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Enhanced magnetization of the Marlboro Clay as a product of soil pyrogenesis at the Paleocene–Eocene boundary?

Dennis V. Kent[a,b,*], Luca Lanci[c], Huapei Wang[d], James D. Wright[a]

[a] Earth and Planetary Sciences, Rutgers University, Piscataway, NJ 08854, USA
[b] Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA
[c] Department of Pure and Applied Science, University of Urbino "Carlo Bò", Via S. Chiara 27, I-61029 Urbino (PU), Italy
[d] Planetary Science Institute, School of Earth Sciences, China University of Geosciences, 388 Lumo Road, Wuhan, Hubei 430074, PR China

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ABSTRACT

The kaolinite-rich Marlboro Clay was deposited on the inner shelf in the Salisbury Embayment of the U.S. Atlantic margin at the onset of the carbon isotope excursion marking the 56 Ma Paleocene–Eocene boundary and is characterized by an anomalously high concentration of magnetic nanoparticles of enigmatic origin that give rise to notably intense bulk magnetization. Recent studies point to a magnetic assemblage that is dominated by single-domain magnetite particles that tend to be isolated rather than arranged in chains, the most distinguishing feature of magnetotactic bacteria fossils. On the other hand, it is very unlikely that the nanoparticles can be condensates of an impact plume given the meter-scale thickness of the Marlboro Clay. We obtained new data from a landward proximal site at Wilson Lake on the New Jersey Coastal Plain and find that the abrupt increase in magnetite nanoparticles is virtually coincident stratigraphically with the recently reported impact spherule layer at the base of the Marlboro Clay in the same core. Yet the high field magnetic susceptibility, a measure of total iron concentration, and strontium isotope values on bulk sediment, an indicator of sediment weathering provenance, are not different in the Marlboro Clay from the immediately underlying Vincentown Formation. We suggest that the distinctive magnetic properties of the Marlboro Clay originated from pyromagnetic soil enhancement by widespread wildfires on the adjoining drainage area. The pyrogenetic products were soon washed from the denuded landscape and rapidly deposited as mud-waves across the shelf, becoming the Marlboro Clay. A few percent of incinerated biomass ends up as calcite known as wood ash stone and can inherit its light carbon isotope composition. Disseminated wood ash stone entrained in the Marlboro Clay could contribute to the landward increase in amplitude of the carbon isotope excursion in bulk carbonate data. A plausible trigger for the initial conflagration is a fireball from the impact of a sizable extraterrestrial object at moderate range.

1. Introduction

Expanded marine sections across the carbon isotope excursion (CIE) and the associated Paleocene–Eocene thermal maximum (PETM), manifestations of a massive perturbation of the global carbon cycle that were first identified in deep-sea sediments at ODP Site 690 (Kennett and Stott, 1991) and soon observed in continental sediments in Wyoming (Koch et al., 1992) (see review by McInerney and Wing, 2011), are preserved on the continental margin of Eastern North America (Cramer et al., 1999; Gibson et al., 1993) and helped inspire the current phase of the New Jersey Coastal Plain Drilling Project (Miller et al., 1997). High-resolution stable isotope studies of the proximal Wilson Lake site (Miller et al., 2017) and the somewhat deeper water Millville site (Sugarman et al., 2005) showed that the onset of the CIE was recorded over a meter or more of section but may have been extremely rapid, occurring on a time scale of a decade or less (Wright and Schaller, 2013). This interpretation has not been without dispute. However, the discovery in the Wilson Lake and Millville paleo-shelf sites (as well as in the deep-sea Site 1051) of a thin layer with microtektites at the base of the Marlboro Clay, the lithostratigraphic unit on the Atlantic Coastal Plain in which the CIE is effectively recorded, provides strong supportive evidence for a fast trigger for its onset by way of an extraterrestrial impact (Schaller et al., 2016). This new evidence motivates a reappraisal of the origin of the Marlboro Clay and es-

* Corresponding author.
E-mail address: dvk@rutgers.edu (D.V. Kent).

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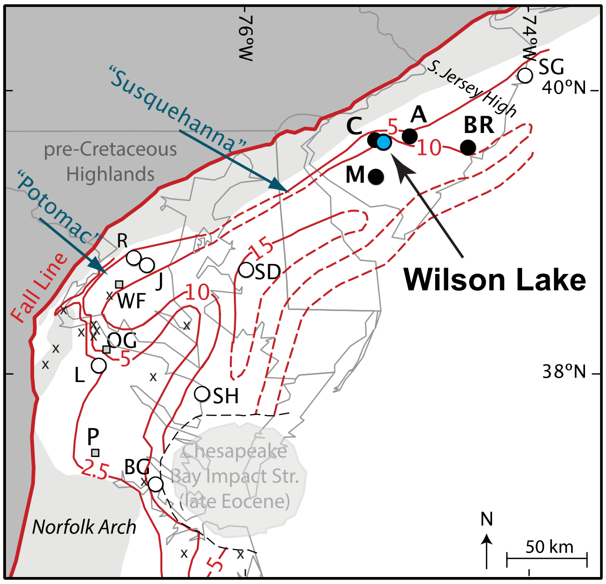

Fig. 1. Locations of key core sites (filled circles) in the vicinity of Wilson Lake (A & B) that penetrated the Marlboro Clay in the northern Salisbury Embayment and discussed in text: A, Ancora; BR, Bass River; C, Clayton; M, Millville. Contoured thickness of Marlboro Clay and locations of other core sites from Kopp et al. (2009). The Clayton and Wilson Lake core sites represent the more proximal shelf facies in relatively shallow paleowater depths (<50 m), the Ancora and Millville sites represent moderate paleowater depths (∼50 to 100 m), whereas the Bass River site is representative of a more distal shelf facies in deeper paleowater depths (∼100 m) (Harris et al., 2010).

pecially its distinctive magnetic properties (Kent et al., 2003a; Kopp et al., 2007), and is the aim of this study.

The Marlboro Clay (formerly the lower Manasquan Formation) is widespread in the subsurface of the Salisbury Embayment of the Atlantic Coastal Plain thickening in places to around 15 meters seaward from its coastal onlap (Fig. 1). The basal contact of the kaolinite-rich unit with the Vincentown (New Jersey) or Aquia Formation (Maryland and Virginia) (Gibson et al., 2000) closely corresponds to the onset of the CIE at the 56 Ma Paleocene–Eocene boundary (Cramer et al., 1999). The Marlboro Clay is also characterized by an anomalously high concentration of single domain (SD) magnetite nanoparticles (generally less than ∼100 nm), exceptional for a shelf deposit (Lanci et al., 2002). The high SD-dominated magnetizations show an increasing landward gradient across the coastal plain of New Jersey (Kent et al., 2003a; Lippert and Zachos, 2007) and extend along-strike into Maryland and Virginia, making the Marlboro Clay a contender for the thickest SD-magnetite dominated sedimentary unit in the world (Kopp et al., 2009) despite its close proximity to sources of clastic sediment.

The magnetite nanoparticles were initially (Lanci et al., 2002) and subsequently by others (e.g., Kopp et al., 2009; Lippert and Zachos, 2007) interpreted to be predominantly bacterial magnetofossils. Magnetosome chains, the most diagnostic property of magnetotactic bacteria (MTB) (Kopp and Kirschvink, 2008), have been observed in transmission electron microscope (TEM) images made on magnetic extracts from the Marlboro Clay (e.g., Kopp et al., 2009; Lippert and Zachos, 2007). However, the extraction efficiency for a widely used procedure was reported to be only a few percent on these clays (Wang et al., 2013) so it is unclear how representative the TEM evidence is. Moreover, results from thermal fluctuation tomography (TFT; Jackson et al., 2006) on bulk samples of Marlboro Clay showed little indication of the grain size and shape distribution expected for magnetosome chains (Wang et al., 2013). Ferromagnetic resonance (FMR) is another technique thought to be sensitive to MTB (Kopp et al., 2007) but samples of Marlboro Clay turn out to have almost identical FMR characteristics as Martian meteorite ALH84001 (Wang et al., 2013). Initial enthusiasm for SD magnetite crystals in ALH84001 as evidence of MTB magnetosomes (Thomas-Keprta et al., 2000) was eventually tempered by the absence of confirming evidence of chains (Weiss et al., 2004). It thus appears that FMR and most other magnetic techniques like hysteresis properties and first-order reversal curves (FORCs) (Egli et al., 2010) can indeed distinguish the presence of SD grains but not whether they are aligned in chains. Imaging of bulk samples of Marlboro Clay using ultrahigh-resolution, synchrotron-based, full-field transmission X-ray microscopy (Wang et al. (2015) was only able to confirm the presence of giant biogenic magnetofossils (Kopp et al., 2009; Schumann et al., 2008) but whose estimated total magnetic contribution is only ∼10% of bulk sediment. In any case, recent work has shown that giant magnetofossils can be found before and after the CIE and may have a rather widespread geographic, environmental, and temporal distribution (Chang et al., 2012).

More speculatively, the magnetic nanoparticles in the Marlboro Clay, by analogy with iron-rich nanoparticles reported in some Cretaceous–Paleogene boundary clays (Wdowiak et al., 2001), were suggested to represent condensates from an otherwise cryptic impact plume (Kent et al., 2003a). An impact dust protolith for the Marlboro Clay could help explain the otherwise puzzling increased concentration of the SD particles toward the landward source of a presumed dust blanket. However, there has long been a serious difficulty with the impact scenario in accounting for the meter-scale thickness of the highly magnetic kaolinitic clays in the Marlboro as condensate and ejecta fallout when such fine-grained (distal) deposits generally amount to a only few centimeters for even major impacts (Collins et al., 2005).

Investigations described here that bear on the enigmatic origin of the SD particles and enhanced magnetization of the Marlboro Clay were motivated by the reported presence of glassy spherules (microtektites) of impact origin in a discrete layer at the base of the Marlboro Clay, close to the onset of the CIE, in several core sites on the eastern margin of North America (Schaller et al., 2016). This finding relieves the burden on the magnetic nanoparticles as direct evidence of an impact but they still require a satisfactory explanation. We focused on the record from the most landward site with impact spherules, at Wilson Lake B (Fig. 1), where a ∼14.5 m-thick section of the Marlboro Clay was recovered (Miller et al., 2017) and the onset of the CIE determined from detailed stable isotope stratigraphy (Wright and Schaller, 2013).

2. Wilson Lake records of CIE

Building on lithologic, biostratigraphic and magnetic studies of the Clayton core (Gibson et al., 2000; Kent et al., 2003a), the nearby Wilson Lake A core provided comprehensive stratigraphic series of dominant lithology, stable (carbon and oxygen) isotope ratios of bulk sediment carbonate and specimens of various benthic and planktonic foraminifera taxa, and magnetic properties across the onset of the CIE (John et al., 2008; Lippert and Zachos, 2007; Zachos et al., 2006). Detailed carbon isotope analyses on bulk carbonate (Wright and Schaller, 2013) followed on the parallel Wilson Lake B core (Fig. 2). The Wilson Lake A and B cores can be precisely correlated; for example, the steep gradient in decreasing δ^{13}C bulk carbonate values at a depth ID of 366′ (∼111.5 m) in Wilson Lake B corresponds to that at 360′ (∼110 m) in Wilson Lake A, demarcating the onset of the CIE. It should be noted that carbon isotope values (δ^{13}C) for foraminifera, especially near-surface dwelling planktonics, tend to be higher than for bulk sediment in the Marlboro Clay, a point we will return to below. At the CIE onset level in each core, the sediment magnetizations – saturation magnetization (M_s) for Wilson Lake A (Lippert and Zachos, 2007) and