AGU PUBLICATIONS

Tectonics

Supporting Information for

Exhumation of the Western Cordillera, Ecuador driven by late Miocene subduction of the Carnegie Ridge

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Text S1.

Methods

Sampling and mineral separation

Samples were collected in the Western Cordillera in Ecuador (Fig. 2A, Table 1, 2, 3 and 4). Apatite grains were separated by ZirChron (Tucson, USA) using heavy-liquid separation technique (methylene iodide with densities of 2.9 and 3.3).

Zircon U-Pb

Zircon U-Pb geochronology was conducted on a Photon Machines G2 excimer laser coupled to the Element2 mass spectrometer at the Arizona LaserChron Center following in-house procedures. The zircon U-Pb geochronology results are presented in Table 1 and Figure S1. Please refer to Tables 1, S1 and S2 for details of the analytical setting .

Apatite (U-Th-Sm)/He

Apatite (U-Th-Sm)/He analysis were done at the Arizona Noble Gas Laboratory (University of Arizona). Apatite grains were selected according to their morphology, size and purity (absence of visible inclusions; from 1 to 5 grains dated per sample, depending on sample apatite quality). The selected crystals were measured and placed in niobium tubes for He extraction. A diode laser was used to heat the niobium tubes at 1065±50°C during 3 min to allow a total degassing of radiogenic ^{4}He. The ^{4}He content was determined by comparison with a known amount of ^{3}He spike added during analysis. After He extraction, niobium tubes were placed into single-use polypropylene vials and apatite grains were dissolved for 1 h at 90°C in a 50 µl HNO3 solution containing a known concentration of ^{235}U, ^{230}Th and ^{149}Sm that then was filled with 1 ml of ultrapure MQ water. U, Th-Sm measurements followed a procedure similar to that of Evans et al. (2005). U, Th and Sm concentrations were measured in the solution using an inductively coupled quadrupole plasma mass spectrometry (Element 2 ICP-MS). The analysis was calibrated using external age standards, including Limberg Tuff and Durango apatite. Single ages were corrected using the calculated ejection factor FT, determined using the Monte Carlo simulation technique of Farley and Stockli (2002). The apatite (U-Th-Sm)/He results are presented in Table 2.

Zircon (U-Th-Sm)/He

Zircon (U-Th)/He analysis were performed at the Arizona Noble Gas Laboratory (University of Arizona) following the method described by Reiners et al. (2004). Zircon grains were selected (from 2 to 3 grains dated per sample) according to their morphology, size and the absence of big inclusions. The selected crystals were measured and placed in niobium tubes for He extraction. We used a diode laser to heat the platinum tubes at 1300±100°C during 20 min to allow a total He degassing, a reheat under the same conditions allowed checking for the presence of remaining He. The ^{4}He content was determined by comparison with a known amount of 3He spike added during analysis. After He extraction zircons were retrieved from the niobium packet and placed into teflon microvials. The samples were spiked with a solution containing a known concentration of ^{233}U, ^{229}Th and dissolved with HF and HNO_3 in Parr bombs. U and Th were measured in a solution using an inductively coupled quadrupole plasma mass spectrometry (Element 2 ICP-MS) at the University of Arizona. The analysis was calibrated using external age standards, including Fish Canyon Tuff zircons. Single ages were corrected using the calculated ejection factor FT, determined using the Monte Carlo simulation technique of Ketcham et al. (2011). The results are presented in Table 3.

AFT analysis

AFT analysis was performed by Stuart Thomson at the University of Arizona. Apatite grains were mounted in epoxy and their surfaces were polished. The mounts were etched with 5.5M HNO3 for 20 seconds at 20 ± 1°C to reveal spontaneous tracks. AFT ages were obtained with the external detector method (Hurford and Green, 1982) using a zeta calibration approach, with a zeta of 343.1±8.7 for the IRMM 540R dosimeter glass. After etching, muscovite foils, as external detectors, were attached to apatite mounts. Thermal neutron irradiation of the samples was carried out at the Oregon State University Radiation Center with a requested total thermal neutron fluence of 1.2×10^{16} neutrons.cm^{2}. After irradiation, mica detectors were etched for 18 minutes in 48% HF at 20 ± 1°C to reveal induced tracks. Tracks were counted and track lengths were measured using an Olympus optical microscope at a magnification of ×1250, according to the recommendations of Laslett *et al.* (1994). AFT ages are reported as central age at ±1σ. Dpar (mean fission-track etch pit diameter, parallel to the C axis of the crystal) measurement was used to estimate the kinetic behavior of single grains (Donelick, 1993). The AFT results are presented in Table 4, the detail of length measurements for each sample is provided in the supplemental tables S3-S24".

Text S2.

Results

Zircon U-Pb

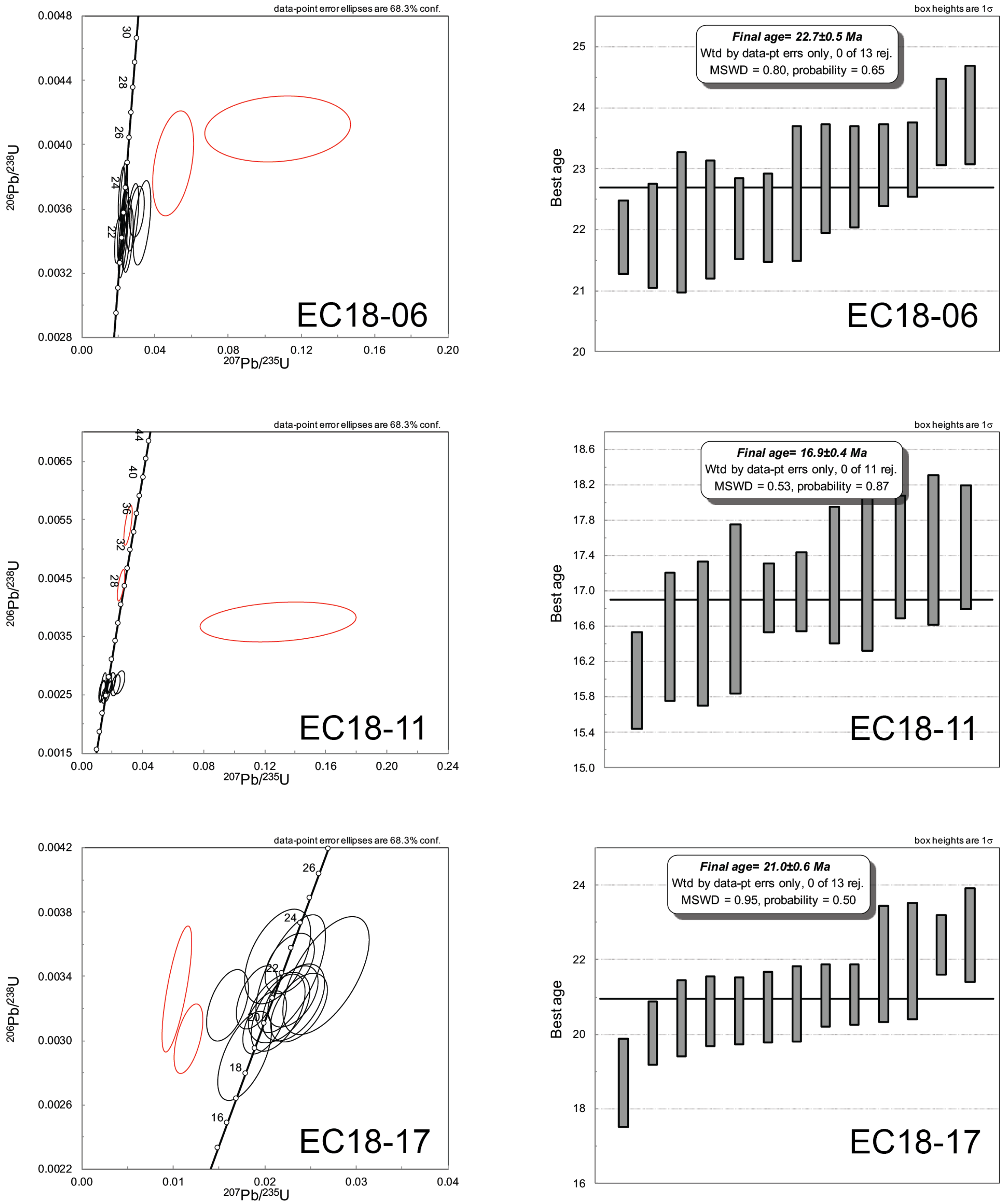

Figure S1. Zircon U-Pb analyses results for samples from the Western Cordillera.

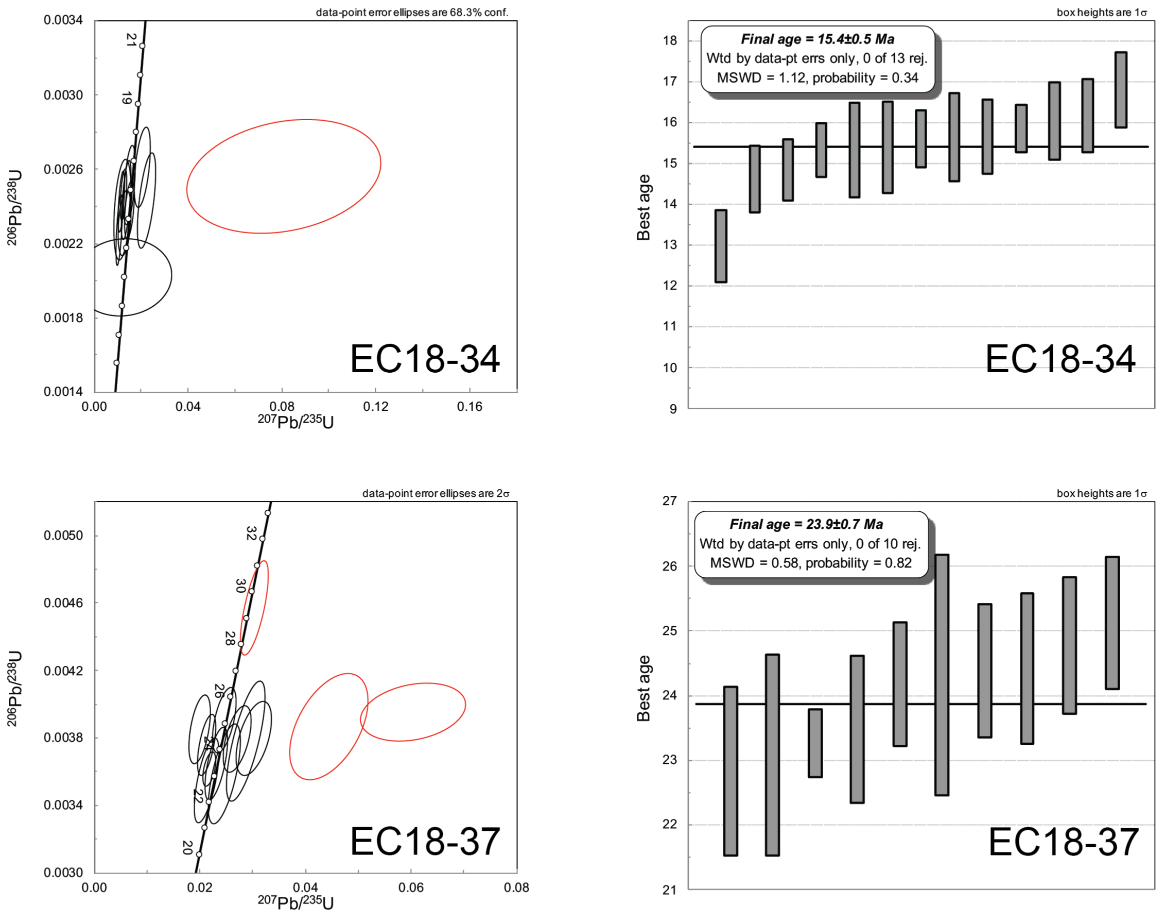

Figure S1 (continued). Zircon U-Pb analyses results for samples from the Western Cordillera.

Apatite (U-Th-Sm)/He

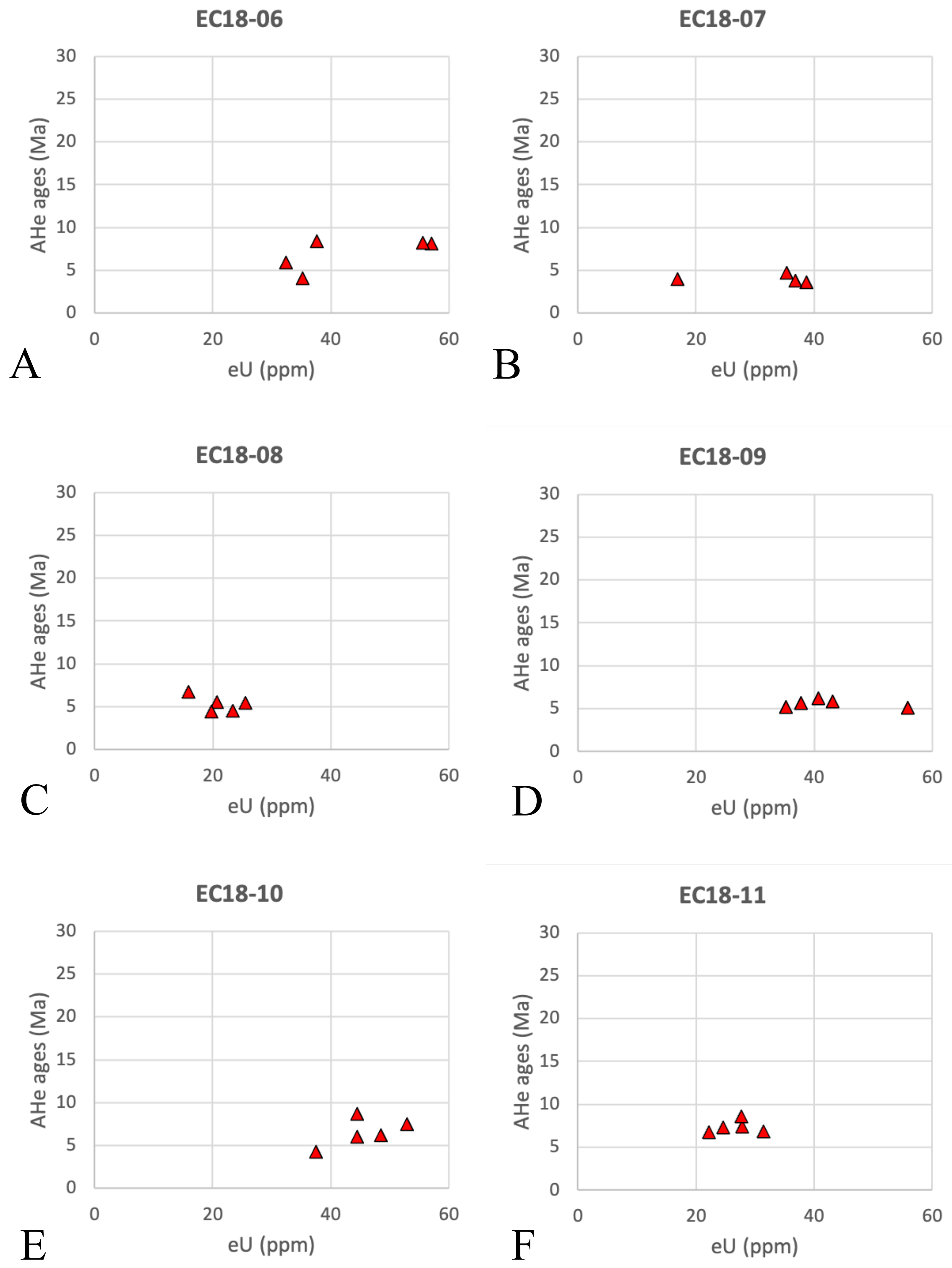

Figure S2. AHe ages – eU plots for samples from the Cuenca area.

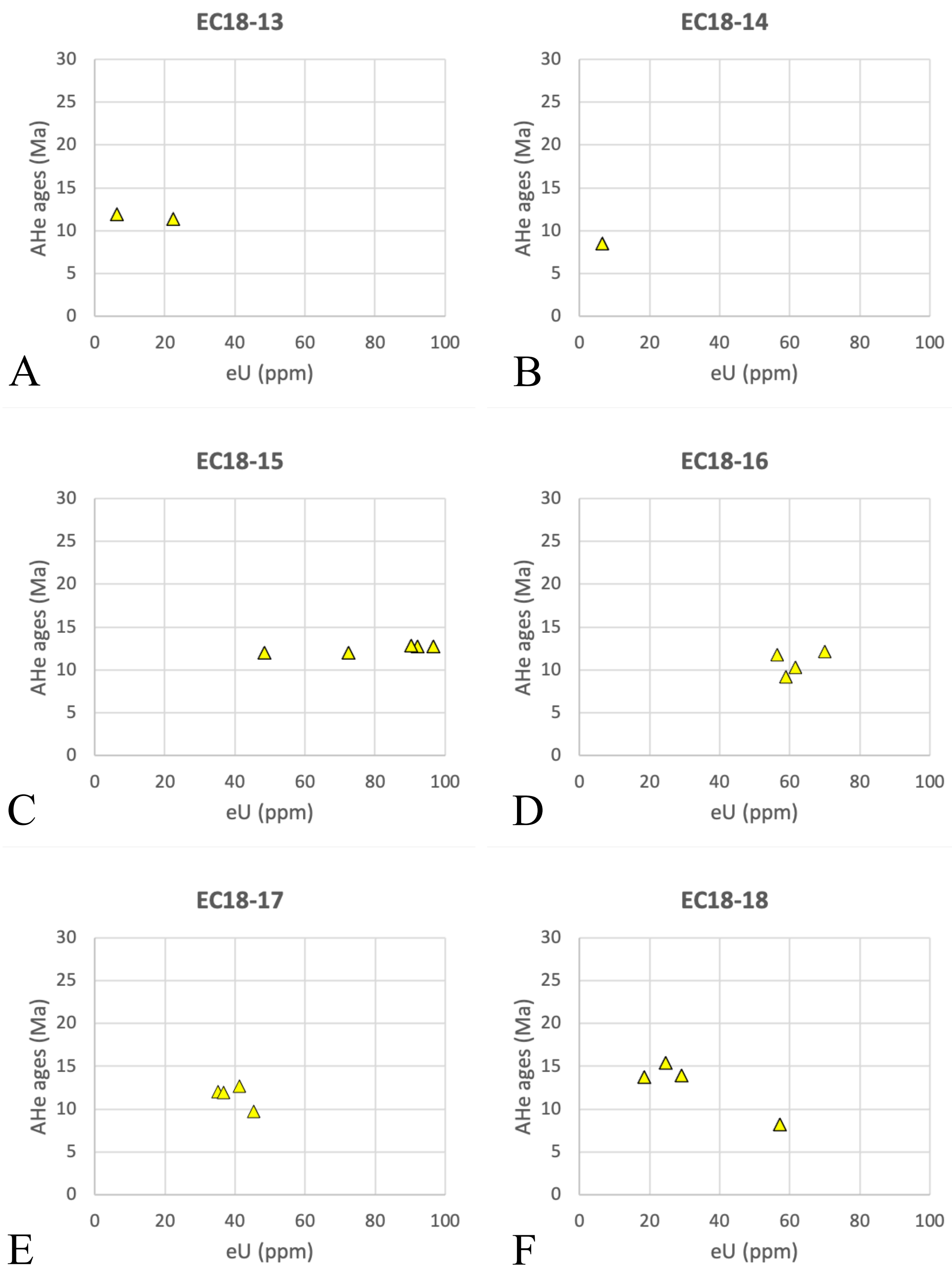

Figure S3. AHe ages – eU plots for samples from the Guaranda area.

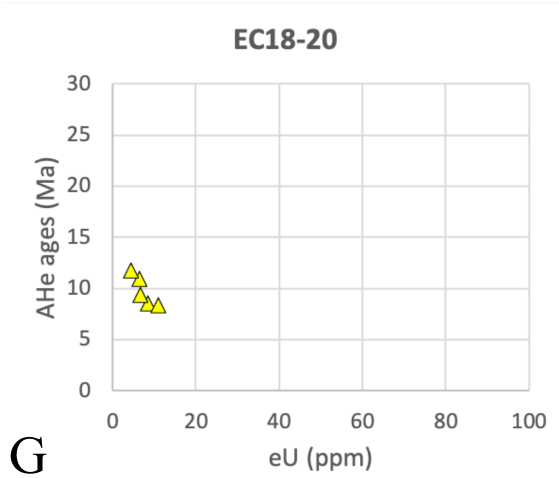

Figure S3 (continued). AHe ages – eU plots for samples from the Guaranda area.

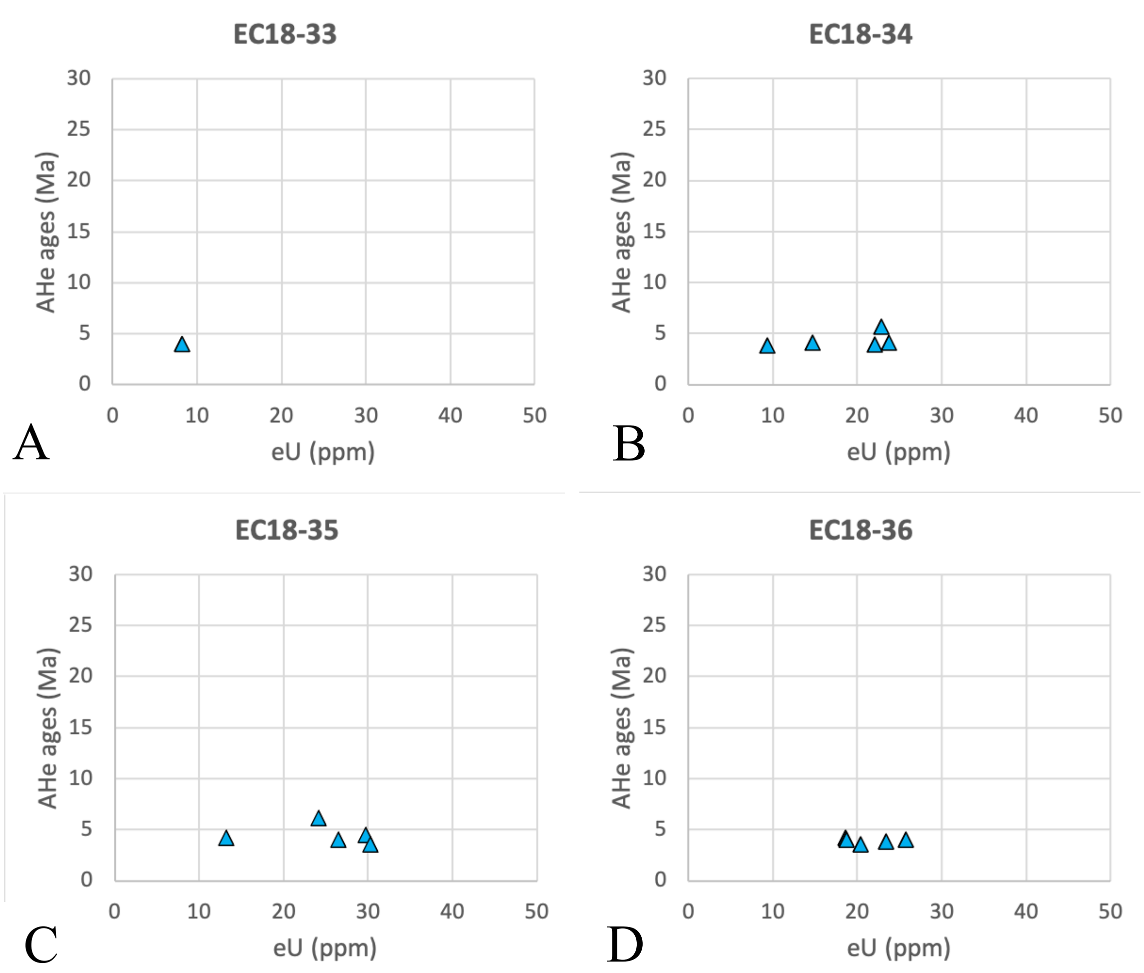

Figure S4. AHe ages – eU plots for samples from the Apuela area.

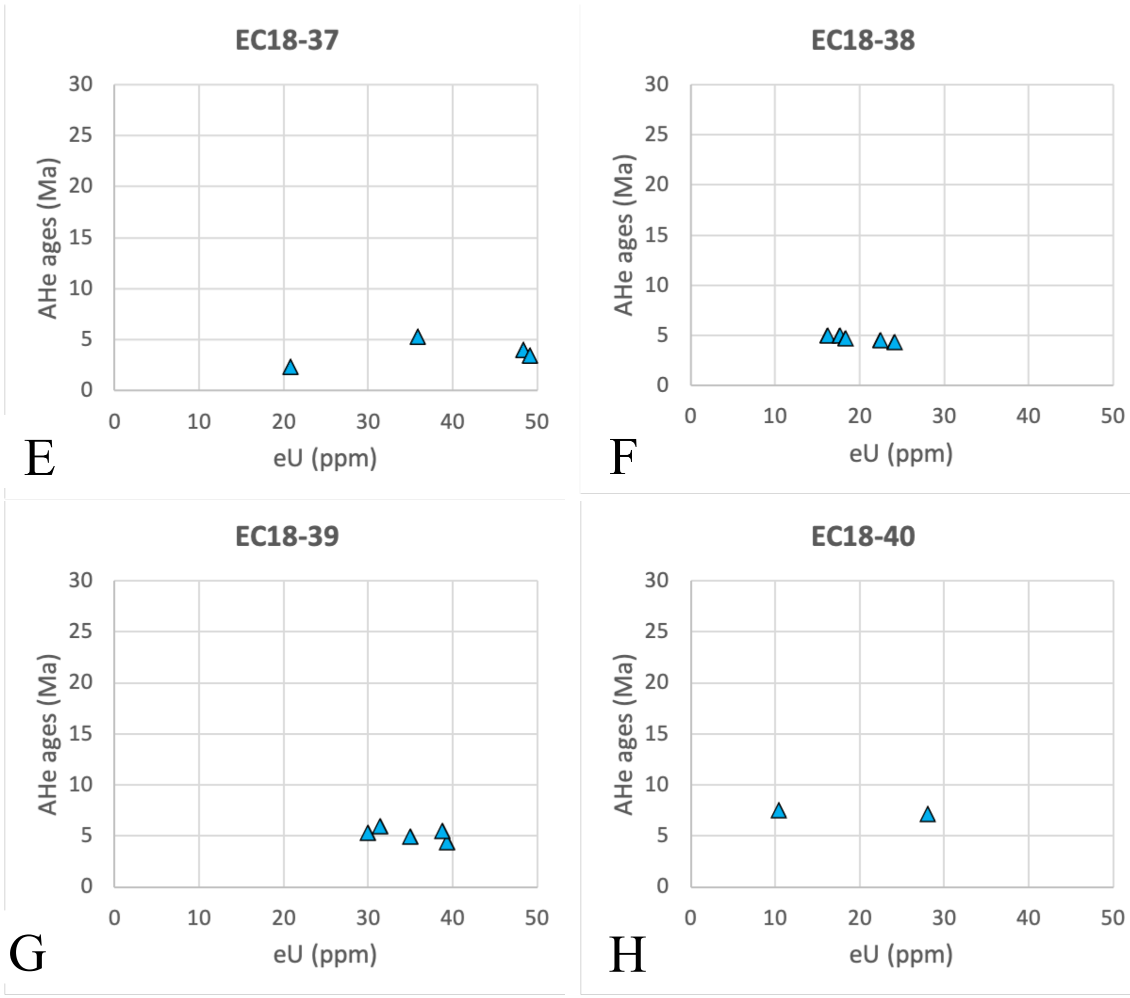

Figure S4 (continued). AHe ages – eU plots for samples from the Apuela area.

Zircon (U-Th)/He

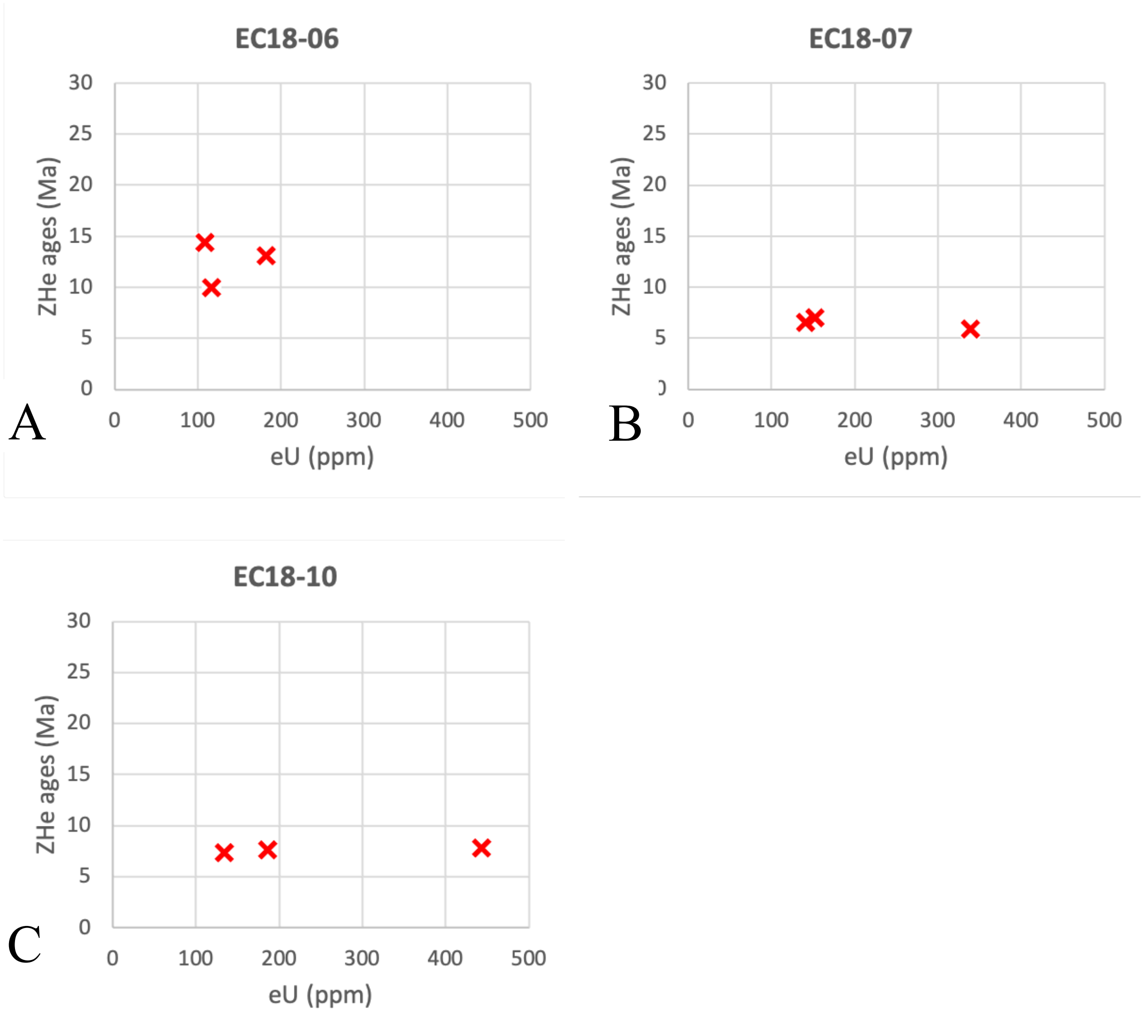

Figure S5. ZHe ages – eU plots for samples from the Cuenca area.

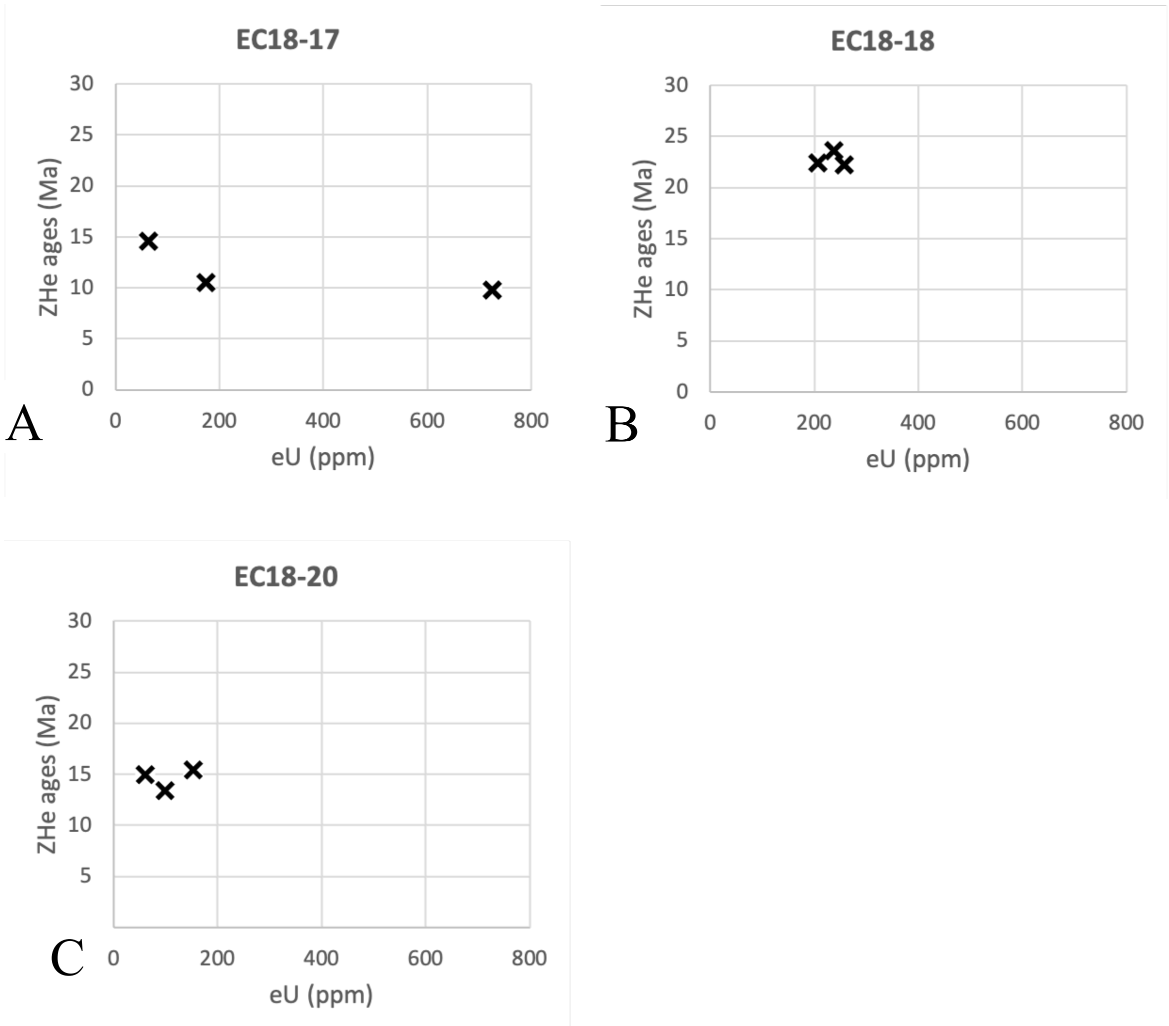

Figure S6. ZHe ages – eU plots for samples from the Guaranda area.

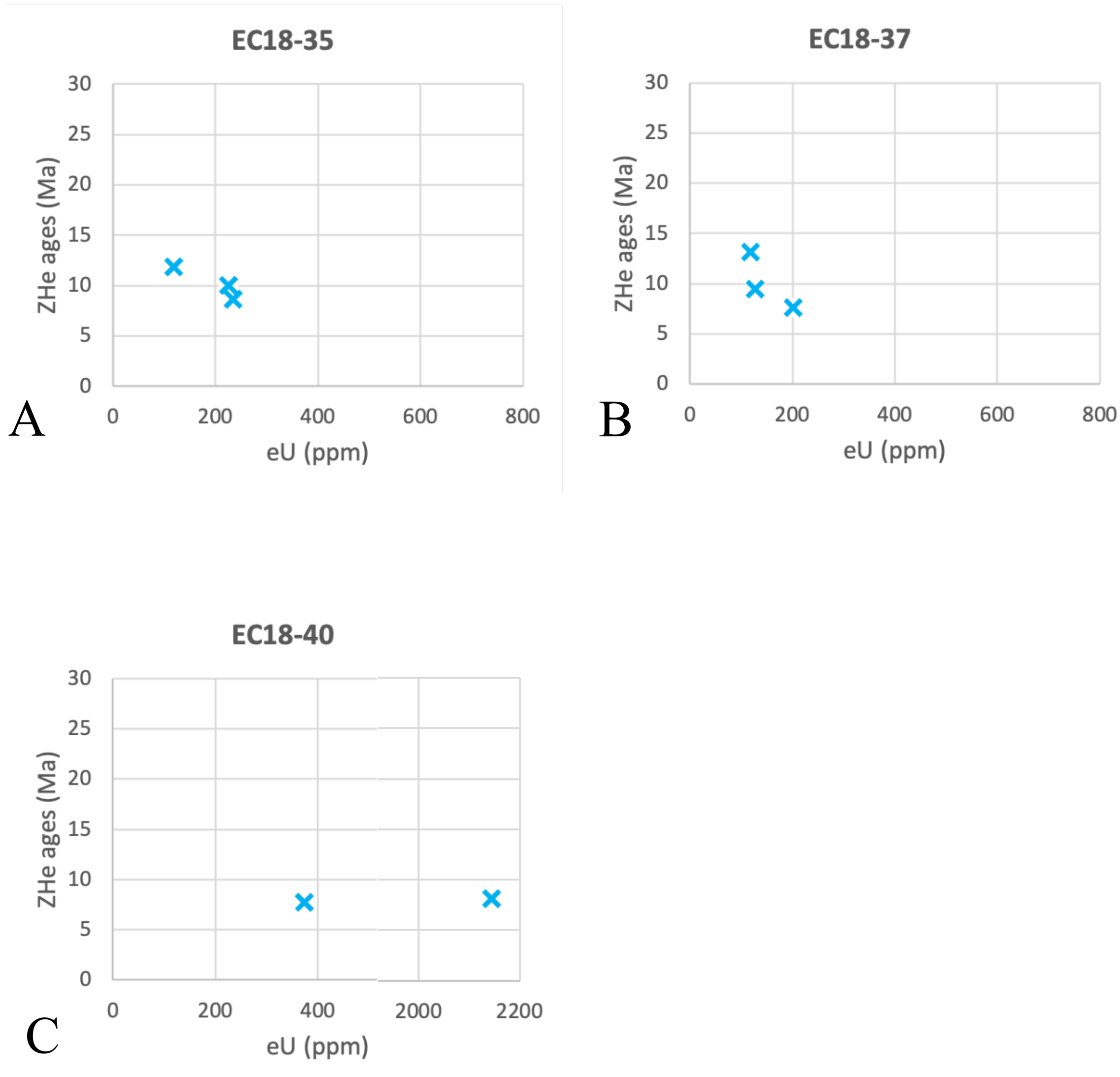

Figure S7: ZHe ages – eU plots for samples from the Apuela area.

Text S3.

Thermal history modeling

Thermal histories were determined using the software QTQt that allows inverting AFT annealing and AHe diffusion parameters using a Bayesian Markov chain Monte Carlo approach (Gallagher *et al.*, 2009; Gallagher, 2012) for complete vertical profiles. The inversion code incorporates kinetic models of He diffusion in apatite (Flowers *et al.*, 2009; Gautheron *et al.*, 2009) and an AFT multi-kinetic annealing model (Ketcham *et al.*, 2007). The modeling procedure is detailed in Gallagher (2012). The input parameters used to model each profile were the AFT grain count data, the track length distribution, the Dpar values, and the single-grain AHe ages with grains sizes and chemical characteristics. The ZHe thermochronometer is sensitive to temperature ranging from 200 to 20°C depending on the radiation damage of the zircons (Guenthner *et al.*, 2013; Ginster *et al.*, 2019; Ault *et al.*, 2019). The ZHe thermochronometer has a wide range of temperature sensitivity depending of the damage of the zircons (e.g., Ault *et al.*, 2019), all the cause for age dispersion are not recognized yet. As our ZHe data did not show a clear correlation between the single grain ages and eU and we were not able to reproduce the measured ZHe ages with the diffusion model included in QTQt (i.e., Guenthner *et al.*, 2013), ZHe data were excluded from the modeling.

For the Ibarra profile the beginning of the thermal history model is fixed at t = 17±6 Ma and T = 800±50°C based on U-Pb crystallization ages (12.9±0.4 Ma, 23.9 ± 0.7 and 15.4 ± 0.5 Ma; Schütte *et al.*, 2010; this study). For the Guaranda profile, based on U-Pb crystallization ages (25.5±2.4 Ma and 21.0±0.6 Ma; respectively from Schütte *et al.*, 2010 and this study), the beginning of the model is fixed at t = 23±3 Ma and T = 800±50°C. For the Cuenca profile the beginning of the model is fixed at t = 16±3 Ma and T = 800±50°C based on U-Pb crystallization ages (14.8±0.4 Ma and 16.9±0.4 Ma; respectively from Schütte et al., 2010 and this study). For all the areas, at 0 Ma, the temperature was fixed at 5±5°C for the upper most sample and the atmospheric temperature gradient was fixed at 7°C/km.

Thermal history simulations are the product of 100,000 iterations, that were sufficient to obtain stable and robust solutions (e.g., discussion in Gallagher, 2012). For all models, the grain chemical composition range (and hence potential radiation damage) was taken into consideration following Gautheron *et al.* (2013). We performed simulations using the AFT annealing model of Ketcham *et al.* (2007) and the He radiation-damage model of Gautheron *et al.* (2009) for all three profiles. The results are reported in Fig. 4.

Table S1. Analytical Settings for U-Pb Geochronology at the Arizona LaserChron Center (Element 2 Single Collector).

Table S2. Zircon U-Pb analyses of standards.

Tables S3-S24. Apatite fission-track lengths measurements from all the samples (Western Cordillera, Ecuador).