/CNRS 7193, Sorbonne Université, Paris, France.*

⁷ *TotalEnergies/OneTech, Centre Scientifiques et Techniques Jean-Féger (CSTJF), av. Larribau, Pau, 64018, France.*

Correspondence: Bérénice Cateland (berenice.cateland@univ-pau.fr)

Abstract

What controls the crust-mantle connectivity during the early stages of continental-plate boundary development remains poorly constrained. Crustal thinning, lithospheric-scale faults and elevated heat flow are commonly regarded as the main drivers of mantle-fluid transfer, yet their relative importance remains unclear. The Betics (SE Spain) combine all these features in a context of a nascent diffuse plate boundary between Africa and Iberia.

We combine noble gas and stable isotope analyses of spring and associated travertines sampled across several crustal- to lithospheric-scale faults. Despite favorable conditions for mantle degassing, mantle-sourced helium is limited to a highly localized zone in the northeastern part of the region, where it accounts for 2 to 6%. Elsewhere, most springs record a $\geq 99\%$ crustal helium signature, even where the crust is thinnest (≤ 20 km). Travertines show the clearest thermogenic signatures along the most seismogenic fault of the region. Combined with paleofluid data, this study shows that crust-mantle connectivity shifted from the western and southeastern Betics during the Eocene-Miocene to the northeastern Betics since the Pliocene. This mantle-fluid migration mirrors the localization of present-day seismicity, indicating that active strain partitioning and localized transtension play a key role in sustaining crust-mantle connectivity under an overall compressional regime.



50 INTRODUCTION

51 Plate boundaries provide efficient pathways for the upward migration of mantle-sourced fluids through
52 the crust. These fluids provide insight into crust-mantle connectivity along major faults in active tectonic
53 settings, and their origin can be traced using helium (He) isotopes. For instance, mantle contribution
54 account for up to approximately 50% of the helium transported along the San Andreas Fault and ~80%
55 along the Marmara segment of the North Anatolian Fault (Kennedy et al., 1997; Burnard et al., 2012).
56 In Europe, the transfer of fluid from the mantle to the surface is efficient in extensional domains where
57 the crust is thinner than ~25 km, including the Pannonian Basin, the Rhine and Rhône rifts ($R/R_a = 1.7$ -
58 6; Marty et al., 1992; Wallentin et al., 2026). Yet the relative roles of crustal thickness, lithospheric-scale
59 faulting, and active deformation in controlling mantle-fluid transfer along faults remain poorly
60 constrained.

61 The Betics in southeastern Spain provide an opportunity to investigate the factors controlling mantle-
62 sourced fluid migration along active faults. There, extensional deformation has locally reduced crustal
63 thickness to less than 25km, and heat flow exceeds 70 W.m⁻². Several faults penetrate the lower crust
64 and extend into the lithospheric mantle, and volcanism attests to Miocene and Plio-Quaternary mantle
65 degassing (Duggen et al., 2004; Mancilla et al., 2015; Díaz et al., 2016; Larrey et al., 2023). The tectonic
66 evolution of the Betics was driven by deep lithospheric processes, including subduction, slab retreat,
67 slab tearing and detachment, followed by lithospheric delamination. These processes controlled the
68 transition from Eocene convergence to Miocene extension and Pliocene compression (Jolivet and
69 Faccenna, 2000; Duggen et al., 2004; Mouthereau et al., 2025). Global Navigation Satellite System
70 (GNSS) observations show that present-day deformation is partitioned among several crustal blocks
71 bounded by crustal- to lithospheric-scale faults, defining the Eastern Betic Shear Zone (EBSZ) as an
72 incipient plate boundary between Africa and Eurasia (Palano et al., 2015; Billi et al., 2023; Portela et al.,
73 2025).

74 Helium isotopes provide one of the most sensitive tracers of mantle-sourced fluids. Primordial ³He is
75 hosted in the mantle, whereas radiogenic ⁴He is continuously produced within the continental crust by
76 U-Th decay (Clarke et al., 1969). Because helium is chemically inert, even a small mantle contribution
77 can be detected despite dominant radiogenic signature. Carbon isotopes further constrain the origin of
78 CO₂ in gases and associated travertines, which form where CO₂-rich fluids discharge at the surface,
79 recording deep fluid (mantle or crustal) circulation over timescales of thousands of years (Crossey et al.,
80 2009; Newell et al., 2023). Hereafter, modern fluids refer to present-day bubbling gases and spring
81 waters; sub-modern fluids to Quaternary travertines; and paleofluids to fluid circulation recorded in
82 fault-rock (quartz; calcite) over Myr timescales.



83 In the Betics, recent He isotope analyses of paleofluids reveal that mantle-sourced fluids circulated
84 along faults from the Eocene to the Pliocene (Cateland et al., 2026). However, mantle-sourced He never
85 exceeded ~10%. These results indicate weak but persistent crust-mantle connectivity over geological
86 timescales, during both extensional and compressional tectonic regimes. In contrast, analyses of
87 modern fluids have identified a prevailing crustal origin, despite a geodynamic setting considered
88 favorable for mantle degassing (Pérez et al., 1996; Lix et al., 2018). It however remains unclear whether
89 this result reflects the cessation of regional crust-mantle connectivity or more localized, punctual, fluid
90 flow within the plate boundary. Previous studies, however, did not sample the eastern Betics, where
91 crustal thinning is the largest (<25 km) and active deformation is most pronounced. Here, we investigate
92 modern and sub-modern fluids across the entire belt to test whether present-day crust-mantle
93 connectivity is controlled by crustal thickness, fault architecture, tectonic setting, or localized
94 deformation along the evolving plate boundary.

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1. Structure and tectonic evolution of the Betic Cordillera

The Betic Cordillera, in southeastern Spain (91a), resulted from Miocene extension within the Alboran domain, driven by slab retreat and delamination during Africa-Eurasia convergence. Extension exhumed E-W trending HP-LT (high pressure - low temperature) metamorphic complexes in the Internal Zone (Alpujárride and Nevado-Filábride complexes), separated by Neogene intramontane basins (Figure 1b). During the Tortonian and late Miocene (8-5 Ma), slab tearing propagated westward, and from the Pliocene the tectonic regime shifted to shortening (Larrey et al., 2023; Mouthereau et al., 2025). Late Miocene delamination and mantle upwelling were accompanied by a shift in volcanism from the calc-alkaline Cabo de Gata Volcanic Province (CGVP) towards more alkaline compositions. The associated regional uplift progressively restricted the Gibraltar marine gateway, triggering the onset of the Messinian Salinity Crisis (MSC; Mouthereau et al., 2025). As a result of Neogene extension and lithospheric delamination, crustal thickness decreases from 40 km to 20 km towards the southeastern margin. Present-day heat flow increases from 35 W.m⁻² near Granada to >75 W.m⁻² towards the southeast (Figure 1b; Mancilla et al., 2015; Díaz et al., 2016, ihfc-iugg.org). Seismic tomography confirms that the Alboran slab is now detached beneath the eastern and central Betics, extending westward to the Western Alboran domain near Málaga, offshore from the Ronda peridotites (Figure 1c; Mancilla et al., 2015).

The Internal Betics are intersected by major crustal to lithospheric-scale strike-slip fault systems that accommodate the present-day Africa-Eurasia convergence, such as the Eastern Betic Shear Zone (EBSZ; Figure 1b). The EBSZ accommodates up to one third of the 5-6 mm yr⁻¹ Africa-Eurasia convergence through dominant sinistral strike-slip and reverse motion along the Carboneras (CF), Palomares (PF) and Alhama de Murcia (AMF) faults. Other major active structures include the dextral Cádiz-Alicante Fault System (CAFS), the Crevillente Fault (CrF) and the Alpujarras Fault Corridor (AFZ; Figure 1b). Geological and geophysical studies indicate that the CF, PF, AFZ, AMF and CAFS are major crustal- to lithospheric-scale fault systems, although their continuity at depth remains variably constrained (Faulkner et al., 2003; Sanz de Galdeano, 2008; Herrero-Barbero et al., 2020; Larrey et al., 2023).

The Eastern Betics have experienced several destructive shallow earthquakes (~1 to 10 km depth) in recent decades, including the Mw 5.1 Mula (1999); Mw 4.7 Bullas (2005), and Mw 5.2 Lorca (2011) earthquakes (Figure 1b). These events occurred along major active structures including the eastern segment of the CAFS, the CrF, and the AMF (Bufoñ & Sanz de Galdeano, 2001; Bufoñ et al., 2006; Vissers & Meijninger, 2011; Herrero-Barbero et al., 2020). Based on geodetic, seismological, and GNSS observations, recent studies interpret the eastern Betics as a nascent diffuse plate boundary propagating onshore within the EBSZ between Africa and Eurasia (Figure 1a; Palano et al., 2015; Billi et al., 2023). In the eastern Betics, present-day convergence is partitioned among several crustal blocks,



151 highlighted by a fan-shaped velocity field and local domain of extension and compression at the regional
 152 scale (Figure 1a; Palano et al., 2015; Billi et al., 2023; Portela et al., 2025).

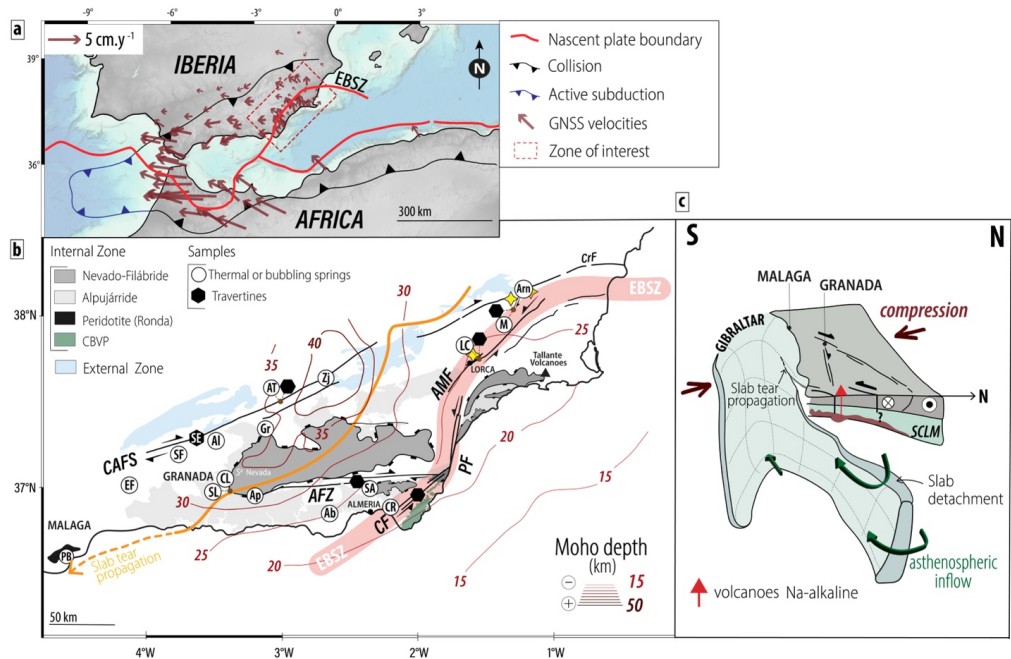
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154 **2. Thermal springs and travertines**

155 Springs are unevenly distributed across the Betics. In the western and central Betics, springs cluster
 156 along the Cádiz-Alicante Fault System (CAFS), highlighting its role as a major fluid pathway (e.g., Sierra
 157 Elvira, Zújar, Graena, Alicún de las Torres; Sanz de Galdeano, 2008; Lix et al., 2018). In contrast, springs
 158 are sparse in the southeastern Betics, where extensive greenhouse agriculture and groundwater
 159 exploitation have substantially reduced natural groundwater discharge (e.g., Carboneras-Palomares
 160 area; Figure 1b). Noble gas studies of modern fluids report exclusively crustal signatures throughout the
 161 western and central Betics, with mantle-sourced He contribution $\leq 1\%$ (e.g., Alicún de las Torres, Zújar,
 162 Sierra Elvira, El Frontil, and Capuchina de Lanjarón; see Pérez et al., 1996; Lix et al., 2018).

163 Travertine precipitation is widespread throughout the Betics and commonly associated with springs
 164 outlet within major fault systems. U-Th ages indicate travertine deposition during the Middle to Late
 165 Pleistocene, with some systems remaining active today, such as Lorca-Carraclaca (~306 ka to present;
 166 Martínez-Díaz and Hernández-Enrile, 2001; Canora et al., 2023), Alhama de Almería (~220 ka to present;
 167 García del Cura et al., 2012), and Alicún de las Torres (Pleistocene to present; Prado-Pérez et al., 2013),
 168 whereas travertine deposition at Tabernas occurred between ~354 and 8 ka (Larrey et al., 2020).
 169 Fracture-travertines at Sierra Elvira record an older precipitation event dated at 2 Ma (from U-Pb dating;
 170 Figure 2c; Cateland et al., 2026).

171 Previous $\delta^{13}\text{C}$ analyses of travertine carbonates from Tabernas and Lorca revealed unusually high values,
 172 consistent with a significant contribution of deep carbon, whether crustal or from the mantle (Larrey et
 173 al., 2020; Canora et al., 2023).



174
175 **Figure 1:** (a) GNSS velocities in a fixed Eurasian reference, active subduction, and the nascent Africa-
176 Iberia plate boundary along the Trans-Alboran Shear Zone (TASZ) and the Eastern Betic Shear Zone
177 (EBSZ) (after Booth-Rea et al., 2007; Palano et al., 2015; Billi et al., 2023). (b) Simplified structural map
178 of the eastern Betics showing the main fault systems, crustal thinning, Moho depth contours, slab-tear,
179 and sampling locations (springs and travertines). Major tectonic structures belong to the EBSZ. Fault
180 abbreviations are: Carboneras Fault (CF), Alpujarras Fault Zone (AFZ), Palomares Fault (PF), Alhama de
181 Murcia Fault (AMF), Crevillente Fault (CrF), and Cádiz-Alicante Fault System (CAFS). Sampling sites are
182 PB, Puerto Blanco; EF, El Frontil; AL, Alfacer; Gr, Graena; AT, Alicún de las Torres; ZJ, Zújar; LC, Lorca-
183 Carralaca; M, Mula; Arn, Archena; CR, Carboneras-Retamar; SA, Sierra Alhamilla; Ab, Albuñol; Ap, Agria
184 de Pórtugos; Cl, Capuchina de Lanjarón; and SL, Salado de Lanjarón. Modified after Vissers and
185 Meijninger (2011), Sanz de Galdeano et al. (2012), Alonso-Henar et al. (2021), and Larrey et al. (2023).
186 Moho depth contours and slab-tear geometry are from Mancilla et al. (2015).
187 (c) Three-dimensional schematic model of slab morphology beneath the Betic Cordillera, illustrating slab
188 tearing, major faults cross-cutting the crust and suspected asthenospheric inflow.



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203 **3. Sampling and analytical methods**

204 **3.1 Travertines**

205 Twelve travertine samples were collected from six sites: Carraclaca (n=3), Alicún de las Torres (n=4),
 206 Tabernas (n=2), Mula (n=1), Sierra Elvira (n=1) and Carboneras (n=1) (Figure 1a, Figure 2, Table 1, Figure
 207 S1). Most samples were collected near active springs with previously documented travertine formation,
 208 including Alicún de las Torres, Tabernas and Lorca-Carraclaca (García del Cura et al., 2012; Larrey et al.,
 209 2020; Canora et al., 2023). Other travertine samples were collected in inactive systems hosted in
 210 centimetric-scale fault openings (Sierra Elvira and Carboneras; Figure 2b, Figure 2c).

211 Carbon and oxygen isotope analyses ($\delta^{13}\text{C}_{\text{carb}}$, $\delta^{18}\text{O}_{\text{carb}}$) on travertine were performed at IStEP (Sorbonne
 212 Université, Paris, France) using a Kiel IV automated carbonate preparation device coupled to a Delta V
 213 Advantage isotope ratio mass spectrometer. Analytical procedures are described in the Supplementary
 214 data. Isotopic compositions are reported relative to the VPDB standard, with analytical precisions of
 215 $\pm 0.03\text{‰}$ for $\delta^{13}\text{C}$ and $\pm 0.06\text{‰}$ for $\delta^{18}\text{O}$.

216 Where macro-textural heterogeneity was observed (e.g., banding or changes in fabric), multiple
 217 microsamples were drilled from the same travertine (Table S1). Isotopic variability within individual
 218 samples was negligible, indicating that textural variations did not affect isotopic composition. Mean $\delta^{13}\text{C}$
 219 and $\delta^{18}\text{O}$ values are therefore reported for each travertine (Table 1).

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221 **3.2 Thermal water and bubbling springs**

222 A total of 16 sites were investigated, including bubbling springs (n=8) and non-bubbling springs (n=8)
 223 (Figure 3). The concentrations of O_2 , N_2 , CO_2 , CH_4 and ^4He in the gas bubbles and in the water were
 224 measured in the field using a portable miniRUEDI quadrupole mass spectrometer (Gasometrix,
 225 Switzerland; Brennwald et al 2016; Figure 4; Table 2). The instrument was calibrated using two standard
 226 gas mixtures and ambient air at each site (see composition of the standard bags and detailed methods
 227 in Supplementary Data). Water was sampled as close as possible to the spring vent using a submersible
 228 pump to avoid gas/water exchange with atmosphere (Figure 4). A particle filter was used where
 229 suspended sediments or algae were abundant (Figure 3; e.g. Retamar-Carboneras). Springs with a
 230 dominantly atmospheric composition were excluded from the dataset (cf. the Albuñol spring).

231 Samples for analysis of H_2 concentration and isotope analyses ($\delta^{13}\text{C}\text{-CO}_2$, $\delta^{13}\text{C}\text{-CH}_4$ and $\delta\text{D}\text{-CH}_4$) were
 232 collected from bubbles (n=6; Zújar, Archena, Sierra Alhamilla, Capuchina de Lanjarón, Alfacar and Puerto
 233 Blanco) and from water spring (n=1; Retamar-Carboneras) using a portable gas/water equilibrator
 234 (GEMSS). The gas was transferred into 10 mL vials and analyzed at ISOLAB (Netherlands). Carbon and
 235 hydrogen isotope analyses were performed using an Agilent 7890A gas chromatograph coupled to a



236 Thermo Fisher MAT 253 isotope-ratio mass spectrometer. Gas samples from bubbling sites were
237 collected with an inverted funnel (Figure 4; Daskalopoulou et al., 2022; Bernard et al., 2024) into copper
238 tubes for noble gas analyses (He, Ne, Ar) (Figure 4). The sampling system was flushed until no
239 atmospheric air remained, as monitored by bubbling through a water-filled beaker for ~40 min
240 depending on the gas flow. The copper tubes were then sealed with stainless steel pinch-off clamps
241 (Beyerle et al. 2000). Noble gas isotope ratios in bubble samples were measured at Université de Pau et
242 des Pays de l'Adour (UPPA, France).

243 At non-bubbling springs, water was collected in copper tubes connected to the pump using silicone
244 tubing. Dissolved gases were extracted from the water under ultra-high vacuum, purified cryogenically,
245 and analyzed at ETH Zürich using magnetic-sector noble gas mass spectrometers following Beyerle et
246 al. (2000). Most sampling sites correspond to historical *balnearios* (thermal spas). Sampling targeted all
247 accessible thermal and bubbling springs known to us along the investigated fault systems.

248 This study provides the first noble gas characterization of Retamar-Carboneras, Graena, Archena, Mula,
249 Lorca-Carraclaca and Puerto-Blanco, and reports previously undocumented bubbling gas emissions at
250 Archena, Zújar and Lorca-Carraclaca.

251 Helium isotopes are expressed as R/R_a , where R is the measured $^3\text{He}/^4\text{He}$ ratio of the sample and R_a is
252 the atmospheric $^3\text{He}/^4\text{He}$ ratio (1.38×10^{-6} ; Clarke et al., 1976). Because ^{20}Ne is predominantly
253 atmospheric, the $^4\text{He}/^{20}\text{Ne}$ ratio was used to estimate the atmospheric He contamination. The
254 measured R/R_a was then corrected to obtain R_c/R_a , where R_c is the $^3\text{He}/^4\text{He}$ ratio of the sample after
255 correction for atmospheric He (Ballentine and Burnard, 2002). Bubble samples were corrected using air
256 as the atmospheric end-member ($R/R_a = 1$; $^4\text{He}/^{20}\text{Ne} = 0.319$, Ozima and Podosek, 2002), whereas
257 dissolved samples were corrected using air-saturated water (ASW; $R/R_a = 0.983$; $^4\text{He}/^{20}\text{Ne} = 0.285$;
258 Benson and Krause, 1980). ASW differs from air endmember due to the different solubilities of He, Ne
259 and isotopic fractionation during dissolution (Kipfer et al., 2002).

260 Hereafter, mantle and radiogenic He fractions (in %) refer to the terrigenous He component only (i.e.,
261 crustal + mantle He), excluding atmospheric He.

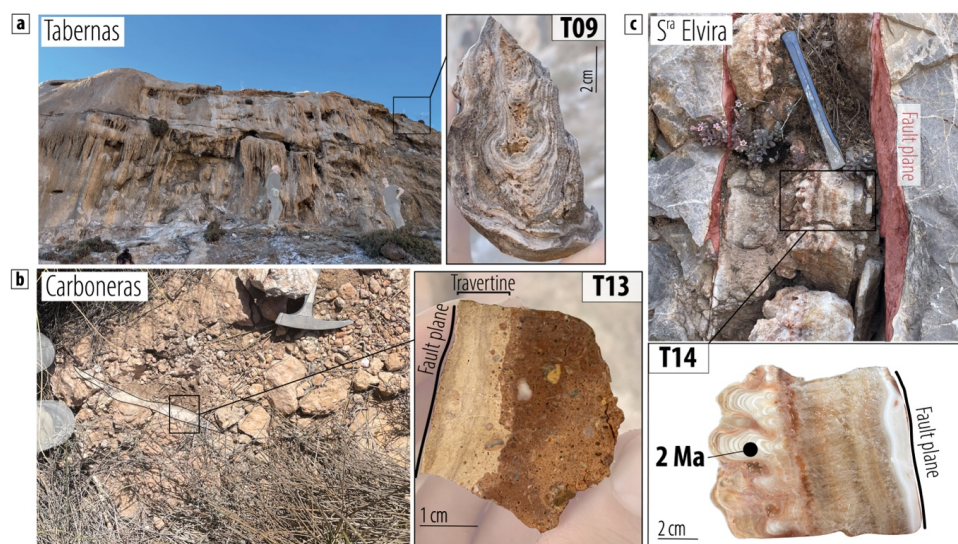


Figure 2: Field photographs and hand samples of active travertine in (a) Tabernas dated from 300 ka to 8 ka by U-Th from Larrey et al., 2020 and fault-related travertines in (b) Carboneras and (c) Sierra-Elvira dated at 2 Ma (Cateland et al., 2026).

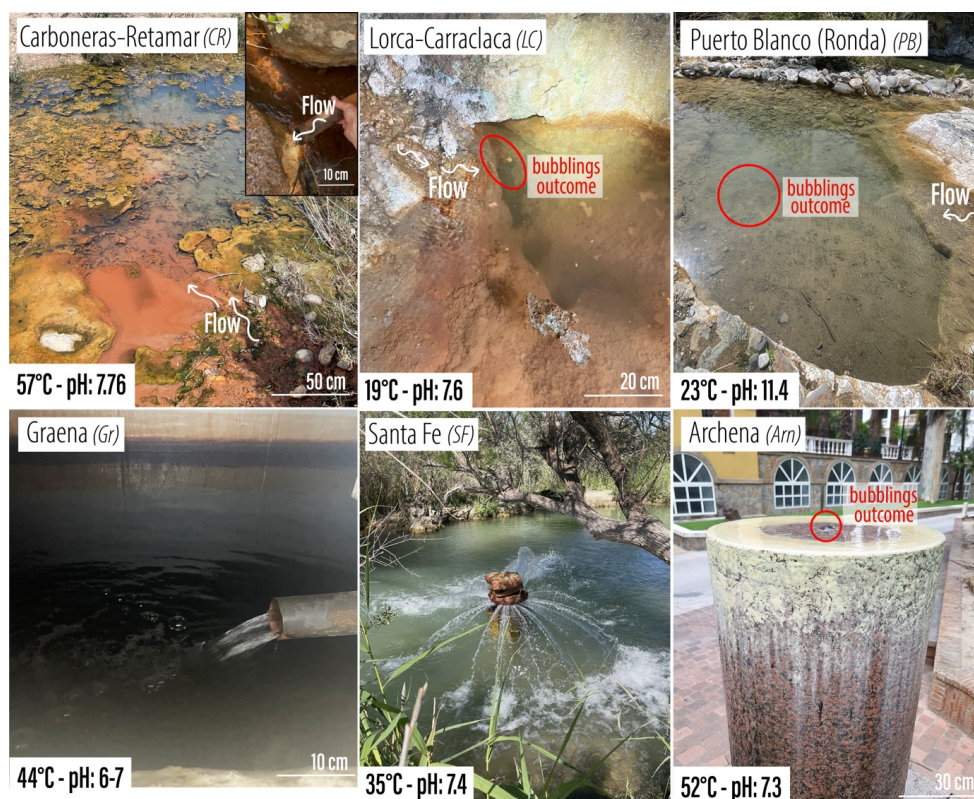


Figure 3: Field photographs of a few sampled thermal and bubbling springs in the Betic Cordillera. Red circles indicate bubbling gas emissions.

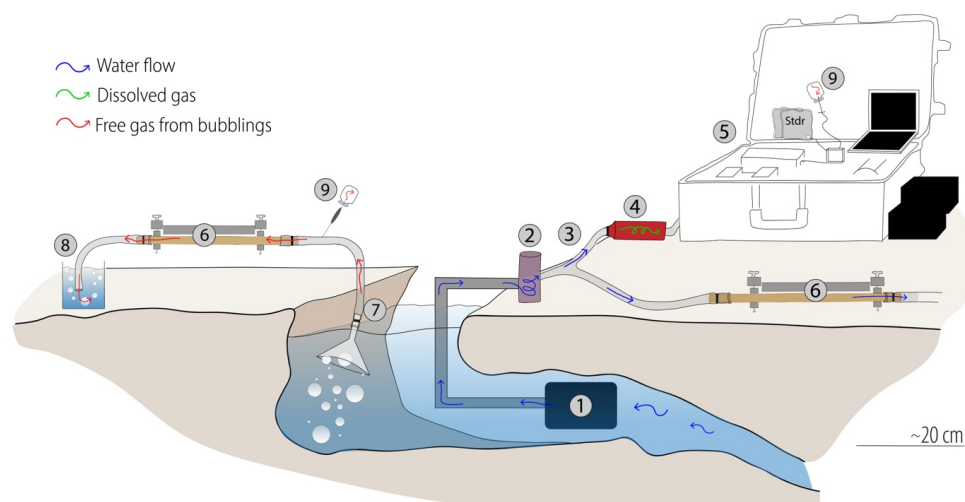


Figure 4: Sampling setup: (1) water pump; (2) particle filter; (3) flexible tubing; (4) gas/water equilibrator module for GE-MIMS; (5) miniRUEDI portable mass spectrometer; (6) copper tubes with stainless-steel clamps (7) inverted funnel for bubbling gas collection; (8) gas outlet bubbling through a water-filled beaker; and (9) Vacutainer vials for miniRUEDI and ISOLAB analyses. Stdr stands for standards.



4. Results

4.1 Stable isotopes in travertines

Carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) isotope analyses in travertines are displayed in Table 1 and Figure 5 with analytical accuracies of $\pm 0.03\text{‰}$ and $\pm 0.06\text{‰}$, respectively. The $\delta^{13}\text{C}$ values range from -6.54 to +10.01 ‰ VPDB, whereas the $\delta^{18}\text{O}$ values range from -9.84 to -4.41 ‰ VPDB. The highest $\delta^{13}\text{C}$ values were recorded in samples from Carracalaca and Tabernas, while negative values were observed at Sierra Elvira, Carboneras, and Mula (Table 1; Figure 5).

Table 1: Mean $\delta^{13}\text{C}$ (‰, VPDB) and $\delta^{18}\text{O}$ (‰, VPDB) values for travertine samples along major strike-slip fault zones or/and associated to thermal springs. Individual analytical values are provided in the Supplementary Data (Table S1).

Faults	Lat.	Long.	Samples	$\delta^{13}\text{C}$ (‰VPDB ; $\pm 0.03\text{‰}$)	$\delta^{18}\text{O}$ (‰VPDB ; $\pm 0.06\text{‰}$)
Lorca - Carracalaca (AMF)	37°41'48.92"N	1°39'50.69"W	T1	5.78	-5.61
			T2	6.40	-5.47
			T3	10.01	-4.82
Alicún de las Torres (CAFS)	37°30'35.10"N	3°6'33.95"W	T4	0.56	-9.74
			T5	0.28	-9.57
			T6	0.80	-6.24
			T7	-0.46	-9.84
Tabernas (AFZ)	37°1'12.67"N	2°27'16.58"W	T8	3.07	-5.47
			T9	0.51	-5.32
Baños de Mula (CAFS/CrF)	38°2'15.82"N	1°25'35.14"W	T12	-6.54	-7.095
Carboneras (CF)	36°54'21.71"N	2°5'38.27"W	T13	-8.21	-4.41
Sierra Elvira (CAFS)	37°13'53.13"N	3°43'12.36"W	T14	-10.65	-7.32

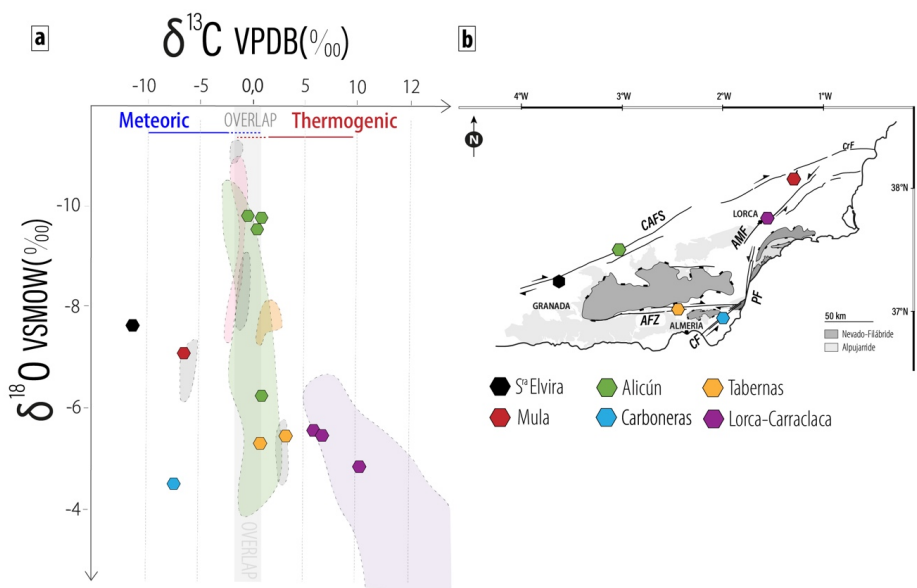


Figure 5: Stable isotopic constraints. a) $\delta^{13}\text{C}$ (‰ VPDB) versus $\delta^{18}\text{O}$ (‰ VPDB) values for travertine samples along major strike-slip fault zones or/and associated with thermal springs. Data from this study are shown as colored hexagons (see legend). Published isotopic data from regional travertine systems are reported as ranges (colored dash-limited areas): Mazarrón in gray (Rodrigo-Naharro et al., 2013); Alhama de Almería in pink (García del Cura et al., 2012), Alicún de las Torres in green (Prado-Pérez et al., 2013); and Lorca-Carraclaca in purple (Canora et al., 2023 with full range: $\delta^{13}\text{C} = 4.5\text{--}18\text{‰ VPDB}$ and $\delta^{18}\text{O} = -6.6$ to -1.1‰ VPDB ; the field is truncated here for clarity). Meteoric and thermogenic fields are defined according to Pentecost (2005).

b) Travertine location across the Betics. Fault abbreviations are: Carboneras Fault (CF), Alpujarras Fault Zone (AFZ), Palomares Fault (PF), Alhama de Murcia Fault (AMF), Crevillente Fault (CrF), and Cádiz-Alicante Fault System (CAFS).



341 **4.2 Major gases and C-H isotopes**

342 Spring temperatures and pH values measured at the source range from 19 to 57°C and from 5.8 to 11.4,
 343 respectively (Table 2 and 3). Assuming that O₂ in bubbling gases primarily reflects atmospheric
 344 contamination introduced during sampling, its concentration indicates that contamination is generally
 345 limited, with values >3 vol% at six of the eight bubbling sites. Higher O₂ concentrations of 14-16 vol %
 346 are measured at El Frontil and Alfacar (see Table S2 for non-corrected concentrations). Gas
 347 concentrations of bubbling samples are dominated by N₂ and/or CO₂, with N₂ concentrations ranging
 348 from 36.6 to 95 vol% and CO₂ from 0.047 to 98.8 vol% (Table 2, 3, Figure 6a).

349 Most bubbling gases are N₂-dominated, with N₂ concentrations ranging from 76 to 95 vol% at Alfacar,
 350 Sierra Alhamilla, Archena, El Frontil, Puerto Blanco and Zújar. Lorca-Carraclaca shows a mixed N₂-CO₂
 351 composition, with 36.6 vol% N₂ and 61.1 vol% CO₂, whereas Capuchina is strongly CO₂-dominated (98.8
 352 vol%). CO₂ concentrations at the remaining N₂-dominated sites range from 0.047 to 6.3 vol% (Table 2).

353 CH₄ is generally present at trace to minor concentration ≤0.8 vol% in bubbles, but reaches higher
 354 concentration at Alfacar and Puerto Blanco (16 and 12.4 vol%, respectively; Table 2).

355 Aqueous gas concentrations are reported separately in mol·L⁻¹, as gas-water equilibrium cannot be
 356 assumed (Table 3). N₂ concentrations range from 6.9×10^{-5} to 6.03×10^{-4} mol·L⁻¹, while O₂
 357 concentrations range from 7.12×10^{-6} to 1.60×10^{-4} mol·L⁻¹. Aqueous CH₄ concentrations range from 1
 358 $\times 10^{-7}$ to 1.4×10^{-5} mol·L⁻¹. Aqueous CO₂ concentrations were not calculated because of uncertainties
 359 associated with CO₂ gas-water partitioning.

360 For visualization purposes, air-corrected relative gas concentrations are also shown for dissolved gas
 361 and bubbling phase to facilitate comparison between these two fluid types (Figure 6a, Figure S2, Table
 362 S3). This comparison remains qualitative, as gas-water equilibrium is not assumed.

363 δ¹³C-CH₄ range from -70‰ VPDB at Alfacar to +7.4‰ VPDB at Sierra Alhamilla. Intermediate values (-
 364 28.5 to -16‰) occur at Puerto Blanco, Zújar and Archena. δD-CH₄ values range from -343‰ to +375‰
 365 VSMOW, with the lowest values at Alfacar and Puerto Blanco (≤-300‰) and the highest at Zújar and
 366 Sierra Alhamilla (≥+126‰) (Figure 6b).

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Table 2: Air-corrected gas concentrations and isotopic signatures of free gases (bubbling springs) of the Betic Cordillera. Concentrations of N₂, CO₂, CH₂, O₂ and ⁴He were measured using a portable miniRuedi mass spectrometer. CO₂ and CH₄ (δ¹³C) as well as hydrogen isotopes in CH₄ (δD) were measured in a gas chromatograph (GC; ISOLAB). "NaN" indicates no measurement was performed and blanks cell refer to not detected. Grey shading highlight samples previously analyzed by Lix et al. (2018). Non-air corrected gas compositions (including O₂ contents) are provided in Table S2.

SITES	Label code	Lat.	Lon.	T°C	pH	N ₂ vol %	CO ₂ vol %	CH ₄ vol %	⁴ He (ppmv)	δ ¹³ C CO ₂ (‰V/PDB)	δ ¹³ C CH ₄ (‰V/PDB)	δD CH ₄ (‰V/SNOW)
ALFACAR (B)	Al	37°14'47.8 3"N	3°33'13.5 8"W	18	NaN	76 ± 3	1.38 ± 0.01	16 ± 2	9.4 ± 0.5	-17.2	-70.0	-343
(Sierra) ALHAMILLA (B)	SA	36°57'39.6 4"N	2°23'47.4 5"W	51	7.1	89 ± 3	6.3 ± 0.7	0.5 ± 0.2	480 ± 40	-10.3	7.3	126
ARCHENA (B)	Arn	38° 7'41.66"N	1°18'11.3 0"W	52	6.8	93 ± 3	3.06 ± 0.02	0.8 ± 0.1	1500 ± 20	-8.9	-16.0	-6
CAPUCHINA (B) (Lanjarón)	CL	36°55'8.42" N	3°29'26.0 0"W	21	6.1	NaN	98.8 ± 0.4	0.05 ± 0.06	8.2 ± 0.3	-5.3		
EL FRONTIL (B)	EF	37°10'38.5 9"N	4° 7'57.19" W	18	7.5	92 ± 4	1.18 ± 0.01	0.05 ± 0.01	58.3 ± 0.9	NaN	NaN	NaN
LORCA-CARRACILACA (B)	LC	37°42'17.6 6"N	1°39'21.5 8"W	19	7.7	36.6 ± 0.8	61.1 ± 0.3	0.03 ± 0.02	273 ± 5	-3.4		
PUERTOBLANCO (RONDA) (B)	PB	36°35'42.1 8"N	4°43'32.1 1"W	23	11.4 2	85 ± 1	0.0473 ± 0.0009	12.4 ± 0.8	15.5 ± 0.3	-16.0	-28.5	-300
ZÚJAR (B)	Zj	37°35'50.4 6"N	2°48'54.1 8"W	35	6.8	95 ± 1	1.755 ± 0.007	0.12 ± 0.03	484 ± 5	-7.5	-27.7	373



Table 3: Aqueous gas concentrations in water springs of the Betic Cordillera. N_2 , O_2 , CH_4 and ^4He concentrations are reported in $mol \cdot L^{-1}$ and were determined using a portable miniRUEDI mass spectrometer. Aqueous CO_2 concentrations were not calculated because of uncertainties related to CO_2 gas-water partitioning, see partial pressure Table S3. Grey shading highlight samples previously analyzed by Lix et al. (2018).

Sites	Label code	Lat.	Long.	T (°C)	pH	N_2 ($mol \cdot L^{-1}$)	O_2 ($mol \cdot L^{-1}$)	CH_4 ($mol \cdot L^{-1}$)	^4He ($mol \cdot L^{-1}$)
ALICÚN	AT	37°30'31.88"N	3°6'25.90"W	34	6.7	$(4.9 \pm 0.1) \times 10^{-4}$	$(7.6 \pm 0.1) \times 10^{-5}$	$(1 \pm 1) \times 10^{-7}$	$(3.33 \pm 0.08) \times 10^{-8}$
ARCHENA	Am	38°7'41.66"N	1°18'11.30"W	52	7.3	$(5.34 \pm 0.10) \times 10^{-4}$	$(9.6 \pm 0.2) \times 10^{-6}$	$(1.4 \pm 0.2) \times 10^{-5}$	$(3.67 \pm 0.08) \times 10^{-7}$
CAPUCHINA (lanjaron)	CL	36°55'10.17"N	3°29'25.29"W	21	6.1	$(2.26 \pm 0.03) \times 10^{-4}$	$(1.119 \pm 0.004) \times 10^{-4}$	$(9 \pm 6) \times 10^{-7}$	$(2.12 \pm 0.04) \times 10^{-9}$
GRAENA	Gr	37°18'14.19"N	3°12'32.97"W	44	n.m	$(4.56 \pm 0.05) \times 10^{-4}$	$(1.120 \pm 0.009) \times 10^{-4}$	$(6 \pm 1) \times 10^{-7}$	$(1.204 \pm 0.020) \times 10^{-8}$
MULA	M	38°2'17.58"N	1°25'33.42"W	35	7.1	$(5.34 \pm 0.06) \times 10^{-4}$	$(1.038 \pm 0.003) \times 10^{-4}$	$(1.7 \pm 0.4) \times 10^{-7}$	$(3.66 \pm 0.05) \times 10^{-8}$
RETAMAR-CARBONERAS	RC	36°50'57.82"N	2°17'25.89"W	57	7.76	$(3.81 \pm 0.05) \times 10^{-4}$	$(2.57 \pm 0.03) \times 10^{-5}$	$(5.4 \pm 0.9) \times 10^{-6}$	$(2.02 \pm 0.04) \times 10^{-7}$
SALADO	SL	36°55'15.31"N	3°29'27.77"W	26	5.8	$(6.9 \pm 0.2) \times 10^{-5}$	$(2.08 \pm 0.03) \times 10^{-5}$	$(6 \pm 5) \times 10^{-7}$	$(1.54 \pm 0.05) \times 10^{-9}$
SANTA FE	SF	37°9'21.62"N	3°45'11.42"W	32	7.4	$(6.03 \pm 0.08) \times 10^{-4}$	$(7.12 \pm 0.05) \times 10^{-6}$	$(7 \pm 3) \times 10^{-7}$	$(9.2 \pm 0.2) \times 10^{-8}$
ZÚJAR	ZJ	37°35'50.46"N	2°48'54.18"W	35	6.8	$(3.96 \pm 0.06) \times 10^{-4}$	$(1.60 \pm 0.01) \times 10^{-4}$	$(2 \pm 1) \times 10^{-7}$	$(5.16 \pm 0.07) \times 10^{-8}$

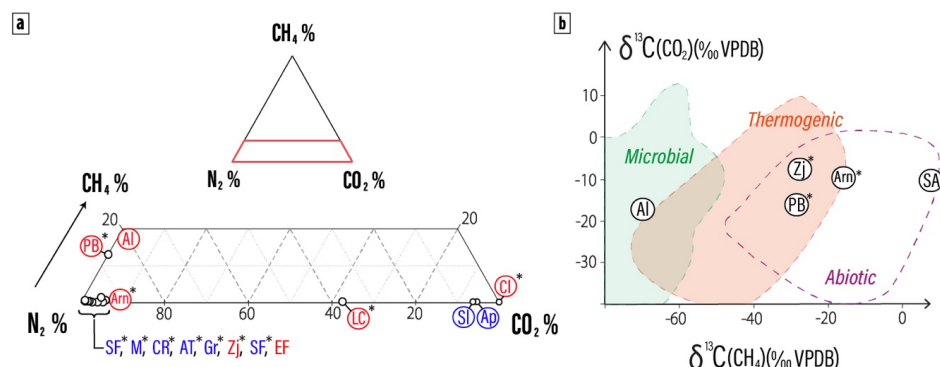


Figure 6: (a) CH₄-CO₂-N₂ ternary diagram showing relative gas concentration for bubbling gases (red) and gases dissolved in water (blue). For both sample types, ternary proportions were calculated from the N₂, CO₂ and CH₄ partial pressures and normalized to their sum (Table S3). (b) Carbon isotopic composition of methane and carbon dioxide (δ¹³C-CH₄ vs. δ¹³C-CO₂) used to constrain methane origin (Milkov and Etiope, 2018). PB: Puerto Blanco; EF: El Frontil; AL: Alfacar; Gr: Graena; AT: Alicún de las Torres; ZJ: Zújar; LC: Lorca-Carraclaca; M: Mula; Arn: Archena; CR: Carboneras-Retamar; SA: Sierra Alhamilla; Ap: Agria de Pórtugos; CL: Capuchina de Lanjarón; and SL: Salado de Lanjarón. Samples marked with an asterisk are also reported in Figure 7 showing noble gas isotope compositions.

4.3 Noble gas concentrations and isotopes

MiniRUEDI ⁴He concentrations in bubbles range from 8.2 to 1500 ppmv, with the highest concentration measured at Archena. Relatively high concentrations are observed at Zújar (484 ppmv) and Sierra Alhamilla (480 ppmv), whereas the lowest concentrations occur at Capuchina (8.2 ppmv) and Alfacar (9.4 ppmv; Table 2). In the aqueous phase, ⁴He concentrations range from 1.54 × 10⁻⁹ mol. L⁻¹ at Salado to 3.67 × 10⁻⁷ mol. L⁻¹ at Archena (Table 3). For the subset analyzed in the noble-gas laboratory, ⁴He concentrations range from 2.67 × 10⁻⁹ to 4.31 × 10⁻⁷ mol. L⁻¹, with corresponding ³He concentrations ranging from 3.25 × 10⁻¹⁵ to 1.93 × 10⁻¹³ mol. L⁻¹. Ar concentrations range from 7.07 × 10⁻⁶ to 1.42 × 10⁻⁵ mol. L⁻¹ (Table 4).

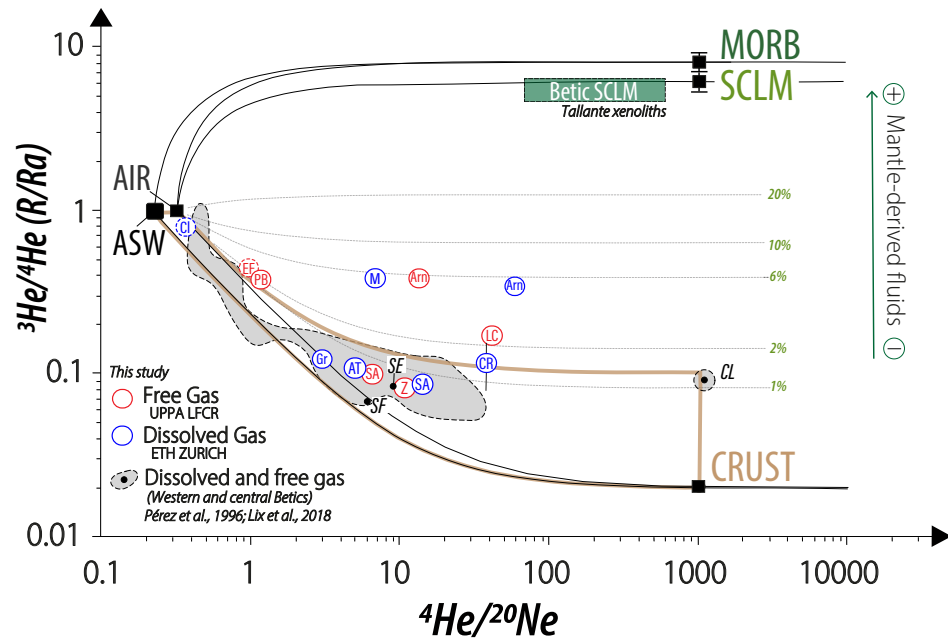
³He/⁴He, ⁴He/²⁰Ne, and ⁴⁰Ar/³⁶Ar ratios measured in waters and bubbles are reported in Table 4.

The measured He isotopic ratio (R/Ra) ranges from 0.090 to 0.78 in dissolved gases and from 0.080 to 0.38 in bubbles. ⁴He/²⁰Ne ratios range from 0.313 to 58.0 in dissolved gases and from 1.11 to 42 in bubbles. The highest ⁴He/²⁰Ne ratio measured at Archena dissolved phase, whereas Capuchina and El Frontil display ratios <1, indicating a strong atmospheric component (cf. dashed blue and red circles on Figure 7).

The air-corrected He isotopic ratio (Rc/Ra), ranges from 0.028 at Graena to 0.35 at Mula in dissolved gases, and from 0.042 at Sierra Alhamilla to 0.36 at Archena in bubbling gases. Measured ⁴⁰Ar/³⁶Ar ratios range from 293.59 at Capuchina to 324.2 at Archena.



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Figure 7: R/Ra versus $^4\text{He}/^{20}\text{Ne}$ diagram showing the relative contributions of atmospheric, mantle, and crustal end-members. The dashed curves represent mixing trajectories between Air ($^3\text{He}/^4\text{He} = 1.38 \times 10^{-6}$; $^4\text{He}/^{20}\text{Ne} = 0.319$; Ozima and Podosek, 2002), Air-Saturated water (ASW; $R/Ra=0.983$, and $^4\text{He}/^{20}\text{Ne}=0.285$; Benson and Krause, 1980), European Sub-continental lithospheric mantle (SCLM; $R/Ra=6.32 \pm 0.39$; Gautheron et al., 2005), MORB-like mantle ($R/Ra=8 \pm 1$; Graham, 2002), and crustal fluids ($R/Ra=0.02$; Graham, 2002). The percentage labels along the curves indicate proportion of SCLM-sourced He, computed from Sano and Wakita (1985). The green rectangle represents the range of He isotopic compositions measured in xenoliths from the Eastern Betic SCLM (Tallante; Martelli et al., 2011). The gray field represents previously published dissolved- and free-gas compositions from the western and central Betics (Pérez et al., 1996; Lix et al., 2018), with selected sites (SF, SE and CL) highlighted individually as black points. Dashed colored symbols indicate samples with $^4\text{He}/^{20}\text{Ne} \leq 1$, corresponding to atmospheric-dominated samples. Abbreviations are PB: Puerto Blanco; Gr: Graena; AT: Alicún de las Torres; ZJ: Zújar; LC: Lorca-Carraclaca; M: Mula; Arn: Archena; CR: Carboneras-Retamar; SA: Sierra Alhamilla; Ap: Agria de Pórtugos; CL: Capuchina de Lanjarón; SE: Sierra Elvira; SF: Santa Fe.

Table 4: Noble gas isotopic compositions and concentrations of gases dissolved in water (D) and in bubbles (B). R/Ra corresponds to the measured $^3\text{He}/^4\text{He}$ ratio normalized to the atmospheric ratio. Rc/Ra represents the atmospheric-corrected He isotope ratio, using air for bubbles (B) and ASW for dissolved gases (D). Samples highlighted in grey were also analyzed by Lix et al. (2018). Values in italics are compiled from bibliography (Pérez et al., 1996; Lix et al., 2018). “n.r.” stands for “not reported”, blank cells for not measured.

Sites	Label	R/Ra	$^4\text{He}/^{20}\text{Ne}$	$^{40}\text{Ar}/^{36}\text{Ar}$	Rc/Ra	^4He (mol·L ⁻¹)	^{40}Ar (mol·L ⁻¹)
AUCÚN (D)	AT	0.110 ± 0.004	5.07 ± 0.07		0.058 ± 0.004	4.64 × 10 ⁻⁸	
ARCHENA (B)	Am	0.38 ± 0.01	12.5 ± 0.5	324.2	0.36 ± 0.01		
ARCHENA (D)	Am	0.34 ± 0.01	58.0 ± 0.8		0.34 ± 0.01	4.31 × 10 ⁻⁷	1.42 × 10 ⁻⁵
CAPUCHINA (lanjarón) (D)	CL	0.78 ± 0.03	0.313 ± 0.004	293.59		2.67 × 10 ⁻⁹	7.07 × 10 ⁻⁶
EL FRONTIL (D)	EF	0.46 ± 0.02	0.96 ± 0.04	295.93	0.24 ± 0.03		
GRAENA (D)	Gr	0.120 ± 0.004	2.96 ± 0.04	295.1	0.028 ± 0.005	1.86 × 10 ⁻⁸	1.26 × 10 ⁻⁵
LORCA-CARRACIACA (B)	LC	0.160 ± 0.006	42 ± 2	318.4	0.154 ± 0.006		
MULA (D)	M	0.38 ± 0.01	6.59 ± 0.09	296	0.35 ± 0.01	4.47 × 10 ⁻⁸	1.32 × 10 ⁻⁵
PUERTOBLANCO (RONDA) (B)	PB	0.37 ± 0.01	1.11 ± 0.05	298.2	0.12 ± 0.02		
RETAMAR-CARBONERAS (D)	RC	0.120 ± 0.004	38.1 ± 0.5	296	0.113 ± 0.004	2.67 × 10 ⁻⁷	1.14 × 10 ⁻⁵
SIERRA ALHAMILLA (B)	SA	0.090 ± 0.003	6.4 ± 0.3	301.49	0.042 ± 0.004		
SIERRA ALHAMILLA (D)	SA	0.090 ± 0.003	13.8 ± 0.2		0.071 ± 0.003	8.46 × 10 ⁻⁸	1.08 × 10 ⁻⁵
ZÚJAR (B)	ZJ	0.080 ± 0.003	10.9 ± 0.5	295.49	0.052 ± 0.003		
SANTA FE (D), Lix et al., 2018	SF	0.067 ± 0.002	5.9 ± 0.3	n.r.	0.024 ± 0.004		
SIERRA ELVIRA (D), Lix et al., 2018	SE	0.083 ± 0.002	9.2 ± 0.5	n.r.	0.057 ± 0.003		
CAPUCHINA LANJARÓN (B), Pérez et al., 1996	CL	0.10 ± 0.03	1780	n.r.	0.10		



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471 **5 Discussion**

472 **5.1 Spatial variability in deep fluid sources and connectivity**

473 The mantle contribution in the fluids system is observed in only three springs out of the thirteen in our
 474 dataset: Lorca-Carraclaca, Mula and Archena. These sites contain 2 to 6% mantle-sourced He and cluster
 475 in the northeastern Betics, along the AMF and the CrF (Figure 7, Figure 8). Most springs define a mixing
 476 trend between atmospheric and crustal end-members (Figure 7). High radiogenic He ($\geq 99\%$) dominate
 477 the western and central Betics, including Alicún, Zújar, Sierra Alhamilla, El Frontil, Graena, Santa Fe,
 478 Puerto Blanco with minor mantle He contribution ($\leq 1\%$), consistent with previous studies (Lix et al.,
 479 2018). El Frontil and Capuchina (Lanjarón) show gas dominated by atmospheric source. At Capuchina, a
 480 similarly atmosphere-dominated signature was reported by Lix et al. (2018), whereas Pérez et al. (1996)
 481 reported a clear crustal helium signature from the same source ($R/R_a = 0.10$; $^4\text{He}/^{20}\text{Ne} = 1780$). The
 482 previously detectable crustal signature is no longer expressed, and is now dominated by an atmospheric
 483 signature ($R/R_a = 0.78$; $^4\text{He}/^{20}\text{Ne} = 0.313$), suggesting reduced deep connectivity and crustal He input,
 484 now masked by shallow atmospheric dilution.

485 The fluid system at the Carboneras Fault does not show a clear mantle contribution despite being a
 486 major active fault cutting through a crust of only ~ 20 km thick. Within uncertainty, Retamar-Carboneras
 487 falls within the radiogenic group of western and central Betic springs ($\leq 1\%$ mantle-He; Figure 8b).

488 The largest mantle contributions occur in N_2 -dominated springs containing only minor CO_2 (3 vol%). At
 489 Mula and Archena, mantle-sourced He accounts for approximately 5-6% of He, compared with only $\sim 2\%$
 490 at Lorca-Carraclaca, despite a much larger CO_2 fraction (61 vol%). The dominant carrier gas transporting
 491 helium to the surface is therefore either N_2 or CO_2 .

492 The geochemical origin of N_2 was not investigated in this study, and it may reflect either terrigenous
 493 (mantle or crust) sources or atmospheric N_2 introduced during recharge by meteoric water (e.g., Léger
 494 et al., 2025). Regarding CO_2 origin, in sites showing mantle-sourced He such as Archena, $\delta^{13}\text{C}$ (CO_2)
 495 display values around -8.9 ‰ VPDB, slightly below the MORB range (-8 ‰ to -4 ‰; Pineau and Javoy,
 496 1983). The combined $\delta^{13}\text{C}$ of CO_2 and CH_4 signatures further indicate an abiogenic or thermogenic gas
 497 source (Figure 6b). At Lorca-Carraclaca, CO_2 is isotopically heavier (-3.4 ‰ VPDB) than MORB CO_2 ,
 498 suggesting isotopic modification during crustal migration.

499 In the western and central Betics, radiogenic and/or atmospheric He signatures are associated with
 500 either N_2 -rich compositions (e.g., Zújar, Graena, Alicún, Santa Fe, Sierra Alhamilla and Retamar-
 501 Carboneras) or CO_2 -rich systems (e.g., Capuchina de Lanjarón, Salado de Lanjarón; Pérez et al., 1996;
 502 Lix et al., 2018). Major gas compositions and carbon isotopes show no systematic relationship with fluid
 503 origin. At Zújar, $\delta^{13}\text{C}$ (CO_2) (~ -7.5 ‰ VPDB) falls within the MORB range despite low CO_2 concentrations
 504 (1.5 vol%; Pineau and Javoy, 1983), Capuchina similarly shows a $\delta^{13}\text{C}$ - CO_2 value of -5.3 ‰ VPDB, despite



505 crustal- or atmosphere- dominated He signature. This highlights the ambiguity of reactive carbon tracers
 506 and the ability of chemically inert noble gases to constrain fluid origin (Sherwood Lollar and Ballentine,
 507 2009).

508 Across both eastern and western Betic springs, combined $\delta^{13}\text{C-CO}_2$ and $\delta^{13}\text{C-CH}_4$ values indicate
 509 dominantly thermogenic or abiotic gas sources (Figure 6b). Only Sierra Alhamilla shows isotopic values
 510 clearly within the abiotic field, indicating CH_4 production through inorganic mineral–fluid processes.

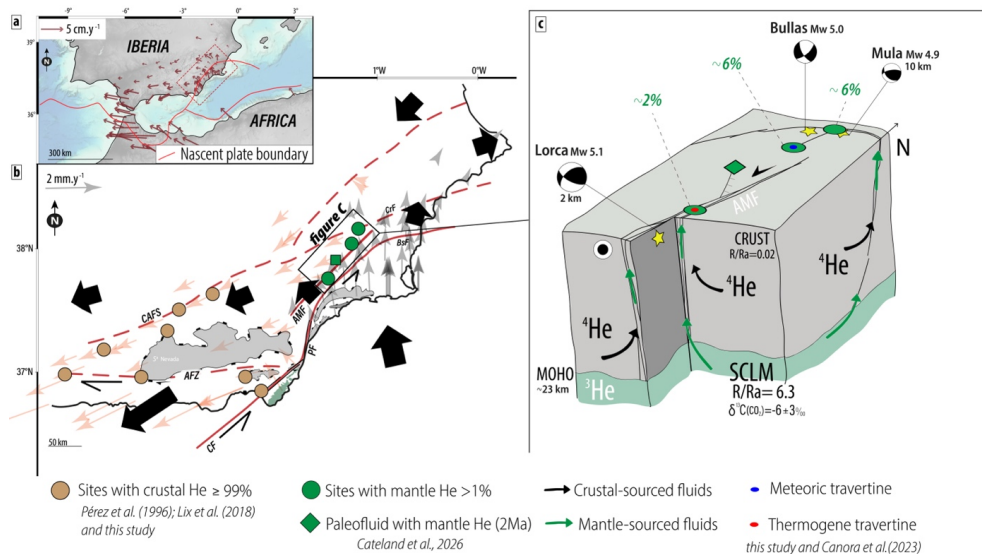
511 Archena, despite showing a mantle-sourced He, does not stand out from the other springs and plots
 512 within the overlapping abiotic-thermogenic domain. The few methane-rich springs show a microbial
 513 methane signature at Alfacar and methane generated by serpentinization within the Ronda peridotites
 514 at Puerto Blanco (Figures 6b and Figure S3, Etiope et al., 2016; Milkov and Etiope, 2018). $\delta\text{D}(\text{CH}_4)$ values
 515 are unusually high (-50 to $+360$ VSMOW‰) and fall outside defined genetic fields (Figure S3), suggesting
 516 secondary methane oxidation during fluid migration (Whiticar, 1999; Daskalopoulou et al., 2018; Humez
 517 et al., 2019).

518 Travertines at Lorca-Carraclaca (approx. 306 ka to the present) display exceptionally positive values of
 519 $\delta^{13}\text{C-CO}_2$ (Figure 6a), placing it within the thermogenic field after Pentecost (2005), as already suggested
 520 by Canora et al. (2023). This clear thermogenic travertine signature is consistent with precipitation from
 521 deep (mantle and/or crustal) CO_2 -rich fluids along the AMF, where associated springs contain small
 522 mantle-sourced He ($\sim 2\%$). The Lorca-Carraclaca travertines coincide with one of the most active fault
 523 segments of the EBSZ, the AMF (Herrero-Barbero et al., 2020; Canora et al., 2023). The $\delta^{13}\text{C}$ of the
 524 Tabernas travertines also plot within the thermogenic field, consistent with the nearby Sierra Alhamilla
 525 spring, where radiogenic He likely reflects crustal CO_2 circulation. The relationship between the origins
 526 of travertines and spring waters, however, does not seem to follow a clear systematic pattern. For
 527 instance, the O, C isotopic values of the travertines from Mula plot within the meteoric field despite the
 528 relatively high mantle-sourced He fraction recorded in the nearby springs along the CrF fault ($\sim 6\%$),
 529 indicating that carbonate precipitation involved predominantly shallow fluids at this site (Figure 8c). O,
 530 C isotopic values of the travertines from Carboneras fault plot within the meteoric field, indicating more
 531 likely shallow carbonate precipitation. Meanwhile, nearby springs show a strong crustal He signature,
 532 pointing to a deeper crustal contribution. Other travertines in the western Betics display meteoric or
 533 mixed isotopic signatures without a clear pattern (e.g. Sierra Elvira; Alicún de las Torres; Figure 5). This
 534 variability highlights the strong heterogeneity of fluid circulation along fault systems and/or suggests
 535 that travertines and springs record different processes and/or timescales of fluid circulation.

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543 **Figure 8:** Present-day tectonic framework and spatial distribution of crustal and mantle-sourced fluids.
544 (a) GNSS velocities (Palano et al., 2015) and inferred propagation of the nascent plate boundary (Billi et
545 al., 2023). (b) Localized mantle He (in green) in the NE of the Betics. Crustal blocks direction (thick black
546 arrows), and GNSS velocity vectors (colored thin arrows) are from Portela et al. (2025): beige arrows
547 show westward extrusion motion, grey arrows indicate NNE-directed motion. (c) Conceptual 3D
548 diagram illustrating mantle He migration to the surface in the eastern Betics (AMF, eastern CAFS and
549 CrF), and associated travertine origin. Number in percentage indicate the estimated mantle He
550 contribution. Stars show the epicenters of 1999 Mula, 2005 Bullas and 2011 Lorca earthquakes. SCLM
551 stands for Sub-Continental Lithospheric Mantle.
552 Fault abbreviations are: Carboneras Fault (CF), Alpujarras Fault Zone (AFZ), Palomares Fault (PF), Alhama
553 de Murcia Fault (AMF), Crevillente Fault (CrF), and Cádiz-Alicante Fault System (CAFS).
554

555 5.2 Explaining the low mantle contribution in the Betics

556 At mature plate boundary, mantle-sourced helium accounts for ~50% of the helium budget along the
557 San Andreas Fault and ~70-80% along segments of the North Anatolian Fault beneath the Marmara Sea
558 (Kennedy et al., 1997; Burnard et al., 2012). The relatively low $\leq 6\%$ mantle contribution in the Betics is
559 consistent with limited crust-mantle transfer, restricted to only few fault segments. The elevated
560 geothermal gradients in the SE Betics ($40-50\text{ }^{\circ}\text{C km}^{-1}$; Muñoz-Cemillán et al., 2025) may enhance the
561 radiogenic ^4He helium contained in crystals by diffusion, leading to dilution of the mantle ^3He signal
562 (Farley, 2000; Huang et al., 2026; Mulaya et al., 2026). Yet these fluids show no evidence for preferential
563 ^4He enrichment relative to $^{40}\text{Ar}^*$. The $^4\text{He}/^{40}\text{Ar}^*$ ratio (~ 4.5) remains close to the crustal production value
564 (4-6), unlike the strong He-Ar fractionation observed in the Otway basin (~ 69 ; Brown et al., 2026). The
565 lack of clear excess of radiogenic ^4He argues against the preferential ^4He diffusion as a significant process
566 (Figure S4).



Groundwater residence time may also contribute to the low R_c/R_a values. Water stored within the crust can accumulate radiogenic ^4He , thereby masking the ^3He signature over time. For instance, deep aquifer directly exploited from the basement (e.g., Graena, Archena, Capuchina, Salado de Lanjarón, and Carboneras Retamar) may acquire more radiogenic ^4He than springs naturally discharging system such as Lorca-Carraclaca and Mula.

Another factor that may contribute to the low mantle contribution in the Betics, is the composition of the SCLM beneath southern Iberia. Relatively low $^3\text{He}/^4\text{He}$ values, attributed to metasomatism by subduction-related components (Martelli et al., 2011) enriched in U, Th, and radiogenic ^4He are expected. The regional mantle end-member may therefore itself be more radiogenic than a typical European-SCLM and spatially heterogeneous. For instance, an old “closed” SCLM with limited asthenospheric ^3He supply may accumulate radiogenic ^4He , progressively lowering $^3\text{He}/^4\text{He}$ with time (Day et al., 2015; Izerumugaba et al., 2026). Using a modelling approach, Izerumugaba et al. (2026) estimate that a 300 Ma European SCLM, assuming a representative ^3He flux of $1 \text{ atom cm}^{-2} \text{ s}^{-1}$, within the range predicted for a closed SCLM (Day et al., 2015), could have an end-member as low as $\sim 2.4 R_a$, with even lower values expected for older SCLM. To reproduce the average R_c/R_a values of 0.15-0.20 in the Betics, different ages and ^3He flux combinations are possible: (1) a Variscan-age SCLM (300 Ma) with low ^3He fluxes of $0.38\text{-}0.52 \text{ atoms cm}^{-2} \text{ s}^{-1}$, or (2) an older SCLM (2 Ga) with higher ^3He flux close to $1 \text{ atom cm}^{-2} \text{ s}^{-1}$.

5.3 Tectonic controls on crust-mantle fluid transfer at an evolving plate boundary

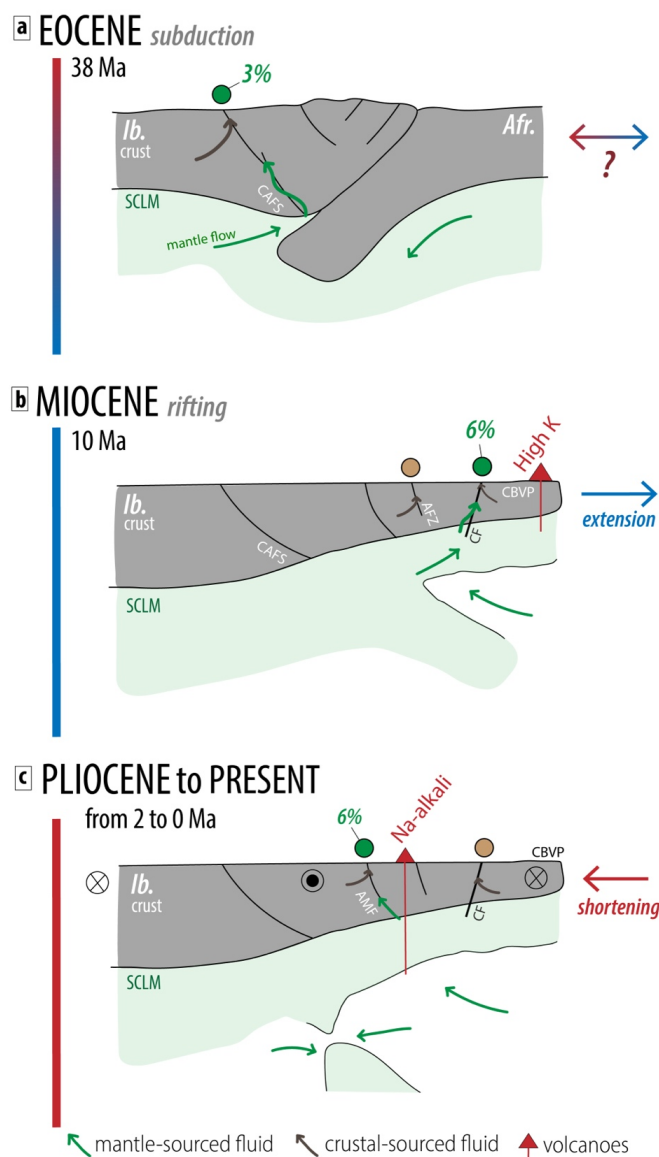
Our results show exclusively radiogenic He signatures ($\geq 99\%$; brown circles in Figure 8b) in the western and central Betics, whereas eastern sites record mantle He contributions ($>1\%$; green circles in Figure 8b). This contrasts with previous analyses of paleofluids, which indicated that $\sim 3\%$ of He in the west along the CAFS was mantle-sourced during the Eocene and $\sim 6\%$ along the CF in the central part during Miocene extension, when the region recorded significant crustal thinning (Cateland et al., 2026; Figures 9a and 9b). The AFZ records predominantly crustal fluids in both ~ 10 Ma paleofluids and modern springs, suggesting that the fault mainly drain waters from crustal reservoirs. Mantle-fluid transfer is therefore inactive or is strongly attenuated in the western and central Betics. The eastern Betics preserve a different record. Despite the onset of shortening ~ 4.5 Ma ago, mantle-sourced He was detected in ~ 2 Ma paleofluids along the AMF and remains detectable in modern springs. Crust-mantle connectivity has therefore only persisted in the eastern Betics over time and under compressional regime (Figure 8).

During Miocene extension, mantle fluids were localized where the crust was most strongly thinned (Figure 9b), which is no longer the case in modern fluids, where mantle sourced fluid occurs further north (Figure 8). This spatial shift is broadly parallel to the northward migration of magmatism from Miocene calc-alkaline to Pliocene Na-alkaline volcanism (Figures 9b and 9c; Hoernle et al., 1999). Both



602 may reflect the lithospheric reorganization associated with slab retreat and the subsequent tectonic
 603 switch (Mouthereau et al., 2025).
 604 Regionally, R_c/R_a in the Betics reaches only 0.35 at Archena and Mula, where the crust is ~25 km thick.
 605 This contrast with European Neogene rifts, where contribution of mantle He are associated with
 606 moderately thinned crusts (~25 km). R/R_a values reach ~6 in the Pannonian Basin, ~3.6 in the Rhône
 607 Rift, and 1.7 in the Rhine Graben (Marty et al., 1992; Wallentin et al., 2026).
 608 In the Betics, no mantle-sourced He is detected across much of the margin, where crustal thickness
 609 exceeds 30 km (Figure 1b). However, the Carboneras Fault which overlies one of the thinnest crustal
 610 domains of the Betics with high heat flow ($>75 \text{ W.m}^{-2}$) yet shows no mantle contribution today.
 611 Therefore, crustal thinning appears to control the regional occurrence of mantle fluid but does not
 612 necessarily determine their precise point of emission. Portela et al. (2025) model the Carboneras Fault
 613 as a highly locked structure with both active sinistral and reverse motion. This compressional
 614 component may reduce vertical permeability and limit present-day mantle-fluid transfer. For
 615 comparison, deformation in the eastern Betics is concentrated along the most active segment of the
 616 EBSZ, where transtensional kinematics are locally observed (Figure 8). Since ~4-5 Ma, Africa-Iberia
 617 convergence has partitioned deformation among crustal blocks bounded by major strike-slip faults.
 618 GNSS models show that block divergence occurs at junctions between westward-moving blocks driven
 619 by Alboran extrusion and north- to northeast-moving blocks (Portela et al., 2025; Figure 8). These
 620 junctions coincide with present-day seismicity and with sites recording mantle-sourced He since ~2 Ma
 621 (Figure 8 b, c), including the 1999 Mula, 2005 Bullas, and 2011 Lorca earthquake areas. This is consistent
 622 with the deformation-enhanced permeability proposed by Kennedy and van Soest (2007), whereby
 623 localized shear maintains pathways for mantle fluids through the ductile lower crust. Although the onset
 624 of shortening and the associated decline in magmatic activity may have reduced mantle-fluid transfer
 625 at the regional scale (Mouthereau et al., 2025), active deformation and strain partitioning maintain
 626 localized shear along plate-boundary faults, preserving the main conduits for mantle fluids.

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636 **Figure 9:** Evolution of crust- and mantle-fluid pathways throughout the tectonic evolution of the Betic
 637 Cordillera along a NW-SE transect. Brown circles indicate surface measurements dominated by crustal
 638 He (>99%), whereas green circles indicate sites with a mantle He >1%. (a) Eocene subduction; (b)
 639 Miocene extension and slab tearing; (c) Pliocene to present shortening with slab detachment.
 640 Schematic NW-SE lithospheric cross-sections illustrate the evolution of mantle- (green arrows) and
 641 crustal- (dark brown arrows) sourced fluid pathways in relation with the regional dominant tectonic
 642 regime (red: compression; blue: extension). Paleofluid ages (U-Pb) and origin are from Cateland et al.
 643 (2026). Percentage labels indicate contribution of the mantle-sourced helium. CGVP stands for Cabo
 644 de Gata Volcanic Province; SCLM for Sub-Continental Lithospheric Mantle.



645 **CONCLUSION**

646 The study of springs in the eastern Betics allows us to investigate the controls on mantle-sourced fluid
647 migration throughout the crust in active faults. Despite thin crust, lithospheric-scale faults, Neogene
648 volcanism, slab tearing and ongoing deformation, mantle He is detected at only a few springs in the
649 eastern Betics (2 to 6%, Lorca-Carraclaca, Mula and Archena), while all other sites record exclusively
650 crustal-sourced He in the central and western Betics. Our results show that crustal thinning appears to
651 control the regional occurrence of mantle fluid but does not necessarily determine their precise point
652 of emission. Sustained crust-mantle connectivity instead requires a clear connection to the Moho and
653 active deformation. Along the EBSZ, localized shear and strain partitioning along the most active fault
654 segments maintain these pathways (cf, Alhama de Murcia Fault), whereas faults with a significant
655 compressional component can inhibit vertical mantle-fluid transfer (cf, Carboneras).
656 Sub-modern fluids (travertines) record a clear thermogenic origin along the most seismogenic segments
657 of the region. Combined with paleofluid noble gas data from fault-rock inclusions, these results show
658 that mantle- sourced fluids have circulated in the Betics from the Eocene, through Miocene extension,
659 to present-day compression. However, mantle He contributions have remained remarkably low, with
660 R_c/R_a never exceeding 0.35. At other plate boundaries worldwide, relative mantle contributions are at
661 least five times higher than those measured in the Betics. We therefore interpret the weak mantle signal
662 as reflecting limited and highly localized mantle-crust connectivity along the developing eastern Betic
663 plate boundary, amplified by crustal He accumulation, diffusion, and by a radiogenic SCLM with low ^3He
664 fluxes.

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Competing interests:

At least one of the (co-)authors is a member of the editorial board of Solid Earth.

Data Availability Statement:

Additional figures, detailed methods and further descriptions are available in the Supplementary Data file. Further data can be available upon request.

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