Climate, dust, and fire across the Eocene-Oligocene transition, Patagonia

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ABSTRACT

The Eocene-Oligocene transition (EOT) is typically interpreted as a time of drastic global cooling and drying associated with massive growth of a glacial icecap in Antarctica and the shift to an "icehouse" climate. The effects of this transition on the terrestrial environments, floras, and faunas of the Southern Hemisphere, however, have been unclear. Here we document simultaneous changes in fire regime and plant community in Patagonia, Argentina. Decreases in the concentration of magnetite in loessites from the Eocene-Oligocene Vera Member of the Sarmiento Formation correlate with decreases in the fraction of burnt palm phytoliths as well as more consistently palm-dominated phytolith assemblages. Association of magnetite and burnt palm phytoliths suggests intense wildfires, which appear to have been suppressed for ~200 k.y. shortly after the EOT. The disappearance of fire-related characteristics near the EOT is possible if changes in regional wind patterns—consistent with observed changes in sediment particle sizes—caused changes in seasonal precipitation. These results imply a more important role for fire in structuring Eocene-Oligocene landscapes than previously thought.

INTRODUCTION

The Eocene-Oligocene transition (EOT) is recognized as a time of dramatic global cooling (Zachos et. al., 2001), ascribed to a drop in atmospheric CO_2 (e.g., DeConto and Pollard, 2003) and a change in ocean heat transport linked to initiation of the Antarctic Circumpolar Current (Kennett, 1977). Marine $\delta^{18}O$ records delineate a small cooling step at ca. 33.9 Ma and a considerably larger step at ca. 33.7 Ma (Oligocene isotope stage 1 [Oi-1]; Miller et. al., 1987; Coxall et. al., 2005). In northern-latitude continents, cooling, drought, and increased seasonality in temperature (e.g., Zanazzi et. al., 2007) and/or precipitation (e.g., Terry, 2001) are hypothesized across the EOT. Paleoclimate records from southern high latitudes are critical for understanding the effects of the EOT on floral and faunal evolution in the Southern Hemisphere, but terrestrial records are rare.

The Vera Member of the Sarmiento Formation (ca. 42.0–18.5 Ma) at Gran Barranca, central Patagonia, Argentina (Fig. 1), is the only known terrestrial sedimentary rock deposit in the Southern Hemisphere that is continuous across the EOT and Oi-1 (Dunn et. al., 2013). This member includes the La Cancha Tuff, dated at 33.581 ± 0.015 Ma (Dunn et. al., 2013) and is interpreted as largely homogeneous tephric loess (following Bellosi [2010]).

Here we highlight the role that both fire and wind played in shaping the Eocene-Oligocene landscape in Patagonia. Fire structures vegetation in many modern environments and has done so throughout the Cenozoic (e.g., Keeley and Rundel, 2005; Bowman et. al., 2009). Fire regime is commonly viewed as tightly linked to climate, especially rainfall seasonality (e.g., Kitzberger et. al., 1997; Bowman et. al., 2009), though recent work points to more complexity (e.g., Archibald et. al., 2013). No studies have explored how fire regime impacted ecosystem change across the EOT.

Previous work in the Sarmiento Formation has interpreted EOT environmental change in two contrasting ways. Bellosi and Gonzalez (2010) used paleosol physical character to infer a change from humid-subhumid conditions during the middle to late Eocene (Lower Puesto Almendra Member) to an open landscape with abundant eolian deposition (Vera Member). Other studies have inferred climate stasis based on fossil mammal tooth $\delta^{18}O$ (Kohn et. al., 2004) and plant assemblages (Strömberg et. al., 2013; Dunn et. al., 2015). The present study differs by focusing on landscape change within the Vera Member using different climate proxies at much higher stratigraphic resolution.

SAMPLING AND STRATIGRAPHY

Samples were taken along a transect through the Vera Member with a stratigraphic spacing of 2–4 m between sites (one sample per site; see the methods section of the GSA Data Repository[1]). The transect used here is profile M (Bellosi, 2010; Ré et. al., 2010; Dunn et. al., 2013; Strömberg et. al., 2013), one of the thickest and most complete exposures of the Vera Member. Our profile contains the La Cancha interval (~48–51 m), a resistant bed underlying the La Cancha tuff (Fig. 2A; additional details are provided in the Data Repository).

Soil development, indicated mainly by fine root traces, Mn staining, and evidence of bioturbation, is very weak to weak throughout most of the Vera Member (Bellosi and González, 2010; Fig. 1; Fig. DR1 in the Data Repository). Soils are slightly better developed in the upper ~50 m of the profile than below (Fig. 2A; Bellosi and González, 2010), likely related to a decrease in deposition rate (Dunn et. al., 2013). Only one, relatively thin, fluvial deposit is present in the Vera Member, ~150 m to the east of the profile studied.

METHODS

Particle size distributions (PSDs; acidified to remove carbonate, then deflocculated) were measured using a Coulter LS-200 laser particle size analyzer. The <63 µm and 63–125 µm size fractions of crushed sediment from representative specimens were dispersed in oil and examined in plane- and cross-polarized light.

Phytolith extraction followed standard methods (Strömberg, 2004): biosilica was separated from the <250 µm fraction of crushed samples using heavy liquid (specific gravity 2.38) after removal of carbonates, organic material, and clays. Identification, counting, and analysis followed Strömberg et. al. (2013), with at least 200 diagnostic so-called forest indicator (FI) or grass silica short cell phytoliths identified to ensure statistically robust results (Strömberg, 2009).

Lightly crushed sediment from representative samples was packed into gelatin capsules with

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[1]GSA Data Repository item 2015196, supplemental methods, Figure DR1, Tables DR1–DR6, and taphonomy, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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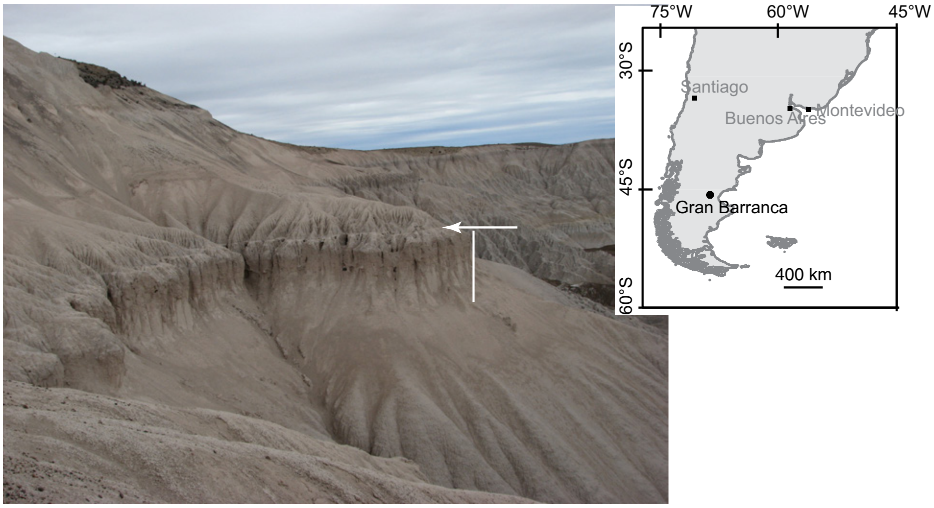

Figure 1. Profile M, Vera Member of Sarmiento Formation, at Gran Barranca (Patagonia, Argentina). Arrow shows La Cancha fossil-bearing bed. White vertical line represents ~4 m. Inset: Location of Gran Barranca (black dot). Additional photographs are provided in the Data Repository (Fig. DR1 [see footnote 1]).

nonmagnetic foam for magnetic measurements. Hysteresis loops and isothermal remanence (IRM) acquisition were measured in fields up to 1 T using a Princeton Measurements MicroMag 3900 vibrating sample magnetometer. IRM was imparted at a logarithmic sequence of applied fields (25 or 75 steps) and analyzed using log-Gaussian fits (e.g., Geiss and Zanner, 2006). Magnetic susceptibility as a function of temperature was measured in argon using a Kappabridge KLY-3.

RESULTS

Biosilica assemblages from the Vera Member are well preserved and compositionally uniform, consisting dominantly of echinate spheres from palms (average 82.9% of diagnostic phytoliths, range of 61.6%–92.8%), with a variable, smaller component of other FI phytoliths (Table DR1 in the Data Repository). Palm phytolith abundances vary until the La Cancha interval (Fig. 2G), within and above which palm forms make up >~80% (and often close to 90%) of diagnostic phytoliths. Many palm phytoliths appear burnt, with dark centers or dark bubbles and rounded surface features (Fig. 3; e.g., Boyd, 2002; Parr, 2006). Burnt morphotype abundances vary through the section (10%–73% of all palm phytoliths) but remain relatively high (on average 52%) except between 52 and 62 m (just above the La Cancha interval), where they make up 10%–30%. Phytolith assemblages appear to result primarily from changes in relatively local vegetation, rather than from long-distance eolian transport of biosilica (see the taphonomy section of the Data Repository, and Table DR6).

Typical IRM spectra from Vera Member sediments contain two components (Table DR4). A low-coercivity component (median coercivity 34 mT) is associated with a Curie temperature of 598 °C, indicating partially oxidized magnetite. A higher-coercivity component (median ~46 mT) is associated with Curie temperatures of ~580 and ~680 °C, indicating the presence of hematite or a phase (e.g., maghemite or goethite) that transforms to hematite on heating.

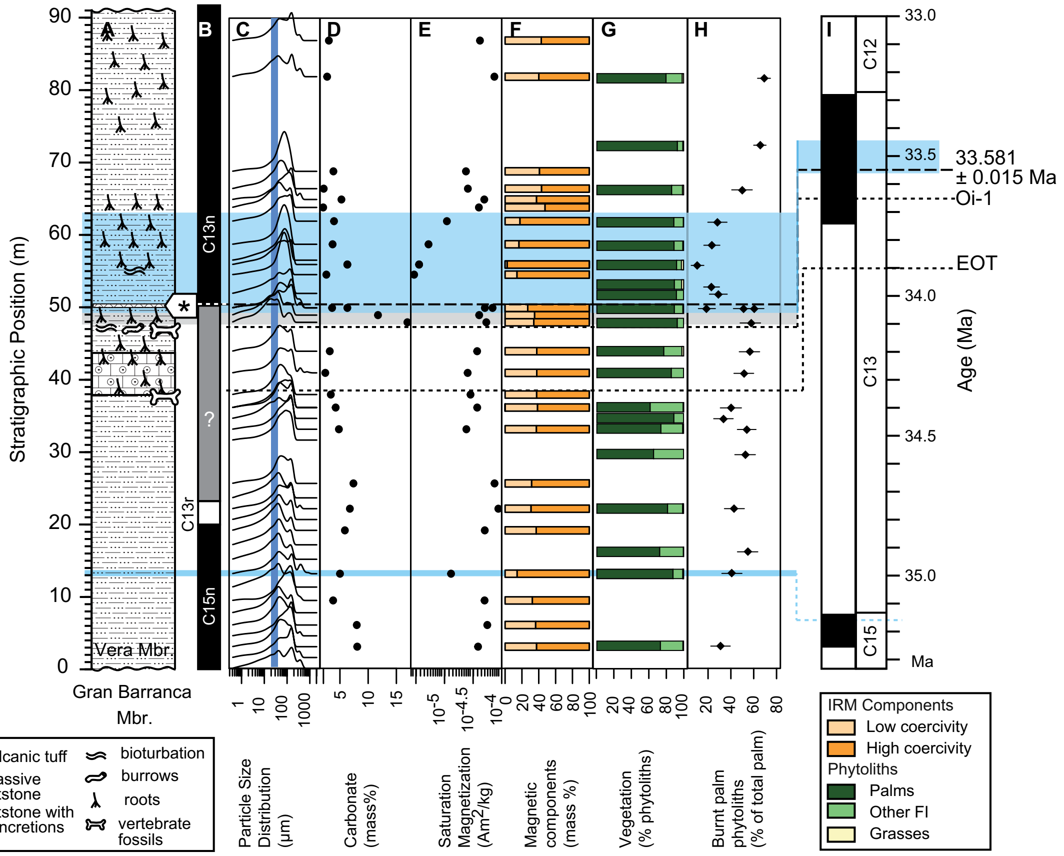

Figure 2. Paleoenvironmental proxies in Vera Member of Sarmiento Formation (Patagonia, Argentina), compared to timing of Eocene-Oligocene transition (EOT) and Oligocene isotope stage 1 (Oi-1) (dotted lines). Gray bar is La Cancha interval. Light-blue bars show upper and lower magnetically depleted intervals. Dashed line is La Cancha tuff (Dunn et. al., 2013). A: Stratigraphic column of profile M used in this work. Mbr.—member. B: Magnetic polarity stratigraphy (Ré et. al., 2010; Dunn et. al., 2013). Asterisk is tuff dated by ^{238}U/^{206}Pb (Dunn et. al., 2013). C: Particle size distributions. Dark-blue bar is approximate size range of silt transported in suspension by modern dust storms (Tsoar and Pye, 1987). D: Mass percent carbonate. E: Saturation magnetization, 1 T. F: Low-coercivity (light orange) and high-coercivity (orange) isothermal remanence (IRM) components. G: Vegetation composition from phytoliths (in part from Strömberg et. al. [2013]). Dark green are palms; light green are other forest indicator (FI) taxa; yellow are grasses. H: Percentage of burnt palm phytoliths. Error bars are 95% confidence intervals. I: Geomagnetic polarity time scale (as used by Pälike et. al. [2012]).

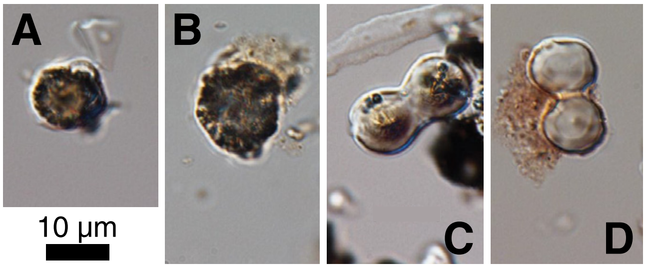

Figure 3. Comparison of experimentally burnt palm phytoliths (A, C) to those recovered from the Vera Member (B, D). A,B: Severe alteration of phytoliths including transformation of shape and opacity. C,D: Fused phytoliths.

Saturation magnetization (M_s), a measure of the total amount of ferromagnetic material, is nearly uniform throughout the section, but is depleted in the low-coercivity component of IRM (~10% of IRM) in two intervals at ~13 m and 51–63 m (Table DR4; Fig. 2F). Hysteresis loops indicate a mixture of single-domain (SD), superparamagnetic (SP), and multidomain (MD) magnetic particles, with the higher-coercivity samples consistently offset away from the SD-MD mixing line (Table DR4).

Multi-modal PSDs are consistent with a polygenetic origin for Vera Member loessites (Fig. 2C). Abundant <20 µm material and fine-skewed PSDs typify dust transported in long-term suspension over thousands of kilometers (Tsoar and Pye, 1987). In contrast, 20–40 µm modes typify material transported hundreds of kilometers in short-term suspension by dust storms (Tsoar and Pye, 1987). A few samples have particle size modes in the size range ~40–125 µm: these may indicate a transition to a local sediment source (resulting in addition of coarse material) and/or a change in wind patterns (resulting in fine particles not reaching or removed from the basin), but might alternatively represent a fluvial component.

The <63 µm particle size fraction comprises mainly glass fragments, potentially sourced directly from the active Andean arc or neighboring intracontinental backarc (Rapela et. al., 1988), or from older volcanic deposits. Particles in the 63–120 µm size range include angular to subrounded glass, feldspar, pyroxene, and amphibole, also consistent with volcanic (or reworked volcanic) material.

DISCUSSION

The association of burnt phytoliths, elevated M_s, and the low-coercivity IRM component suggests that fire may have caused the variations in magnetic properties within the Vera Member. Fire-driven conversion of high-coercivity Fe-oxyhydroxides (e.g., hematite, goethite) to lower-coercivity Fe-oxides (e.g., magnetite, maghemite; Le Borgne, 1960; Clement et. al., 2011) is consistent with the association between the lower Curie temperature and the low-coercivity IRM component, and the occurrence of higher Curie temperatures in the absence of that component. We interpret hysteresis data to reflect mixtures of SD, MD, and SP ferrimagnets in samples with a large low-coercivity IRM component, and a greater antiferromagnetic contribution (higher H_{cr}/H_c) in samples with a larger high-coercivity IRM component. SP particles in the low-coercivity Vera Member loessites are also consistent with magnetic properties of other burnt soils (e.g., Roman et. al., 2013). However, the small amount of sample available made reproducible frequency-dependent susceptibility measurements (for direct comparison with data of Roman et. al. [2013]) impossible. Intense burning is necessary to enrich surface soils (and loess) in SP magnetic material, so we tentatively ascribe the magnetic enhancement to intense wildfires (Roman et. al., 2013).

Alternative explanations for accumulating (partially oxidized) magnetite in Vera Member loessites, e.g., by low-temperature precipitation (e.g., Maher and Taylor, 1988) or as detrital material, appear unlikely. There is no systematic correspondence between the presence of (low-coercivity) magnetite and indicators of soil formation or relative landscape stability as would be expected from authigenic precipitation (e.g., Geiss and Zanner, 2006). Indeed, the dry climate implied by the soil physical characteristics should produce uniformly low concentrations of pedogenic magnetite (e.g., Geiss and Zanner, 2006). A lack of correlation between burnt phytolith abundance and relative abundance of grains in the size range typical of palm phytoliths suggests that the burnt phytoliths are unlikely to have been deposited by wind (see the Data Repository); an eolian origin for the magnetite associated with the phytoliths is thus also unlikely. The lack of a major change in burnt phytolith occurrence or magnetic properties associated with the change in deposition rate in the upper part of the profile also suggests that simple dilution cannot explain the intervals that lack burnt phytoliths.

Fire, Climate, and the EOT

For much of the late Eocene and early Oligocene, phytoliths and magnetic properties suggest that palm-dominated landscapes and intense fires characterized the landscape near modern Gran Barranca. A brief reduction in fire intensity occurred during chron C15n, followed by a more prolonged interval (~200 k.y.) of reduced fire intensity beginning at ca. 33.6 Ma (Fig. 2). Both intervals are characterized by unimodal particle size distributions in the ~64–120 µm range, suggesting a reduced supply of far-traveled fine-grained material. The high (locally derived) phytolith yield and the abundance of 5–15 µm phytoliths from samples in the Vera Member (see the Data Repository) are consistent with a local sediment source. By ca. 33.4 Ma, vegetation, sedimentation, and fire occurrence had returned to states typical of the late Eocene.

Frequent fires like the ones we infer require the growth of abundant plant biomass during a moist growing season, followed (not necessarily directly) by a dry fire season (Kitzberger et. al., 1997; Archibald et. al., 2013). Palms are fire tolerant, and can maintain or even increase in cover with regular burning (e.g., McPherson and Williams, 1998; Menges and Hawkes, 1998). However, gaps created by fire maintain overall plant diversity in Florida (USA) palm scrub (Menges and Hawkes, 1998). We therefore hypothesize that fire disturbance maintained a higher diversity of woody plants (represented by non-palm FI) before Oi-1 (Fig. 2G). During and after Oi-1, when we infer a less pronounced fire regime, the lack of gap dynamics may have promoted relatively homogenous, palm-dominated vegetation. The low grass abundances suggest either that the grass species present did not have the traits that we associate with grasses of fire-prone ecosystems today or that the advantage of grasses over woody plants in such environments (e.g., Bond, 2008) was offset under the relatively higher CO$_2$ levels at the EOT (e.g., Beerling and Royer, 2011). Faster regrowth in palms and other trees at elevated CO$_2$ (Bond et. al., 2003) may have resulted in shorter fire return intervals, promoting more frequent fires, which today are only found in tropical savannas where grass constitutes the dominant fuel (Archibald et. al., 2013).

Seasonality in EOT Patagonia

In present-day Patagonia, interactions between the westerlies and the subtropical high-pressure zone (STH) control patterns of moisture and drought (Kitzberger et. al., 1997; however, see Whitlock et. al. [2007]). In an environment dominated by eolian deposition, migration of the STH and westerlies around the time of the EOT could account for the variable particle size modes in the 40–120 µm range observed in Vera loessites. If shifts in the strength and positions of the STH and westerlies (and, presumably, the polar front) relative to Gran Barranca were responsible for changes to the seasonal wet-dry cycles required for frequent fires, marine sediments in the South Atlantic at the latitude of Gran Barranca should contain an increasing abundance of fine particulate matter of Patagonian provenance. Further deep-sea coring in the South Atlantic is necessary to evaluate such a possibility.

The links among fire, climate, and biotic change proposed here may help to explain other features of the fossil record in Patagonia. In particular, leaf area index (LAI) values >1 in the Vera and underlying El Rosado Members indicate the first instance of open canopy vegetation in the Sarmiento Formation (Dunn et. al., 2015). Frequent fire may have prevented growth of larger woody plants and maintained an open canopy. In turn, this open vegetation type would have allowed for dust brought in by long-distance transport and more local dust storms to settle out on lower-growing vegetation and constitute dietary grit for the herbivore fauna. A heavy dust load would explain natural selection for increased hypsodonty and hypselodonty (ever-growing teeth) in faunas during this time despite the lack of grassland vegetation (Strömberg et. al., 2013; Dunn et. al., 2015).

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