**Supplementary Information to:**

**Middle Eocene Climatic Optimum (MECO) and its imprint in the continental Escanilla Formation, Spain**

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**1 Material and methods**

Analyses were carried out on a suite of sampled paleosols (N = 45), stromatolites (n = 9), and pedogenic nodules (n = 9). Powders of bulk paleosol samples were prepared and analyzed for a suite of geochemical indicators, including total organic carbon (TOC) content, Rock-Eval parameters, organic carbon isotope compositions (13Corg), carbonate carbon and oxygen isotopes (13Ccarb and 18Ocarb), major elements, and clay mineral assemblages. Stromatolite and pedogenic nodule powders were analyzed for 13Ccarb and18Ocarb and clumped isotope compositions (d47 and D47).

**1.1 Sample preparation**

Sampled paleosols (N = 45), stromatolites (n = 9), and pedogenic nodules (n = 9) were prepared for analysis at the University of Lausanne, Switzerland. Paleosols were dried at 45°C for 2–3 days, and then crushed and powdered using an agate mill. Stromatolite samples were cut and micro-drilled to obtain sample powder on which the different analyses were performed.

**1.2 Rock eval analysis**

Rock eval pyrolysis was performed at the University of Lausanne to assess the total organic carbon (TOC) content in the paleosols. The analyses were performed using a Rock-Eval 6 instrument, following the procedure described by Behar et al. (2001).

**1.3 Organic carbon isotopes**

The carbon isotope compositions of organic matter in paleosol samples were analysed in the stable isotope laboratories of the Institute of Earth Surface Dynamics, University of Lausanne (IDYST-UNIL). Samples first underwent de-carbonatation with 10 % v/v HCl, then thoroughly washed with deionized water and dried at 40 °C for 48 h. The 13Corg measurements were made using a Carlo Erba 1100 (Fisons Instruments, Milan, Italy) elemental analyser connected to a Thermo Fisher Scientific Delta V Plus isotope ratio mass spectrometer, both operated under continuous helium flow. Measured 13C values were calibrated and normalized using international reference materials and in-house standards [Spangenberg 2006, 2016] and reported in per mil (‰) vs. Vienna Pee Dee Belemnite limestone standard (VPDB). The precision of the 13Corg values were better than 0.1 ‰.

**1.4 Carbonate isotopes**

Carbon and oxygen isotope compositions (13Ccarb, 18Ocarb) were determined at the IDYST-UNIL laboratories. Bulk paleosol samples containing >10 wt.% CaCO3, including carbonate samples, were analysed using a Thermo Fisher Scientific Gas Bench II carbonate preparation device connected to a Delta V Plus isotope ratio mass spectrometer according to a method adapted after Spötl and Vennemann (2003). CO2 gas was produced by reaction with 99 % orthophosphoric acid at 70 °C. The 13Ccarb and 18Ocarb values are reported in ‰ vs. VPDB. Replicate measurements of the international calcite standard NBS 19 (limestone, *δ*13C = +1.95 ‰, *δ*18O = –2.19 ‰) and an in-house standard (Carrara marble, *δ*13C = +2.05 ‰, *δ*18O = –1.7 ‰) yielded an analytical precision of ± 0.05 ‰ for 13Ccarb and ± 0.1 ‰ for 18Ocarb.

**1.5 Major elements**

SiO2, Al2O3, Fe2O3, MnO, MgO, CaO, Na2O, K2O, P2O5, Cr2O3, NiO, and loss on ignition (LOI), were measured in the powdered bulk paleosol samples by X-ray fluorescence (XRF; Phillips PANalytical PW2400 spectrometer) at the Institute of Earth Sciences of the University of Lausanne (ISTE-UNIL). The analyses were performed on fused glass discs prepared with 1.2000 ± 0.0005 g ignited sample powder and 6.0000 ± 0.0005 g of lithium tetraborate (Li2B4O7). The concentrations of the major elements were expressed as wt.% oxides. The analytical precision (1 *σ*) assessed by replicate analyzed of international reference materials is 0.4 %.

**1.6 Weathering indices**

The chemical index of alteration (CIA in %; Eq. 1), proposed by Nesbitt and Young (1982), was used to quantify the degree of weathering by using the molar ratio of immobile Al2O3 and the mobile oxides CaO, Na2O, and K2O in the silicate fraction [e.g., Deng et al., 2022]. The CIA is commonly used to estimate the intensity of alteration and test for environmental factors (e.g., temperature, precipitation, elevation, slope) affecting silicate weathering.

, where CaO\* is the CaO incorporated in the silicate fraction and is calculated as:

Intense weathering removes mobile oxides, concentrating Al2O3 to a maximum value of almost 100 wt.%; whereas weak weathering would give lower CIA values (<50%) because of dominance of mobile oxides.

For comparison, we used the chemical index of weathering (CIW in %; Eq. 3) proposed by Harnois, (1988), which is a modified version of the CIA to account for potassium metasomatism in paleosols during weathering [Stein et al., 2021].

, where CaO\* is the CaO incorporated in the silicate fraction (Eq. 2).

**1.7 Mean annual precipitation**

Mean annual precipitation (MAP) was estimated from the CIW (Eq. 4; standard error = ± 182 mm yr-1) using the equation proposed by Sheldon et al. (2002) as:

**1.8 Clumped (Δ47) isotopes**

Clumped isotope compositions were measured at the IDYST-UNIL laboratories, using a Nu Perspective dual-inlet mass spectrometer with an automated NuCarb sample preparation device. Carbonate digestion, CO2 purification procedure and measurements followed Anderson et al. (2021). For 47 analyses, 3.8 to 4.2 mg of carbonate were reacted at 70 °C with 110 µl 105 wt.% phosphoric acid (H3PO4), and the liberated CO2 was purified after digestion in a series of temperature-controlled, liquid-nitrogen-cooled cold fingers, including an adsorption trap (packed with Porapak Q 50/80 mesh) held at -30 °C. We applied the acid fractionation factor of +0.088 ‰ (Anderson et al. 2021) to the data in order to compare with the ETH-standards reacted at 90 °C (Bernasconi et al., 2021).

Three standards (ETH-1, ETH-2, ETH-3) have been used to calculate 47 values of unknown samples using linear regression with the respective 47 values of 0.205, 0.209, and 0.613 (Bernasconi et al., 2021). Temperatures are calculated using the calibration of Anderson et al. (2021), where 47 isin ‰ and T in °C, as:

**1.9 Clay mineralogy**

Clay mineralogical assemblages in paleosol samples were determined by X-ray diffractometry (XRD) at the ISTE-UNIL laboratories. Samples were prepared following the procedure described in Adatte et al. (1996). Analyses were made using a Thermo Fisher Scientific ARL X-TRA diffractometer and the intensities of the XRD peaks characteristic for each mineral, were used to estimate the relative percentage of clay minerals in the < 2 µm and 2–16 µm size fractions.

**2 Results and discussion**

**2.1 TOC data**

Total organic carbon (TOC) content in paleosol samples range from 0.1%–0.57% with an average value of 0.07% (Fig. 3A). Low amount of TOC in Escanilla paleosols could be the result of low vegetation due to the presence of an arid climate [Tyson, 1995].

**Supplementary figures**

Diagram, engineering drawing

Description automatically generated

**Figure S1.** Identified clay mineral assemblages (smectite, palygorskite, illite, chlorite, smectite/palygorskite ratio), presented with a 7-point moving average (black line) across the studied Escanilla Formation at Olson. These minerals constitute up to 98% of the total clay mineralogy of the sampled paleosols and indicate an arid (semi-arid) climate with seasonal rainfall and weak chemical weathering conditions

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