# Data report: coarse fraction record for the Eocene megasplice at IODP Sites U1406, U1408, U1409, and U1411[1]

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## Chapter contents



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## Abstract

Integrated Ocean Drilling Program Expedition 342 recovered cores from multiple sites with expanded sections of Eocene sediments, often with exceptional carbonate preservation. These cores presented the opportunity to build an Eocene-spanning, orbital-resolution megasplice for refining the Eocene timescale and detailing paleoceanographic change in a high-latitude North Atlantic location. Here we present a sediment coarse fraction record (i.e., a record of the relative portion of >63 µm sized sedimentary particles), considered alongside shipboard estimates of sedimentation rates, from 8,674 of the 10,829 samples of the Eocene megasplice. Weight percent coarse fraction (wt% CF) data were collected in 10 different laboratories, but we find that long-term trends in wt% CF are robust to interlaboratory differences in sample processing. In particular, this record details a progressive decline in wt% CF from around 5%–8% around 50 Ma to lows of less than 1% around 36 Ma. The decline in weight percent carbonate from ~50–36 Ma is not monotonic; rather, it is interrupted by at least four local highs at around 46.5, 44, 41.7, and 39 Ma. Interestingly, the abrupt onset of drift sedimentation in the early middle Eocene at Site U1409 (~47 Ma) does not coincide with a step decline in wt% CF. Because the early Eocene section of Site U1409 has lower sedimentation rates (mean = 0.99 cm/ky) compared to the middle Eocene section of Site U1408 (mean = 3.08 cm/ky), the generally lower wt% $CaC0_3$ in the middle Eocene section of Site U1408 was hypothesized to be driven by clay dilution in shipboard discussions. However, within the sites with variable sedimentation rates (i.e., Sites U1411, U1406, U1408, and U1409), wt% CF exhibited weak covariance with sedimentation rates (highest $r^2 = 0.112$; significant p-values for Sites U1411 and U1408 on pairwise correlation tests). Precise age models are thus needed to further resolve the relationship between the mass accumulation of clay, nannofossils, and foraminifer-dominated coarse fraction in these sections. Finally, within well-resolved intervals like the middle Eocene section of Site U1408, orbital scale variability is present in the wt% CF record, supporting shipboard observations of pronounced orbital variation in drift lithology (e.g., core color and weight percent carbonate).

# Introduction

A major aim of Integrated Ocean Drilling Program Expedition 342 was to obtain expanded Eocene sequences in clay-rich drift deposits from the North Atlantic (see the "Expedition 342 summary" chapter [Norris et al., 2014a]). Remarkably, Expedition 342 managed to recover Eocene-age deposits in eight sites on the J-Anomaly and Southeast Newfoundland Ridges, thereby providing (near-) continuous coverage through the entirety of the epoch along a cross-site megasplice. Three sites included in the megasplice (Southeast Newfoundland Ridge Sites U1408, U1410, and U1411) are clay-rich drift deposits in the middle Eocene (Sites U1408 and U1410) and across the Eocene/Oligocene transition (EOT) (Site U1411). The temporally expanded sequences and excellent carbonate preservation afforded by the clay-rich drift intervals and the high North Atlantic latitude of all sites drilled during the expedition (39°56′–41°37′N) provide an exceptional opportunity for resolving outstanding questions of Eocene paleoceanography.

Capitalizing on the exceptional coverage of Eocene strata, the initial goal was to generate continuous geochemical and physical property data sets and tuned age models necessary for subsequent investigations. To this end, efforts were initiated to develop X-ray fluorescence (XRF) records at 10 kV as needed for splice refinements and development of an anchored astrochronological timescale for the Eocene and a continuous stable isotopic stack from benthic foraminiferal calcite (e.g., $\delta^{18}O$ and $\delta^{13}C$). To achieve the latter goal, the Eocene Stable Isotope Consortium (ESIC) was established, uniting 10 participating laboratories and more than 20 individuals from around the world. It is the preliminary results of this collaboration that we report here.

ESIC sampling occurred along an Eocene megasplice from Site U1411 (EOT; drift deposit; current water depth = 3300 m) to Site U1406 (EOT to late Eocene, pelagic sedimentation; current water depth = 3800 m) to Site U1408 (middle Eocene; drift sedimentation; current water depth = 3022 m) to Site U1409 (primarily early Eocene; pelagic sedimentation; current water depth = 3500 m). All sites are located on the Southeast Newfoundland Ridge, with the exception of Site U1406 (see Table T2 in the "Expedition 342 summary" chapter [Norris et al., 2014a] for site details). Here we present the weight percent coarse fraction (wt% CF) records from the ESIC samples prepared to date. Weight percent CF records the relative amount of sediment greater than 63 µm in size; in the deep sea this is the size fraction typically comprising foraminifers. These 8674 samples, 80% of the consortium total, already make this record the highest resolution (and longest) sequence of wt% CF data from the Eocene and provide additional insight into the paleoceanographic evolution in the North Atlantic.

# Methods

Shipboard age models suggested sedimentation rates generally greater than 2 cm/ky in megasplice drift sequences at Sites U1411 and U1408 and less than 2 cm/ky in pelagic deposits at Sites U1406 and U1409 (see Fig. F53 in the "Expedition 342 summary" chapter [Norris et al., 2014a]). To capture orbital variability, we sampled every 2–3 thousand years (ky) in the drift deposits (i.e., Sites U1408 and U1411) and every ~5 ky in the pelagic sequences (i.e., Sites U1406 and U1409), based on shipboard sedimentation rate estimates and age models. By site, ESIC sampling included 1807 samples from Site U1411; 1550 samples from Site U1406; 5300 samples from Site U1408, and 2172 samples from Site U1409, most of which were sampled during the postcruise sampling party (February 2013 at the Bremen Core Repository [Germany]).

ESIC samples were distributed among 10 primary groups in six countries: H.K. Coxall, Stockholm University (Sweden); O. Friedrich, Universität Heidelberg (Germany); P.M. Hull, Yale University (USA); S.K. Turner, University of California Riverside (USA); K. Moriya, Waseda University (Japan); R.D. Norris, Scripps Institution of Oceanography (USA); B.N. Opdyke, Australian National University (Australia); P.F. Sexton, Open University (UK); P.A. Wilson, National Oceanography Centre Southampton (UK); and J.C. Zachos, University of California Santa Cruz (USA).

To provide consistency across the consortium, a common sample preparation protocol was developed. Samples were dried (in an oven at ~55°C or freeze-dried), massed, disaggregated in deionized water (DI water; typically for 1–12 h), washed in DI water over a 63 µm sieve, and redried. Samples that were difficult to wash (i.e., not clean within 30 min of misting with DI water) were rewashed. Rewashing involved a several hour soak in boron-free disaggregating solution (dilute sodium metaphosphate solution [20 g/10 L DI water] buffered to pH of 7–7.5) and up to 30 min of DI mist-washing on a 63 µm sieve. Drift sediments commonly required two washes, and those in the deeper sections of Site U1408 washed in the Hull and Zachos laboratories often required three to four such repeats. Samples were rinsed with ethanol (denatured). After drying (at 55°C), the greater than 63 µm size fraction (coarse fraction) was weighed and, with the sample dry weight mass, used to calculate wt% CF. It should be noted that we are technically measuring the mass percent coarse fraction, not the wt% CF. We use the term wt% CF here for consistency with paleoceanographic common usage (however technically incorrect it may be) and for linguistic consistency with other parameters measured shipboard, like weight percent carbonate (wt% carbonate), that are also properly mass percents.

Samples were then split equally into a geochemistry fraction (for benthic and planktonic foraminiferal stable isotope and trace metal geochemistry) and a faunal fraction for biotic studies. In some sections with very low wt% CF (see below) or low numbers of the target benthic species, faunal splits were not made.

Exceptions to the standard ESIC washing protocols were made by various groups based on local equipment availability, protocols, and scientific priorities, and are listed here as follows:

- Stockholm University: Followed protocol, except that samples were not split into faunal and geochemistry fractions because the late Eocene material from Sites U1411 and U1406 contained typically <2% coarse fraction and thus low numbers of benthic foraminifers. Efforts were made to keep a record of every specimen removed, and any unused specimens were returned to the vials.
- Heidelberg University: Followed protocol, except for drying oven temperature (set to 40°C).
- Yale University: None. Followed protocol for Hull, Norris, and Penman sample requests.
- University of California Riverside: Followed protocol, except samples were not rinsed in alcohol at any point and samples were not split into benthic and faunal fractions. Efforts were made to keep a record of every specimen removed, and any unused specimens were returned to the vials. All samples were washed until clean in a single wash (no second washes).
- Waseda University: Followed protocol, except for drying oven temperature (set to 50°C) after washes (initial sediments were freeze-dried). Washing was notably gentle, as electric foggers filled with DI water were used for mist-washing.
- Scripps Institution of Oceanography: None. All samples washed at Yale University (Hull Laboratory), and Yale followed protocol.
- Australian National University: Used several washing protocols optimized for local project goals and site-specific differences in lithology. Throughout, samples were washed in DI water and dried in a 35°–40°C oven. Site U1408 samples were initially washed according to four size fractions (<63, 63–100, 100–200, and >200 µm), a procedure that was quickly changed to saving the fine fraction (<63 µm sediment) and washing two independent splits (63–200 and >200 µm). Site U1408 >200 µm fractions were typically washed in three wash/dry cycles, and the 63–200 µm fractions were washed in 7–8 three wash/dry cycles. Site U1406 sample washing protocols differ from the final Site U1408 protocols in three ways. Calgon (a brand-name water softener similar in washing effect to the boron-free sodium metaphosphate solution used by other groups), diluted to 1 g Calgon/100 mL, was used. Samples were also ultrasonicated for 5 s between washes. Typical Site U1406 samples required 10 wet/dry cycles to clean the 63–200 µm fraction.
- Open University: None. Followed protocol.
- National Oceanography Centre Southampton: Followed protocol, except for the ethanol rise; samples were not rinsed in alcohol at any point.
- University of California Santa Cruz: Followed protocol, except samples were dried at room temperature.

All samples are listed in COARSE_FRACTION.csv in SPLICE in **"Supplementary material"** with the responsible principal investigator (PI). In the text, when referring to specific wt% CF values, we report the mean and standard deviation as mean ± standard devation %. For instance, an interval with a mean wt% CF of 3 and standard deviation of 1.5 would be reported as 3% ± 1.5%.

Shipboard splicing within drift deposits proved difficult in many intervals due to low magnetic susceptibility and (apparently) high lateral variability in sedimentation rates and the continuity of sedimentation. XRF scans of Fe at 10 kV were used to generate a revised spliced depth scale (meters composite depth [mcd]) for Sites U1408 and U1409 that we use here (see 342_REV_SPLICE in SPLICE in **"Supplementary material"**). For Sites U1406 and U1411, we use the shipboard splices (see 342_SPLICE in SPLICE in **"Supplementary material"**) and the corresponding site reports (see the **"Site U1406"** and **"Site U1411"** chapters [Norris et al., 2014b, 2014e). The splice from Site U1408 is still under revision and is being considered with a direct comparison with Site U1410, particularly for Magnetochrons C18, C19, and C20r. COARSE_FRACTION.csv in SPLICE in **"Supplementary material"** provides the original sample ID, meters below seafloor (mbsf; also known as core depth below seafloor, or CSF-A, in other Expedition 342 publications), current meters composite depth as described above (also known as core composite depth below seafloor, or CCSF, in other Expedition 342 publications), and shipboard bio- and magnetostrat-derived age models for every sample. Sample IDs for all shipboard stratigraphic tie points were obtained from the relevant site reports (see the **"Site U1406," "Site U1408," "Site U1409,"** and **"Site U1411"** chapters [Norris et al., 2014b, 2014c, 2014d, 2014e]). Several inconsistencies in the meters below seafloor assignments in the shipboard reports were identified by P. Blum on review, so we updated all assignments for the sample IDs of the stratigraphic tie points using the Laboratory Information Management System (LIMS) Report system (**http://web.iodp.tamu.edu/LORE/**). These updated meters below seafloor values are listed in BIO_PMAG_TIE_POINTS.csv in SPLICE in **"Supplementary material,"** and this table should be used for the generation of further "shipboard" age models. The midpoint depth of biostratigraphic datums and magnetostratigraphic boundaries were translated from meters below seafloor to meters composite depth using the updated splices (where applicable) as described above. Shipboard-like age models were then calculated via linear interpolation between these tie points. Here we calculate all sedimentation rate statistics (that is, interval averages and trends) based on sample specific values provided in COARSE_FRACTION.csv in SPLICE in **"Supplementary material."** Multitaper Method (MTM) spectral analysis was performed on a (polynomial; period 500 ky) detrended subset of samples across Magnetochron C20n at Site U1408 (Yale interval) using the astrochron package in R.

# Results

Roughly 99% of the wt% CF values range from 0.11% to 12.75% (extreme values include some samples with heavy inclusions [e.g., chert at Site U1409] and other complicating factors), with the highest values in the carbonate-rich deposits of the early Eocene at Site U1409 (6.94% ± 3.10%). Middle Eocene drift deposits at Site U1408 had lower wt% CF on average (2.24% ± 1.27%). Three lines of evidence suggest that the decline in wt% CF from the early Eocene at Site U1409 to the middle Eocene at Site U1408 does not reflect a change in preservation potential of foraminifers alone. Paleowater depth estimates put Site U1409 around 500 m deeper than Site U1408 at this time (e.g., Fig. **F1**), and the decline in wt% CF begins in roughly the middle of the Site U1409 record (around 50 Ma). The declining wt% CF carries on through the Site U1408 record, with some local highs in wt% CF (notably from 46–47 Ma at Site U1409). In addition, visual shipboard estimates of planktonic foraminiferal preservation quality were typically described as moderate to good in the early Eocene at Site U1409 (see the **"Site U1409"** chapter [Norris et al., 2014d]) and good to very good in the middle Eocene at Site U1408 (see the **"Site U1408"** chapter [Norris et al., 2014c]). Weight percent CF is expected to decline with a decline in preservation (Broecker and Clark, 1999), so the long-term trend across Sites U1409 and U1408 counters a pure preservation hypothesis. Similarly, increasing clay dilution with the onset of drift deposition also (alone) cannot account for the observed decline in wt% CF because the decline begins well within the early Eocene at Site U1409, before the onset of drift deposition. In addition, the decline continues, with interruptions, through the middle Eocene at Site U1408, long after the lithologically abrupt onset of deep drift deposition captured at Site U1409. In short, some portion of the long-term decline in wt% CF from (very roughly) 50 to 35 Ma likely captures a long-term decline in the mass accumulation rates of planktonic foraminifers, a hypothesis that awaits updates in age model estimates to be tested.

At Site U1408, there is general decline in wt% CF from ~43.5 to ~40 Ma, with three peaks (around 43.4–44.4, 41.1–42.2, and 39.5–40 Ma). Shipboard age models show a local peak in sedimentation rates coincident with youngest peak (39.5–40 Ma) in wt% CF. The previous two peaks (around 43.4–44.4 and 41.1–42.2 Ma) occur during an interval of generally high sedimentation rates. Whether or not higher frequency variation in wt% CF coincides with sedimentation rate changes remains to be tested when cyclostratigraphic age models are available.

Weight percent CF is generally quite low in the moderately preserved, pelagic strata of Site U1406 (0.64% ± 0.51%). Weight percent CF declines steadily from 37.4 to 36.8 Ma from roughly 1.5 to >0.5 wt% CF and remains low for the remainder of the Site U1406 record (35.7–36.7 Ma). There is no clear correlation between preservation and wt% CF from the shipboard observations of planktonic foraminiferal preservation at Site U1406. The decline from 37.4 to 36.8 Ma does coincide with a switch from good to moderate foraminiferal preservation, but the low wt% CF interval that follows (35.7–36.7 Ma) has planktonic foraminiferal preservation observations in the same range as the oldest part of the Site U1406 record (i.e., moderate to good). It is notable that Site U1406 has the deepest paleowater depth estimates of all the sites included (an estimated 3400 m at 45 Ma, compared to 2400 m at Site U1411 or 2100 m at Site U1408). Once again, however, it is unlikely that the water depth alone explains the very low wt% CFs at Site U1406. Where Sites U1411 and U1406 overlap, they show similar trends and absolute values in wt% CF and the deeper portion of the Site U1406 record having wt% CF values comparable with the shallowest samples from Site U1408.

The rapidly accumulating sediments of Site U1411 (typically between 2.27 and 5.50 cm/ky), have wt% CF values of 0.85% ± 0.61%. The late Eocene at Site U1411 has lower wt% CF (mean = 0.59%) compared to that of the early Oligocene (mean = 1.10%). Although this coincides with an overall increase in sedimentation rates (from a mean of 3.05 cm/ky in the late Eocene to a mean of 4.04 cm/ky in the early Oligocene), large variations in sedimentation rates between 2.27 and 5.49 cm/ky (shipboard estimates) in the early Oligocene do not coincide with comparable variation in wt% carbonate (Figs. **F1, F3**).

Although there are likely to be laboratory differences affecting wt% CF, two well-sampled intervals suggest that these effects are unlikely to influence the broad-scale patterns and inferences thereon (Fig. **F2**). The middle Eocene samples from Site U1408 (38.64–45.49 Ma) were washed in four primary locations: Australia National University (38.64–39.43 Ma), Yale University (39.44–40.59 and 42.22–43.58 Ma), University of Southampton (40.59–42.22 Ma), and University of California Santa Cruz (43.57–45.49 Ma). Color-coded by washing location, the Site U1408 coarse fraction data show continuous trends across washing location changes. The same is true of the completed Site U1406 washing, carried out at Heidelberg University (36.89–37.51 Ma), Stockholm University (35.66–36.89 Ma), University of Southampton (32.24–35.65 Ma), and Wasada University (32.16–35.64 Ma) (Fig. **F2B**) and of the Site U1411 record washed in two locations and Site U1409 washed in three locations (comparisons of Sites U1411 and U1409 are not shown).

Within Sites U1408 and U1411 there was a significant, positive correlation between sedimentation rate and wt% CF (Fig. **F3**) using the shipboard age models. Specifically, within-site pairwise correlation tests of linear sedimentation rate and wt% CF at these two sites have p-values less than 0.05. However, generally speaking, very little of the variance in the wt% CF was explained by sedimentation rates at these sites. Site U1408 had the strongest relationship, with a $r^2$ of just 0.112. Refined age models will provide a stronger test of the relationship between wt% CF and sedimentation rates when they become available.

The high-amplitude variability in lithology in shipboard color records and wt% carbonate (e.g., Figs. **F49** and **F50** in the "Expedition 342 summary" chapter [Norris et al., 2014a]) attributed to orbital forcing was also observed in the wt% CF records. In the robustly spliced interval in Magnetochron C20n at Site U1408, for instance, wt% CF records exhibit significant variability at roughly 30 and 23 ky based on shipboard age models. We suspect these two peaks correspond to obliquity and precession, although this remains to be tested with future cyclostratigraphic age model development (Fig. **F4**).

This wt% CF record is provided as a standalone data set that will be useful for ongoing research on Eocene paleoceanography in the North Atlantic, to alert external research groups to the availability of these samples for complementary faunal work and other geochemical applications, and to evidence progress of the consortium's efforts to build the ESIC stable isotope stack. In addition to the benthic isotope work, many PIs in the consortium have committed to generating planktonic foraminiferal or bulk carbonate isotope records for surface and thermocline waters, and some are generating Mg/Ca and other trace metal records as well. There remain, however, thousands of samples without matching planktonic isotope records planned, and we welcome collaboration toward the second goal of producing a parallel surface ocean megastack. In addition, faunal work is planned in a limited number of intervals. Faunal splits are being made and preserved where appropriate. In the drift deposits at Sites U1408 and U1411, preservation is exceptional (glassy to near-glassy) and presents an unprecedented opportunity for long records of Eocene biotic dynamics. The unforeseen difficulty of splicing Site U1408 continuously across the middle Eocene has led to new efforts to sample and cross-correlate between Sites U1408 and U1410 in hopes of fulfilling the initial goals laid out for the ESIC during Expedition 342. Samples from Site U1410 will be added to the consortium records of wt% CF and benthic stable oxygen and carbon isotopes at a later time.

The record presented here represents the first step in an ambitious international collaboration. Already the coarse fraction record provides multiple insights in Eocene paleoceanography in the North Atlantic, including the following:

- Additional evidence for paleoceanographic change following the early/middle Eocene boundary in the steep decline wt% CF records (Fig. **F1**),
- Additional evidence for orbital forcing in Newfoundland Ridge drift deposits (Fig. **F4**), and
- Long-term variation in wt% CF records even within the drift deposits (Figs. **F1, F2**), in some cases possibly relating to intervals of higher average wt% carbonate noted shipboard.

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**MS 342-203**

**Figure F1. A.** Weight percent CF along the Eocene megasplice at Expedition 342 sites (solid lines) overlain with linear sedimentation rates (dotted lines) estimated from shipboard age models. Although the records of wt% CF look noisy at the scale of the Eocene, a zoomed in interval (**B**) at Site U1408 from 42.2 to 43.6 Ma shows variability in wt% CF to be coherent variation in the record, not noise. Intervals with drift sedimentation are indicated in dark blue-green at the top of A. pwd = paleowater depth.

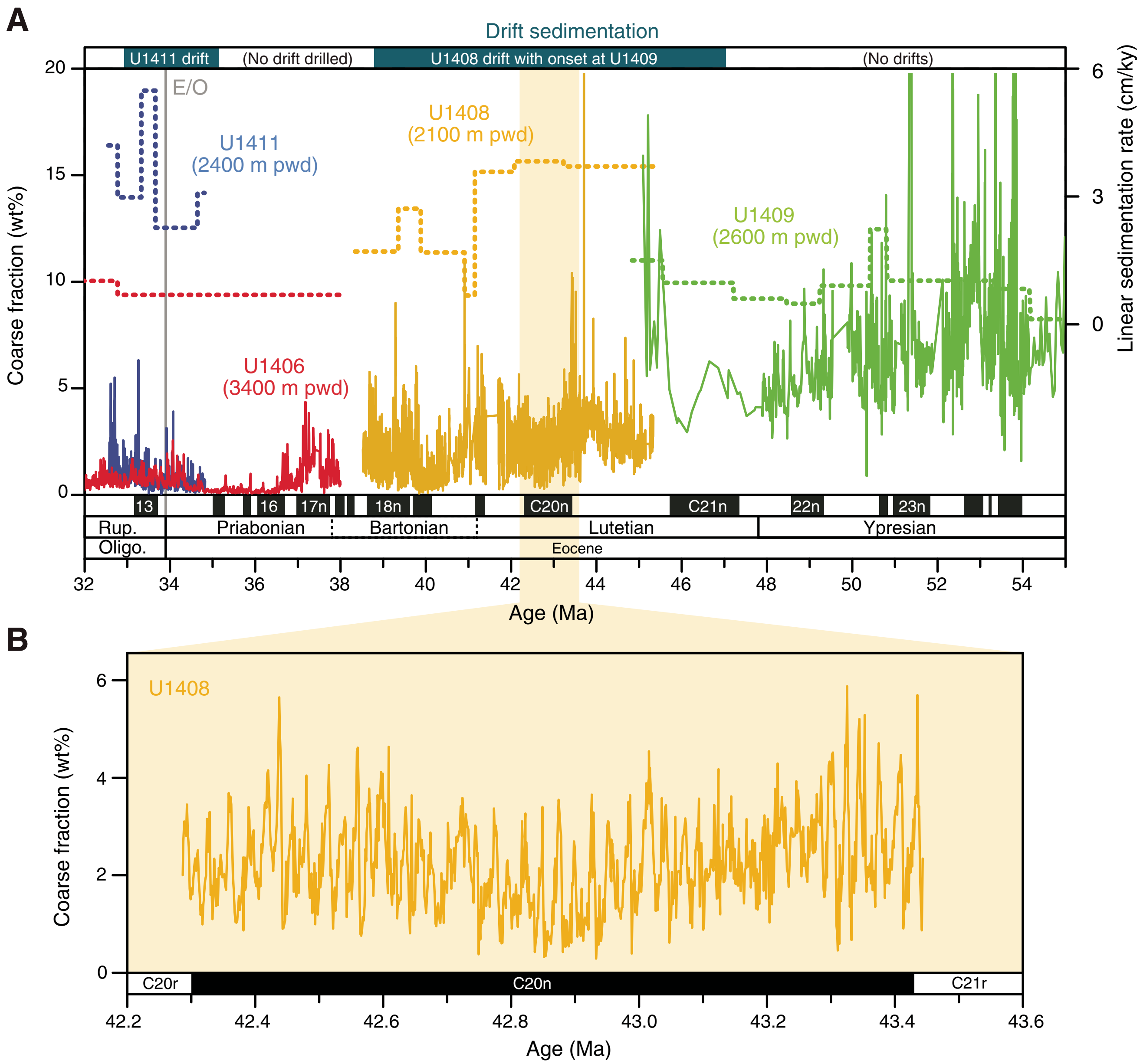

**Figure F2.** Weight percent CF trends do not appear to be influenced by location of washing for (**A**) Site U1408 or (**B**) Site U1406. ANU = Australia National University, NOCS = National Oceanography Centre Southampton, University of Southampton, UCSC = University of California Santa Cruz.

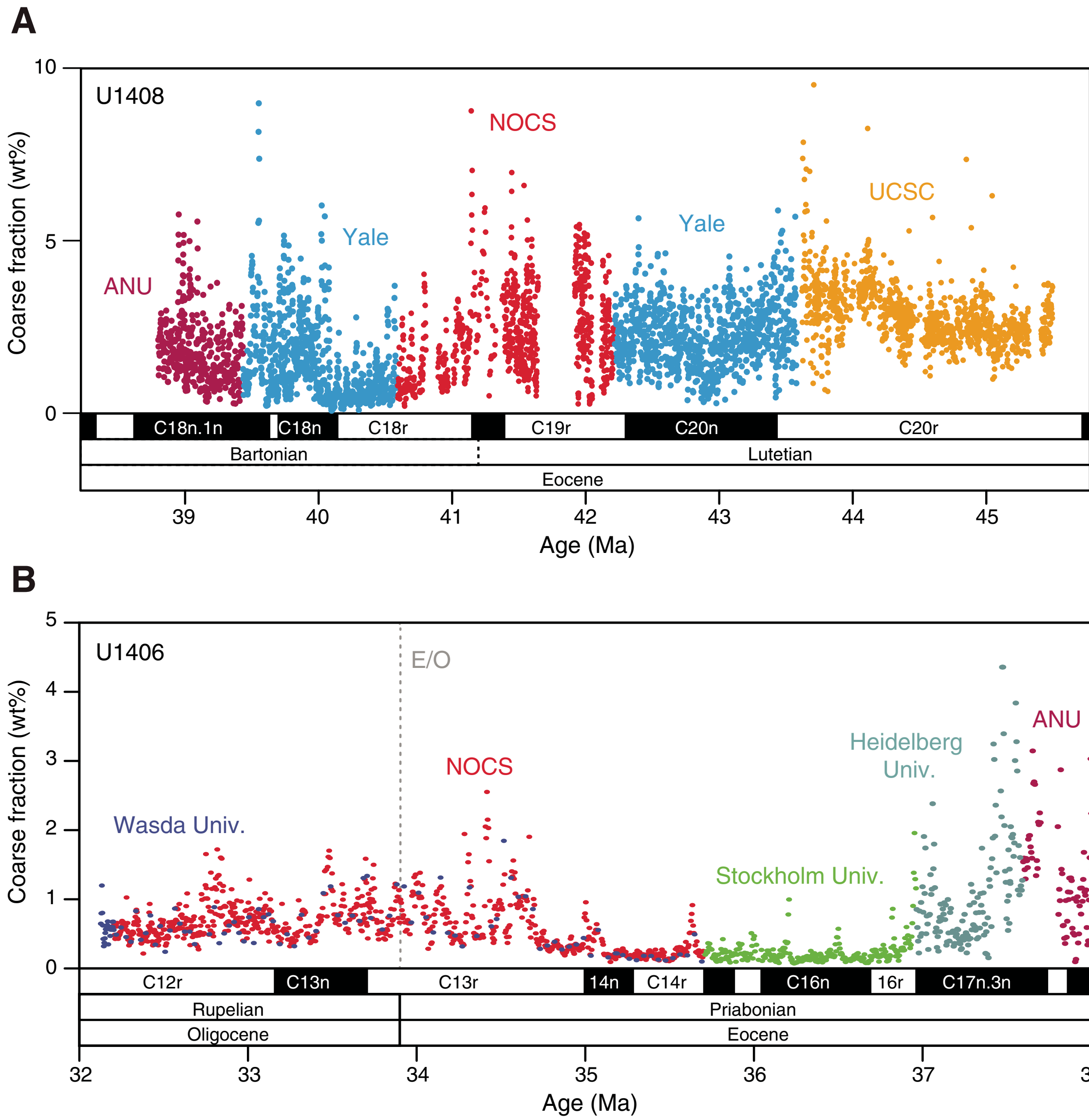

**Figure F3.** Sedimentation rate (calculated from shipboard age models) is correlated to wt% CF in all sites but explains very little of the variation in the records (all $r^2 < 0.10$).

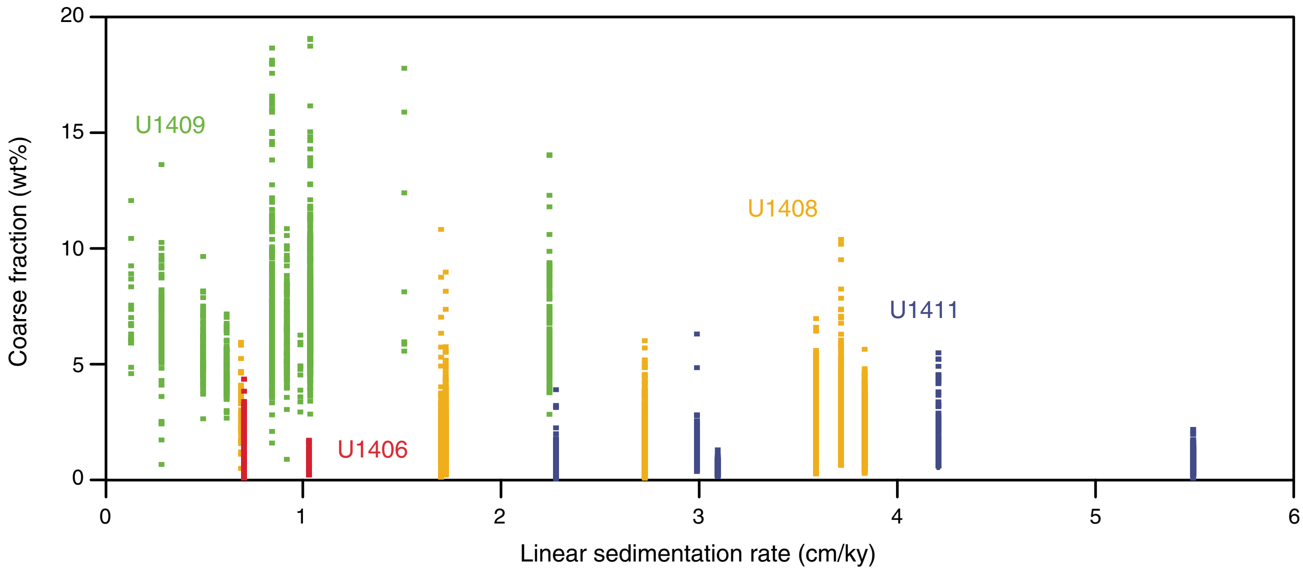


**Figure F4.** Spectral analysis of wt% CF in the depth (left) and age (right) domain (**A.** Linear power scale. **B.** Log power scale) in Magnetochron C20n at Site U1408 show significant power near orbital frequencies. This interval is not long enough to properly test for 400 ky eccentricity forcing.