Clim. Past Discuss., 10, 3303–3325, 2014
www.clim-past-discuss.net/10/3303/2014/
doi:10.5194/cpd-10-3303-2014

Climate of the Past
Discussions
Open Access

Drilling disturbance and constraints on the onset of the Paleocene/Eocene boundary carbon isotope excursion in New Jersey

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Received: 14 July 2014 – Accepted: 30 July 2014 – Published: 13 August 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

The onset of the Paleocene/Eocene thermal maximum (PETM) and associated carbon isotope excursion (CIE; about 56 million years ago) was geologically abrupt but it is debated whether it took thousands of years or was effectively instantaneous. A significant new record of the onset of the CIE was published by Wright and Schaller (2013) who claimed that it could be resolved across 13 annual layers in a drill core through the Marlboro Clay at Millville, New Jersey (Ocean Drilling Program Leg 174X). Supporting evidence of similar layering was also reported from another New Jersey drill site, Wilson Lake B, and a photograph of the Marlboro Clay in outcrop. Such a short duration would imply an instantaneous perturbation of the atmosphere and surface ocean, and the impact of a comet or asteroid as the likely cause. However it was suggested by Pearson and Nicholas (2014) from the published photographs that the layers in the Marlboro Clay could be artifacts of drilling disturbance (so-called "biscuiting", wherein the formation is fractured into layers or "biscuits" and drilling mud is injected in between). Here we report new observations on the cores which support that interpretation, including concentric grooves on the surfaces of the biscuits caused by spinning in the bit, micro-fracturing at their edges, and injected drilling mud. We re-interpret the outcrop evidence as showing joints rather than sedimentary layers. We argue that foraminifer concentrations in the sediments are far too high for the layers to be annually deposited in turbid waters at depths of 40–70 m, indicating that the onset of the CIE in the Marlboro Clay likely took on the order of millennia, not years. Re-coring of Millville to minimize drilling disturbance and allow a higher resolution study of the carbon isotope excursion is highly desirable.

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1 Introduction

The Paleocene/Eocene boundary (PEB) is one of the most intensively studied intervals of abrupt climate change in Earth's past (Kennett and Stott, 1991; Thomas and Shackleton, 1996; Zachos et al., 2005). Its main features are a pronounced global warming spike of over 5° C (Paleocene/Eocene thermal maximum, PETM), which happened in an already warm world, associated with carbonate dissolution and a negative CIE of at least several parts per thousand that persisted and then decayed over approximately 200 ka (reviews by Dunkley Jones et al., 2010 and McInerney and Wing, 2011). All attempts at explaining the event involve the addition of large amounts of isotopically light carbon to the exogenic carbon pool. Non-exclusive possibilities include volcanic emissions (Eldholm and Thomas, 1993; Bralower et al., 1997; Storey et al., 2007), the mobilization and oxidation of seafloor methane from clathrates (Dickens et al., 1995; Katz et al., 1999), emission of thermogenic methane from deeply buried hydrocarbons after igneous intrusion (Kurtz et al., 2003; Svenson et al., 2004), oxidation of organic-rich sediments in epicontinental seas (Higgins and Schrag, 2006), runaway release of methane from rapidly melting permafrost (Deconto et al., 2012), combustion of part of the biosphere (Huber, 2008), and extraterrestrial carbon dumped by a comet, the impact of which could have triggered further methane release (Kent et al., 2003; Cramer and Kent, 2005; Wang et al., 2013). Most stratigraphic records indicate a geologically rapid onset, but that definition could mean any duration between about 20 thousand years (Cui et al., 2011) to a few thousand years (e.g., Kennett and Stott, 1991; Thomas et al., 2002; Zachos et al., 2005, 2007; Aziz et al., 2008) or just a few years, i.e. effectively instantaneous (Kent et al., 2003; Cramer and Kent, 2005). Resolution of this question will provide constraints on the likely source of the carbon and advance our understanding of disturbances of the Earth's carbon cycle and their effect on life.

Although hitherto a minority view, an instantaneous onset of the PETM and associated CIE would have profound implications. For example, it would have caused sudden and substantial acidification of the upper layers of the ocean in contact with the at-

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mosphere, whereas a slower rate of carbon release would have caused a less sharp acidification response because shallow and surface waters which continually mixed into the much larger deep ocean reservoir (Ridgwell and Schmidt, 2010; Hönisch et al., 2012). There was no mass extinction of calcareous plankton and shallow-water smaller benthic foraminifera at the PEB, hence a quasi-instantaneous onset to the event would imply that these organisms adapted to rapid acidification. More generally, the lack of a global mass extinction on land and in the oceans (except among deep-sea benthic foraminifera) would indicate unexpected, and perhaps reassuring, resilience of life to profound and abrupt global warming (Thomas et al., 2004; McInerney and Wing, 2011).

2 Previous discussion

Significant new evidence relating to the pattern and timing of the CIE onset was presented by Wright and Schaller (2013) from a drill site at Millville, New Jersey (Ocean Drilling Program [ODP] Leg 174X; Sugarman et al., 2005). Their data show one of the clearest and best resolved onsets yet published (reproduced here as Fig. 1) with a run of "intermediate" bulk sediment δ^{13}C values showing a somewhat stepped appearance, including intervals of little change or possibly even reversals in the trend. Critically, Wright and Schaller (2013) described the Marlboro Clay formation at Millville and the nearby Wilson Lake B core (as yet unpublished, but a re-drill of a Wilson Lake core studied at high resolution by Gibson et al., 1993; Zachos et al., 2006; Gibbs et al., 2006; Sluijs et al., 2007) as "characterized by rhythmic couplets of silty kaolinitic clay distinguished by 1 to 2 mm layers of swelling smectite clays and micaceous silt, recurring every 1–3 cm through the entirety of the unit". They also referred to similar layers in the same formation in the nearby Ancora Core (ODP Leg 174X; Harris et al., 2010), the South Dover Bridge Core (Maryland, Self-Trail et al., 2012), and an exposure at Medford, the latter without citation. At Millville they counted ~750 such couplets over approximately 12.5 m of Marlboro Clay and just 13 couplets spanning the CIE onset, potentially providing a precise timing.

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The interpretation that the couplets are annual rests first on demonstrating that they are climatic in origin. Wright and Schaller (2013) argued for this partly on the sedimentology (especially the rhythmicity of the layering), and partly on the basis of a high resolution bulk oxygen isotope record through two sections (approximately 25 cm and 10 cm respectively) of the Wilson Lake B core. These sections were claimed to show cyclic variability in δ^{18}O values, with maxima corresponding to the thin smectitic layers. The variability was interpreted as corresponding to temperature and/or salinity fluctuations, and hence likely climatic. Wright and Schaller (2013) rejected the possibility of an orbital control or other long period cycles because the Marlboro clay lies entirely within magnetochron C24r (which has a duration of 2.6 Myr; Cande and Kent, 1995). Therefore they proposed that the couplets must be annual and the variability seasonal, arguing that the implied very rapid sedimentation rate (1–3 cm yr^{-1}) is within the bounds of measured rates in fast-depositing mud-belt areas of modern shelf regions, e.g. close to the Amazon River outflow. If the CIE onset occurred in just 13 years in the sediment, it would seem to show that the atmospheric perturbation must have been effectively instantaneous which in turn rules out all of the proposed sources of carbon as significant contributors to the CIE onset except comet impact or possibly emissions from massive volcanism (Wright and Schaller, 2013).

These claims elicited responses from Pearson and Nicholas (2014) who argued that the supposed annual layers were artifacts of drilling disturbance; from Stassen et al. (2014), who disagreed with the estimated paleodepths and included the argument that planktonic foraminiferal assemblages could not have been deposited in as little as 13 years; and from Zeebe et al. (2014) who argued against an instantaneous event based on geochemical modeling.

Biscuiting is a form of drilling disturbance that occurs when the torque induced by rotary drilling is transferred to the sedimentary formation as it enters the core barrel, inducing repetitive mechanical failure (e.g., Graber et al., 2002; Hubbard, 2007). Drilling slurry can be injected between the biscuits, resulting in thin partings and hence layering. Biscuiting is especially a problem when swelling clays are drilled because these

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expand in contact with water and can cause high pressure around the bit. Pearson and Nicholas (2014) pointed out that overpressure in the hole at Milllville had been reported at the time by the drilling engineer, that the recovered sediment was thicker than the interval drilled, and that injection of slurry into the formation had been noted (see "Operations" in Sugarman et al., 2005). Moreover, sediment loggers repeatedly suggested that the layering in the cores might be artificial (see core description sheets 91, 103, 108, 121, and 139 in Sugarman et al., 2005).

Figure 2 (reproduced from Pearson and Nicholas, 2014) shows an explanation of the biscuiting, and the appearance of Millville and Wilson Lake B cores as compared with another biscuited core obtained by Pearson et al. (2004) from Eocene clays of Tanzania. Pearson and Nicholas (2014) suggested that close observation of the core might resolve the issue, specifically that a "tell-tale feature of this kind of disturbance is that spinning of the biscuits can leave concentric grooves on the contacts with the partings" (Pearson and Nicholas, 2014; see also Hubbard, 2007, for a description and photograph of this phenomenon and other signs of biscuiting).

In response to Pearson and Nicholas (2014) and the other comments (Stassen et al., 2014; Zeebe et al., 2014), Wright and Schaller (2014) acknowledged that mud injection may have occurred at Millville but rejected it as a general explanation for the layers in the Marlboro clay on two main grounds: that no overpressure had been reported when Wilson Lake B was drilled and that layering had also been observed at the Medford outcrop, for which they provided a field photograph in support (reproduced here as our Fig. 3). They suggested in addition that injection and biscuiting during coring "generally follow preexisting zones of weakness, here provided by rhythmic sandy-silt beds observed in outcrop".

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3 New observations on the drill cores

In order to resolve this debate, one of us (PNP) made new observations on the cores at a visit to the Rutgers core repository on 19–21 March 2014. At that time he was able to discuss the issues constructively with J. D. Wright and M. F. Schaller.

The Millville core (Fig. 4) has desiccated and broken up (Fig. 4b) but the layering is still very clear, as are areas of superficial drilling mud. The latter is slightly darker in color even after desiccation and has a swirly texture under a hand lens. Various features confirm that the prominent layering is drilling disturbance. Notable among these are (i) widening of the partings toward the outer edge (Fig. 4d), (ii) physical continuity between the partings and external drilling mud of identical color and texture (Fig. 4d), and (iii) concentric grooves on the surface of biscuits (Fig. 4f).

Unlike Millville, the Wilson Lake B cores have been split into sampling and archive halves. New observations were made on the latter, including an interval of polished core surface originally made by Wright and Schaller (2013). Similar features to those in the Millville cores are evident, especially the concentric grooves on the surface of the biscuits where they are in contact with the soft, injected drilling mud (Fig. 5). Also clearly visible on the polished surface is evidence for micro-fracturing of the formation at the edges of several of the biscuits (Fig. 6). The thin layers divide around these fractures giving proof of intrusion. Hence, we conclude that Wilson Lake B was subject to the same type of drilling disturbance as Millville even if overpressure in the hole was not recorded at the time.

Both Millville and Wilson Lake B cores were scrutinized carefully for signs of bedding. Unfortunately, cores from both holes are now quite oxidized and their surfaces are covered with small gypsum crystals (presumably following oxidation of pyrite in contact with air), so that no clear evidence of bedding could be observed in cores from either hole.

The thicknesses of the drilling biscuits at Millville and Wilson Lake B are remarkably regular (for Millville, 1.9 cm ± 0.8 cm at 1σ as measured by Wright and Schaller, 2013),

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and similar to the Tanzanian core (Fig. 1). We suggest that the regularity has a mechanical origin related to the strength of the formation and the torque induced by the rotating bit, which in turn is related to the core diameter which determines the distance vector component of the torque. Failure of the core likely occurs at some threshold level of torque, and regular biscuiting will result provided that the drilling rate is constant and the formation homogeneous. Good examples of regular drilling biscuits can be found in various cores, including those from ODP Sites 925 and 926 (Curry et al., 1999) and IODP Site U1334 (Pälike et al., 2010), although the New Jersey cores provide the most regular examples of the phenomenon of which we are aware.

The existence of drilling biscuits at Wilson Lake B provides a possible explanation for apparent cyclicity in the bulk sediment oxygen isotope ratios indicated by Wright and Schaller (2013): if some of the samples were contaminated by drilling slurry with a distinct isotopic signature, non-climatic variability in the $\delta^{18}O$ might conceivably have been measured. However we also note that the time series are relatively short and statistically significant cyclicity has not yet been demonstrated.

4 Re-interpretation of the field photograph from Medford

The field photograph from Medford (see Fig. 3) is part of a small exposure at stream level that had been cleaned using vertical strikes of a cutting tool. The photograph was never intended as definitive evidence by itself (J. D. Wright and M. F. Schaller, personal communication, 2014), and further observations on the locality will hopefully shed more light on the sedimentology. The supposedly rhythmic layering in the photograph is picked out by quasi-horizontal features running across the surface of the exposure characterized in places by orange staining, small ledges, and subtle variations in the lightness of the clay. The vertical blows of the cutting tool have to some extent smeared features in the sediment downward, as picked out especially by vertical streaks in the orange staining.

We dispute that the photograph shows evidence of rhythmic sedimentary layering comparable to that observed in the cores. Instead, we interpret the quasi-horizontal layers as joint surfaces along which oxidizing fluids have passed, causing the orange iron oxide staining and potentially introducing or concentrating silt particles along the joints. Oxidation may also have affected the immediately adjacent clay, lightening the color, although smearing on the vertical surface complicates the interpretation. Evidence that the layers are joints and not sedimentary partings is that they curve downward in places, intersecting one another. This interpretation is consistent with previous descriptions of the Marlboro Clay as being massive in both outcrop and cores, with evidence of some irregular sedimentary layers (sand laminae and "pods") or thin, sometimes discontinuous clay laminae in some intervals, but no reported rhythmicity (e.g., Clark and Miller, 1906; Reinhardt et al., 1980; Gibson and Bybell, 1991; Kopp et al., 2009; Self-Trail et al., 2012).

5 Foraminifer accumulation rates

Pearson and Nicholas (2014) stressed that, notwithstanding the drilling disturbance, the Millville cores might provide some broad constraints on the duration of the CIE onset from foraminifer accumulation rates. Stassen et al. (2014) pointed out that sediment "accumulation rates of $\sim 2\,\text{cm}\,\text{yr}^{-1}$ are highly improbable because of the microfossil content", especially the presence of symbiont-bearing planktonic foraminifera which only thrive in relatively open ocean environments with sufficient light intensity. To this can be added the observation that photosynthesizing calcareous nannofossils are also common at all New Jersey PETM drill sites (e.g., Gibson et al., 1993; Gibbs et al., 2006). A possible modern analogue of the sort of environmental setting proposed by Wright and Schaller (2014) for the Marlboro Clay is the muddy and fast-sedimenting Long Island Sound estuary (Latimer et al., 2014), with water depths of ~ 40 m. But here light penetration is less than 5 m and both photosymbiotic planktonic foraminifera and calcareous nannoplankton are absent (Latimer et al., 2014). In general, planktonic

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foraminifera are absent in mud belt sediments deposited on the shelf (Cattaneo et al., 2004) including on the Amazon River shelf at depths < 100 m, where benthic but no planktonic foraminifera have been recorded (Vilela, 2003).

Wright and Schaller (2014) reported concentrations of total (benthic plus planktonic) foraminifera in the > 100 µm size range for the Wilson Lake B core ranging from ~ 150–350 individuals per gram of sediment. The percentage of planktonic foraminifera in PETM sediments in various New Jersey core sites is generally 65–80 % (Gibson et al., 1993; Stassen et al., 2012). If the layers are annual this figure would imply extremely high rates of accumulation of both benthic and planktonic foraminifera. Wright and Schaller (2014) stated that this reflects a production of about 1×10^6 specimens per m^2 per year but did not document how they arrive at this estimate. We offer the following approximate calculation: if we take a roughly average figure of 200 specimens per gram and a dry bulk density of 1.4 (typical for mudrocks at the quoted burial depth; Bryant et al., 1981), this equates to 280 specimens per cm^3. The supposedly annual layers are 2.5 cm thick, hence this indicates 700 specimens per cm^2 per year, or 7×10^6 specimens per m^2 per year. This is much higher than Wright and Schaller's (2014) estimate, but even that exceeds known accumulation rates for both planktonic and benthic foraminifera (Zaric et al., 2006). Hence we suggest that the micropaleontology (both the abundance of specimens and the presence of photosymbiotic foraminifera and calcareous nannoplankton) shows the onset of the CIE at Millville likely represents thousands of years, not years, which would effectively rule out an instantaneous cause such as comet impact.

6 Conclusions

New observations confirm that the prominent rhythmic couplets in the Millville and Wilson Lake B cores are caused by drilling disturbance and are not original sedimentary features. There is no solid evidence that the Marlboro Clay is rhythmically layered, hence no support for the short chronology of the onset to the PETM sug-

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gested by Wright and Schaller (2013). Nevertheless, the record presented by Wright and Schaller (2013) from Millville is clearly important, potentially the best-resolved marine record of the CIE onset yet published, with potential fine detail including possible pulses and even a hint of cyclicity. In our interpretation, foraminifer accumulation rates point to a long-duration onset lasting > 1 kyr, but because the Millville core is much disturbed by injected drilling slurry and the critical interval has been heavily sampled, re-drilling and renewed investigation of the locality should be a high priority.

Acknowledgements. We are very grateful to J. D. Wright and M. F. Schaller for the open and constructive manner in which they have cooperated with our research. We expected nothing less but it was very gratifying nonetheless, and to J. Browning for providing assistance to our investigation at the Rutgers core laboratory. Thanks also to Wright, Schaller, and C. Lombardi for organizing and participating in a constructive day in the field. This research, including rapid response travel funds, was supported by the UK Ocean Acidification Research Program and NERC grant NE/H017518/1 to PNP.

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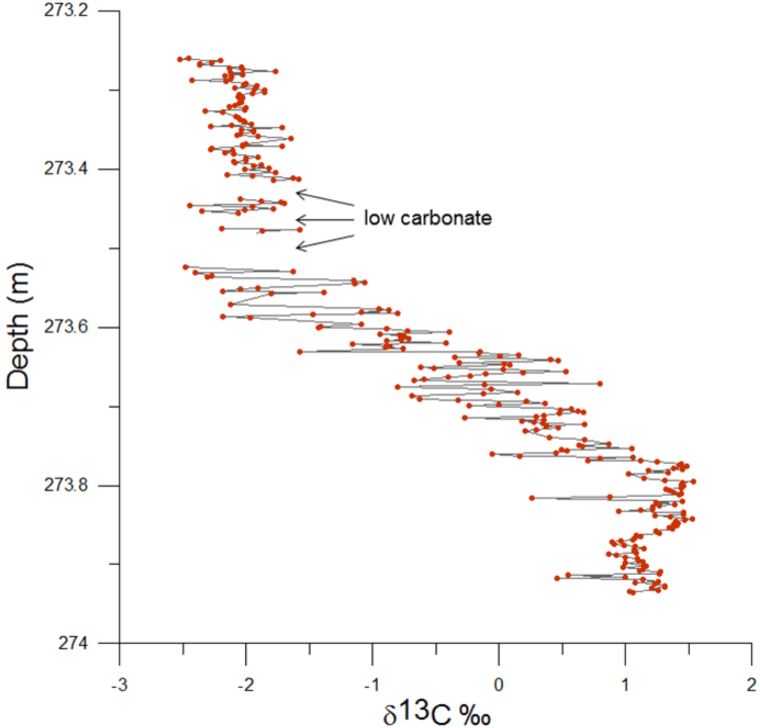

Figure 1. Onset of the carbon isotope excursion at Millville (data replotted from Wright and Schaller, 2013).

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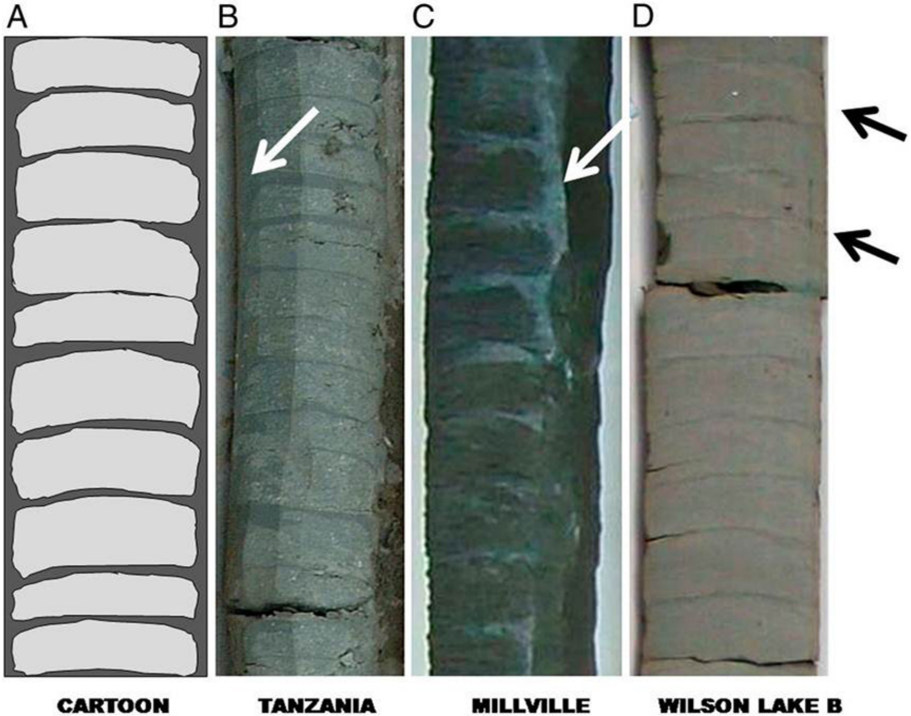

Figure 2. (a) Conceptual model of biscuiting caused by drilling disturbance. **(b)** Detail of Tanzania Drilling Project Site 2 (Pearson et al., 2004). **(c)** Detail of the Millville core (modified from Wright and Schaller, 2013). **(d)** Detail of the Wilson lake B core (modified from Wright and Schaller, 2013). White arrows indicate continuity between the external drilling mud, now mostly scraped off in the Tanzania and Millville cores, and the thin partings between the biscuits. Dark arrows point at possible bedding at an angle to biscuiting. Reproduced from Pearson and Nicholas (2014).

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Figure 3. Photograph of Marlboro Clay exposure reproduced and modified (arrows added) from Wright and Schaller 2014): "Photograph of the rhythmic bedding in the Marlboro Clay exposed in the Ranconas Creek, Medford, NJ. Pencil is ~ 15 cm. The blue/gray clay is interrupted at regular (~ 2 cm intervals) by very thinly bedded silts and very fine sands. These areas also provide zones of weakness along which fractures will form when hand samples from the exposures are dried in the laboratory" (caption from Wright and Schaller, 2014). In our interpretation, the photograph shows several examples where joint surfaces curve and intersect one another in a fish-scale type arrangement. This is seen, for example, in the surface that forms a ledge behind the pencil (highlighted with arrows). No clear sedimentary bedding is apparent.

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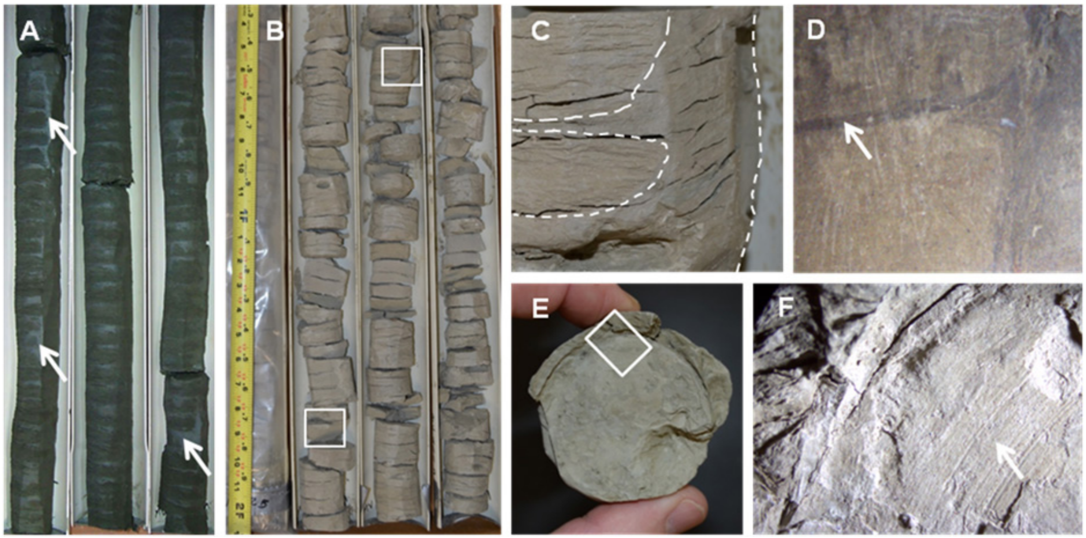

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Figure 4. Evidence for drilling disturbance in the Millville Core from the interval 890–910 feet subsurface (1 foot = 0.3048 m). **(a)** Part of the core when freshly recovered (modified from Wright and Schaller, 2013, arrows added). The horizontal layers were described by Wright and Schaller (2013) as rhythmically bedded couplets, but were interpreted by Pearson and Nicholas (2014) as alternations of drilling biscuits and injected slurry. External drilling mud has been scraped off, but patches remain (as highlighted by arrows). Note that the thin internal partings are reflective like the external mud, and appear contiguous with it in places. **(b)** Part of the same core as viewed on 19 March 2014 after desiccation during nearly a decade of storage. Note that the core has fractured in many places along the slurry partings. **(c)** Detail of upper highlighted area in B, showing a thick layer of external drilling mud still attached to the right hand side. **(d)** Part of the same interval now cut in half-round and viewed under the microscope. The drilling slurry (darker color) forms a thin parting through the centre of the core (highlighted with arrow) which is contiguous with the external mud. **(e)** Top surface of the drilling biscuit from the lower highlighted area in **(b)**, showing an external coating of drilling mud around the upper half from the back of the core where it was not originally scraped off. **(f)** Microscopic detail of highlighted area in **(e)** showing the top surface of the biscuit with concentric grooves, evidence of spinning in the core barrel. Similar observations were made at other levels in the core.

Figure 5. Concentric grooves in various parts of the Wilson Lake B core, as seen in half-round specimens from the archive half. **(a)** top of a biscuit with patches of adhering injected slurry and concentric grooves (highlighted with arrow). **(b)** base of a biscuit with patches of adhering injected slurry and concentric grooves (highlighted with arrow). **(c)** top of a biscuit with patches of adhering injected slurry and concentric grooves. **(d)** Microscopic detail of highlighted area in **(c)** showing a patch of remaining slurry (to the left) unconformably overlying the surface of a drilling biscuit which shows concentric grooves. Similar observations were made at other levels in the core.The lumps on the surface are small gypsum nodules.

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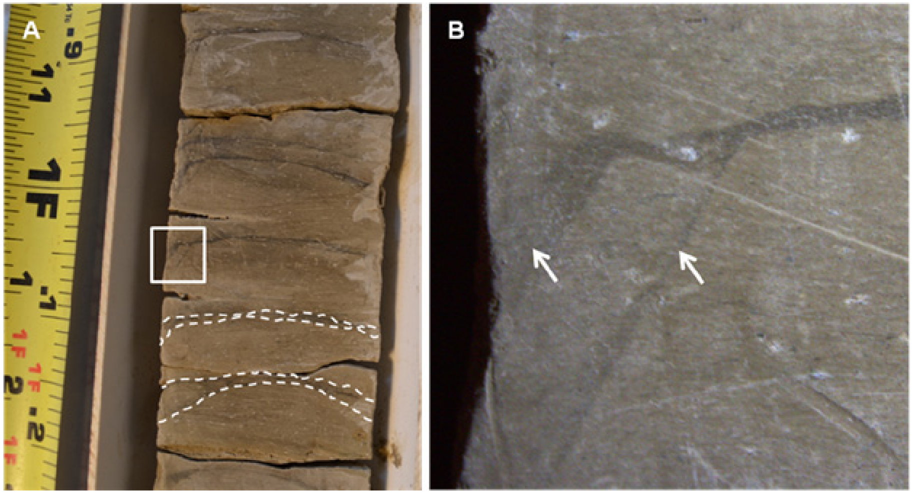

Figure 6. Evidence for drilling disturbance in the Wilson Lake B core; new photographs of part of a polished half-round interval prepared originally by Wright and Schaller (2013). **(a)** Alternating drilling biscuits and injected slurry, thickening to the edges (highlighted) with deformation features at the edge of the core. **(b)** Microscopic detail of highlighted area in **(a)** showing fractured core injected with drilling slurry (darker color, highlighted with arrow).Very similar fracturing features occur in the three overlying biscuits in **(a)**.

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