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Cosmogenic ^3He anomaly K1 vs. the early Campanian isotopic event (ECE) as recorded in pelagic limestones of the Umbria-Marche succession (Italy)

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ABSTRACT

In this paper, we report on a biostratigraphic, magnetostratigraphic, and stable isotope ($\delta^{13}\text{C}$ and ^3He) analysis across three pelagic limestone sections of the Campanian Scaglia Rossa Formation exposed in the classic Bottaccione Gorge at Gubbio (Umbria region), near the village of Furlo, and near the town of Apiro (both in the Marche region), all located in the Umbria-Marche basin of the northeastern Apennines of central Italy. These sections record the coincidental occurrence of an extraterrestrial ^3He ($^3\text{He}_{\text{ET}}$) anomaly known as K1 and a negative shift in the $\delta^{13}\text{C}$ record known as the early Campanian event. Cyclostratigraphic spectral analysis of the Furlo section based on a high-resolution magnetic susceptibility record in these pelagic limestones revealed that the regular orbitally forced Milankovitch cycles are somewhat disturbed or blurred through the interval of the coincident $^3\text{He}_{\text{ET}}$ K1 anomaly and the early Campanian event isotopic anomaly, suggesting a causal effect resulting from the enhanced influx of extraterrestrial material (i.e., interplanetary dust particles and a myriad of small meteorite impacts). This would have altered the transparency of the atmosphere, causing a short-lived climate change event.

INTRODUCTION

Since the beginning of the twentieth century, the Jurassic to Neogene pelagic carbonate succession exposed throughout the Umbria-Marche Apennines of Italy (Fig. 1A) has been the subject of countless stratigraphic studies, which were aimed at reconstructing the geotectonic and sedimentary evolution of this paleobasin as well as the biologic and climatic history of Earth. The Umbria-Marche succession is today regarded as a world reference model for the intercalibration of stratigraphic tools, including direct radioisotope geochronology on interbedded volcanic ashes and astronomical cyclostratigraphy on long series of pelagic rhythmites, particularly through the past 150 m.y. (Alvarez, 2019, and references therein). Another primacy of the Umbria-Marche succession has been its use as a workbench for investigating the stratigraphic record of extraterrestrial events, which influenced the evolution of climate and, ultimately, marine plankton. Noteworthy studies have focused on extraterrestrial impact events, particularly the catastrophic impact at the Cretaceous-Paleogene boundary, which caused a global mass extinction, and the multiple late Eocene impact events, caused most probably by a comet shower or an asteroid bombardment (Montanari and Koeberl, 2000, and references therein). A synoptic model for the Umbria-Marche succession is shown in Figure 2, along with the extraterrestrial event signatures found so far.

An efficient tactic for spotting extraterrestrial events in the stratigraphic record was elaborated

by Farley (1995), who used cosmogenic ^3He concentrations in pelagic sediments of a deep-sea drill core spanning the past 70 m.y. to trace variations in the flux of interplanetary dust particles, which were probably related to asteroidal breakup events or the passage of comets through the inner solar system. As a tracer of extraterrestrial dust flux, ^3He proved to be more sensitive and much easier to measure than iridium or other platinum group elements (PGEs; e.g., Alvarez et al., 1990). This approach was applied by Farley et al. (1998) to the on-land section at Massignano, in the easternmost part of the Umbria-Marche paleobasin, which represents the global stratotype section and point (GSSP) for the base of the Rupelian Stage (Premoli Silva and Jenkins, 1993). The result was the identification of elevated ^3He concentrations up to 10 times higher than background in a stratigraphic interval spanning ~ 1.3 m.y. This interval contained three thin limestone horizons with anomalous Ir concentrations (Montanari et al., 1993; Bodiselitsch et al., 2004). The ^3He anomaly was originally interpreted by Farley et al. (1998) as the signature of a comet shower, whereas Tagle and Claeys (2004) subsequently argued that the anomaly was possibly the result of an asteroidal bombardment. While Fritz et al. (2007) proposed that a late Eocene asteroid shower to the Earth-Moon system resulted in an increased flux of impact-ejected ^3He -rich lunar matter to Earth, Kyte et al. (2011) argued that the absence of relatively large ^{54}Cr excesses in impact spherules from the Upper Eocene Massignano section and in the coeval Ocean Drilling Program (ODP)

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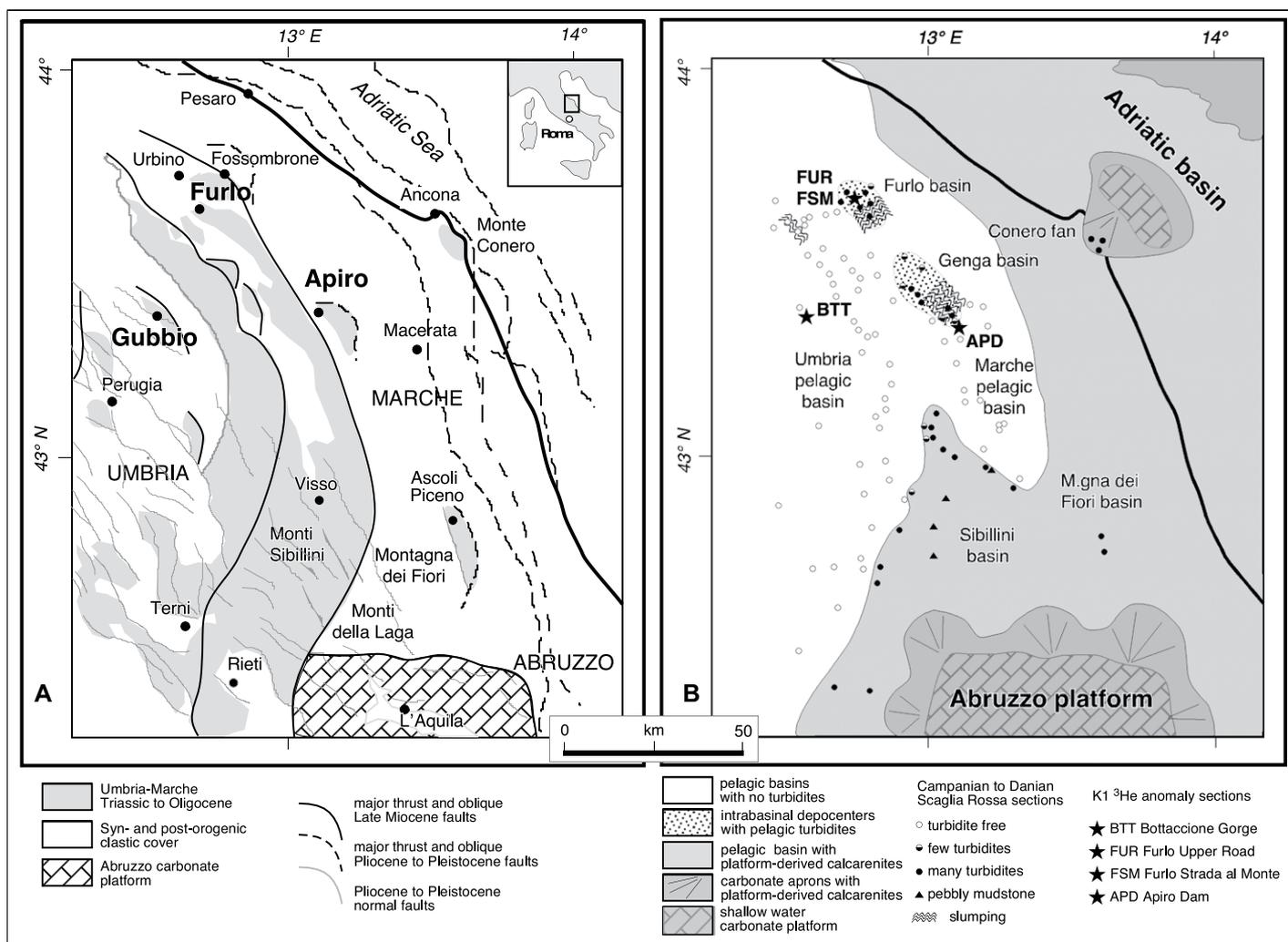


Figure 1. (A) Simplified tectonic map of the Umbria-Marche Apennines. (B) Simplified Upper Cretaceous Scaglia Rossa basin with location of the studied sections containing the ³He anomaly K1 and the early Campanian event (ECE). APD—Apiro Dam section; BTT—Bottaccione section; FSM—Furlo Strada al Monte section; FUR—Furlo upper road section.

Hole 709C (western Indian Ocean) suggested that the multiple impacts and dust deposition in the late Eocene were more likely caused by disruption of a large asteroid in the inner asteroid belt, rather than a comet shower.

Whatever extraterrestrial process was at the origin of the Upper Eocene ³He anomaly, the success of the investigation at Massignano encouraged a systematic search for extraterrestrial ³He signatures back in time through the pelagic carbonate succession of the classic Bottaccione section at Gubbio, from the middle Eocene down to the early Maastrichtian (Mukhopadhyay et al., 2001). In this 35-m.y.-long span of time (Fig. 2), Mukhopadhyay et al. (2001) found small variations of ³He concentrations, which were inconsistent with a long-term comet shower, as was initially hypothesized for the Upper Eocene case of Massignano, but rather more consistent with the faint signatures

of collisions in the asteroid belt and/or the Kuiper belt. The next step was to extend the search farther back in time down through the Bottaccione section to the basal Cenomanian (ca. 100 Ma), tracing the flux of extraterrestrial dust using cosmogenic ³He (Farley et al., 2012). The result of that study was the identification of three ³He anomalies located in the Lower Campanian (ca. 80 Ma), mid-Santonian (ca. 84.5 Ma), and mid-Turonian (ca. 92 Ma), which were named K1, K2, and K3, respectively (Fig. 2). While K2 was modest in magnitude and duration and thus was of limited significance, K1 and K3 were each spread through a few-million-year interval with an ~4-fold increase in mean ³He flux compared with pre-event levels. The K1 and K3 ³He anomalies were similar in most respects (i.e., shape, amplitude, and duration) to two anomalies previously detected in a Cenozoic deep-sea core by Farley (1995), who also suggested that

they represented a major asteroid collision in the late Miocene (i.e., the Veritas asteroidal breakup; Montanari et al., 2017, and references therein).

An interesting aspect of the mid-Turonian K3 anomaly was its close coincidence with an important $\delta^{13}\text{C}$ negative excursion originally determined by Stoll and Schrag (2000) in the Contessa Valley section near Gubbio. Montanari et al. (2017) proposed that there might have been a cause-and-effect relationship between the K3 ³He anomaly and the $\delta^{13}\text{C}$ negative shift. An increased flux of ³He-rich interplanetary dust for a long period of time, on the order of hundreds of thousands of years, which probably was accompanied by a myriad of small meteorite impacts, may have triggered a climate change event by altering the transparency of the atmosphere. In a Lyellian actualistic perspective, i.e., “the present is the key to the past,” if a small atmospheric impact by a 50- to 60-m-diameter meteor

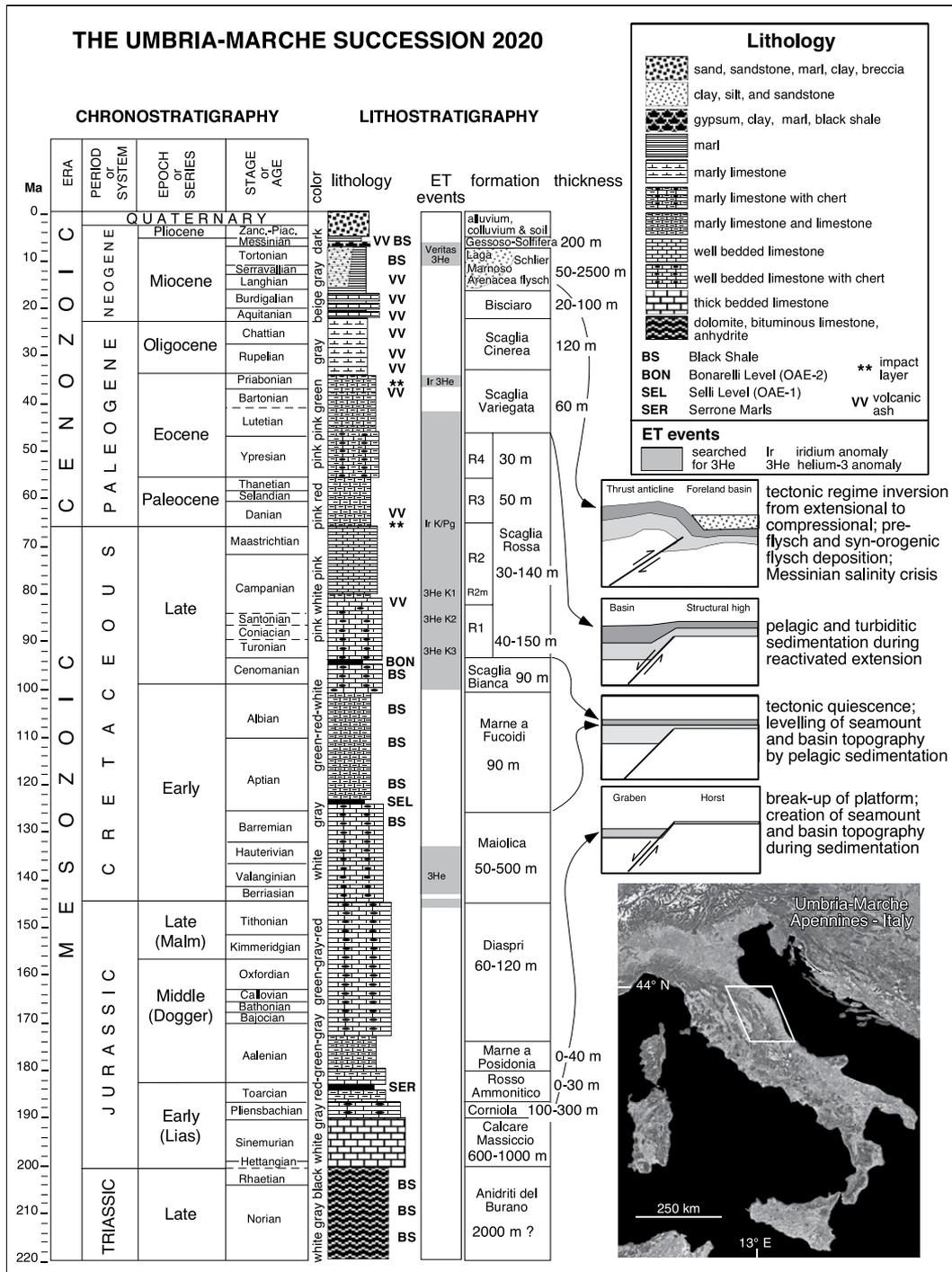


Figure 2. Synoptic stratigraphic model of the Umbria-Marche succession with the intervals searched for ³He by Farley et al. (1998, Upper Eocene at Massignano), Moukhopadhyay et al. (2001, Upper Cretaceous and Lower Paleogene at Gubbio), Farley et al. (2012, Upper Cretaceous at Gubbio), Montanari et al. (2017, Upper Miocene at Monte Conero), and Farley et al. (in progress, Lower Cretaceous in the Maiolica Formation at Monte Catria). ET—extraterrestrial; K/Pg—Cretaceous-Paleogene; LEMIE—late Eocene multiple impact events; OAE—oceanic anoxic event.

air burst at Tunguska in 1908 (eastern Siberia) caused a measurable decrease in atmospheric transparency over most of the Northern Hemisphere (Turco et al., 1982), which lasted a few years after the event, then a sudden increased flux of ³He-rich interplanetary dust coupled with many small meteorite impacts, which lasted for hundreds of thousands of years, may have triggered a climate change at a global scale. The biological-ecological response to such climate

change would have led to an alteration of the carbon cycle and a change in the isotopic fractionation in the oceans, which, ultimately, would be recorded in pelagic carbonate sediments as a $\delta^{13}\text{C}$ negative shift. A similar extraterrestrial ³He anomaly closely coincident with a $\delta^{13}\text{C}$ negative excursion was observed in the Miocene reference section of Monte dei Corvi near Ancona (Hüsing et al., 2007) and attributed to the late Tortonian (ca. 8.5 Ma) Veritas asteroidal

breakup by Montanari et al. (2017) (see it plotted in Fig. 2). However, the original suggestions by Farley et al. (2012) of a relation to a comet or asteroid shower possibly associated with dust-producing lunar impacts are not supported by the detailed study of Martin et al. (2019) on the K3 interval in the same Bottaccione section. Their preliminary analysis of spinel micrometeorite count and composition suggested a more general disturbance of the asteroid belt, where different

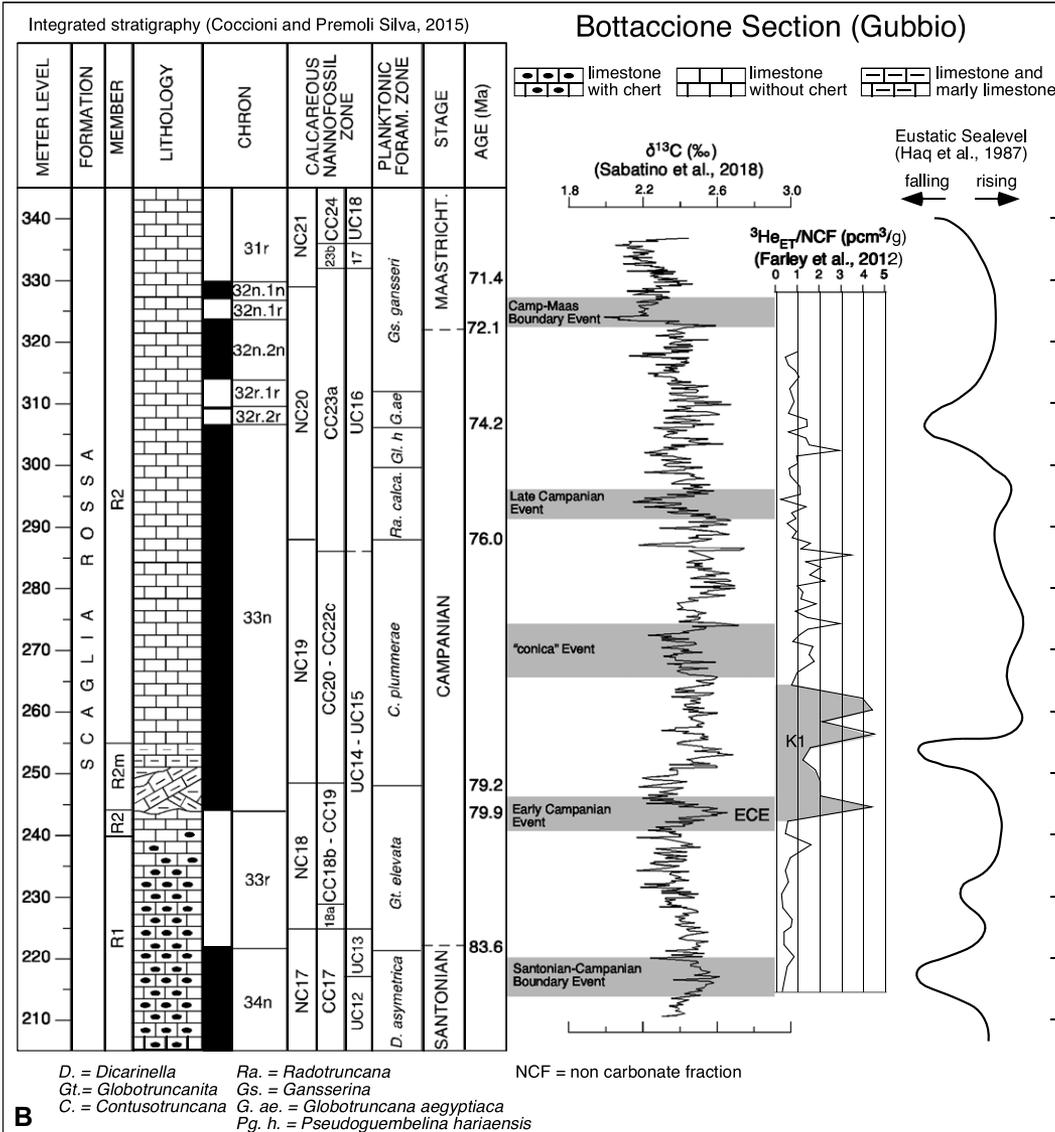
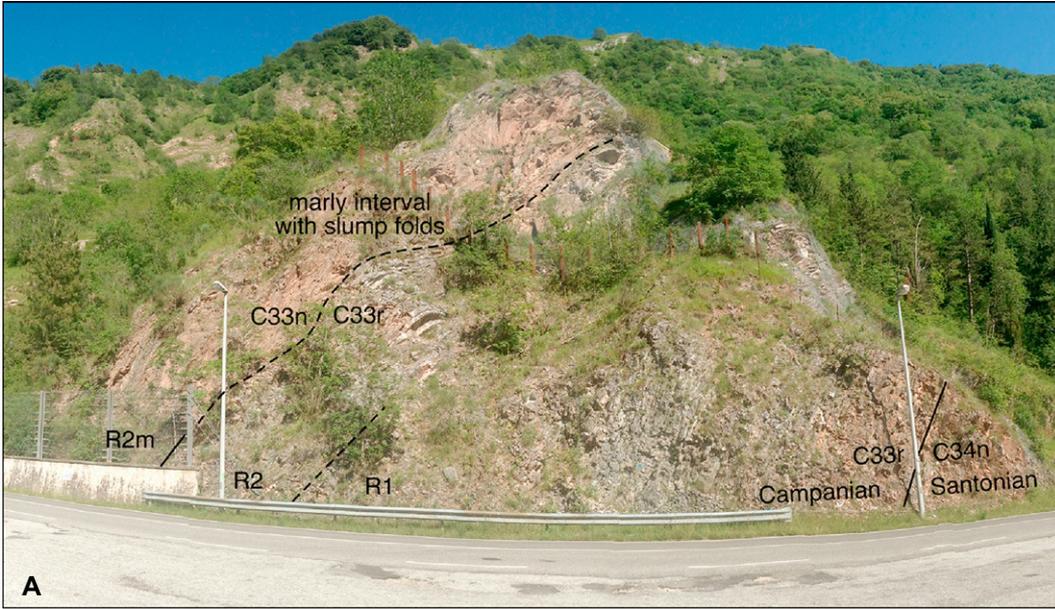


Figure 3. (A) Panoramic view of the Campanian Bottaccione section (43°21'44"N; 12°34'58"E; 560 m above sea level). (B) Lithostratigraphy, biostratigraphy, and magnetostratigraphy of the Bottaccione Upper Cretaceous section at Gubbio, with locations of the main carbon isotopic events and the K1 extraterrestrial ³He (³He_{ET}) anomaly. ECE—early Campanian event; Maas—Maastrichtian.

parent bodies or source regions of micrometeorites were affected at the same time.

As for the K1 ^3He anomaly, Farley et al. (2012) did not elaborate much on the interpretation of this event, mainly because the Lower Campanian interval in the Bottaccione section was disturbed by soft-sediment deformation, which may have been associated with a missing section due to slumping or synsedimentary faulting (Fig. 3A). However, Farley et al. (2012) did suggest that the

K1 ^3He anomaly may have been the record of a collision in the asteroid belt that gave birth to the Baptistina family of asteroids some 80 m.y. ago (Masiero et al., 2011), thus exactly at the time of the K1 ^3He anomaly located at the C33r-C33n chronal boundary (Fig. 2). Just one year later, Masiero et al. (2012) recalculated the breakup time of Baptistina on the basis of new astronomical data, defining a best-fitting age anywhere in the range of 320–140 Ma, thus much older than

the early Campanian age of K1. Nevertheless, Sabatino et al. (2018) found an important $\delta^{13}\text{C}$ excursion right in that Lower Campanian interval of the same Bottaccione section (Fig. 3B), which was referred to as the early Campanian event, and they correlated it with a similar excursion in a coeval section in northern Germany (Voigt et al., 2010), and in a borehole core at Norfolk, UK (Jarvis et al., 2002). Therefore, we engaged in a quest for the K1 ^3He anomaly in other com-

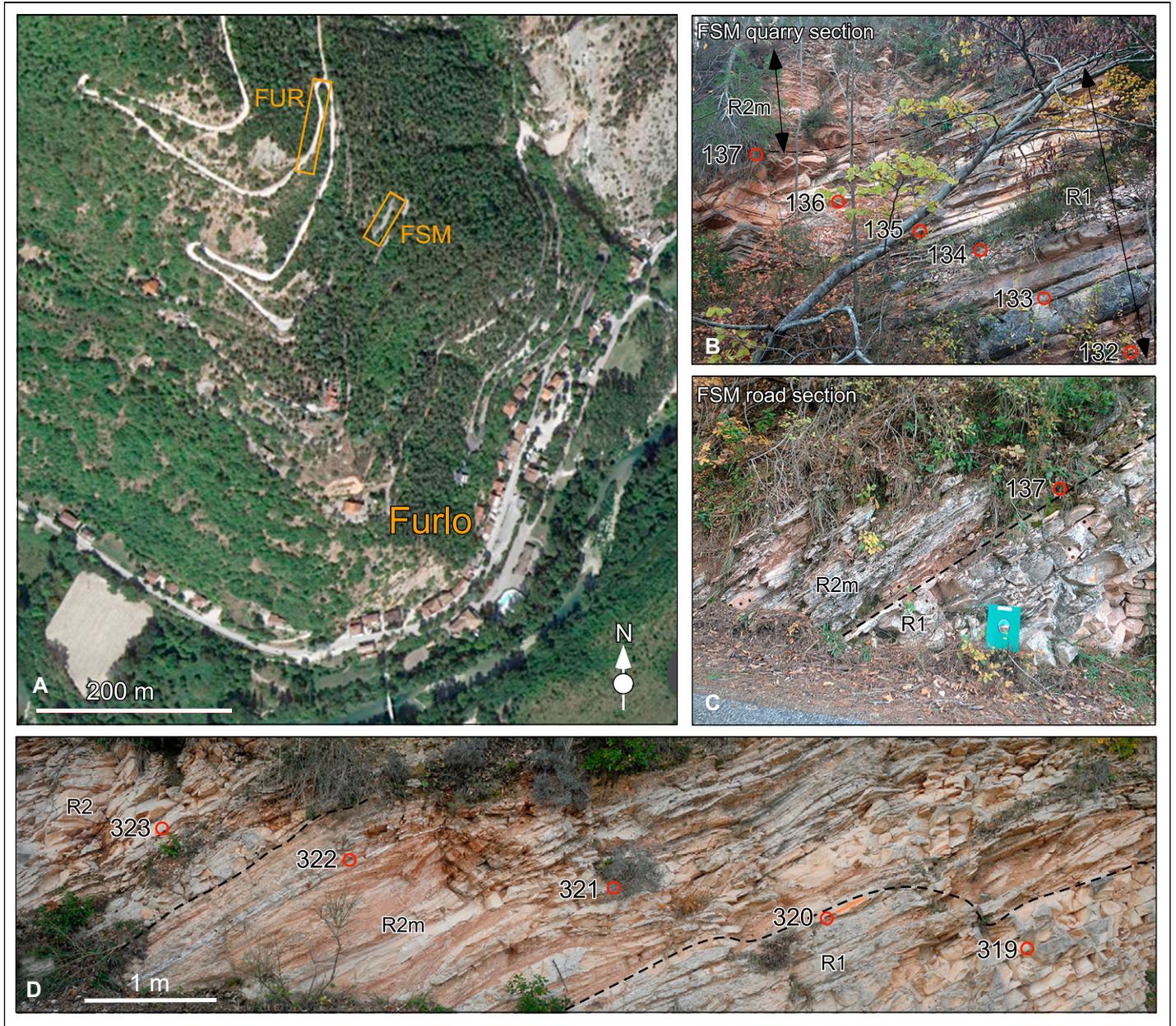


Figure 4. (A) Aerial photograph of the village of Furlo and locations of the two studied sections, Furlo Strada al Monte (FSM) and Furlo upper road (FUR) ($48^{\circ}38'25''\text{N}$; $12^{\circ}42'37''\text{E}$; 380 m above sea level). (B) View of the quarry face of the FSM section, with indicated meter levels (note the undisturbed marly unit R2m up high on the quarry face with the base at meter level 137). (C) Road outcrop just outside the quarry FSM with the contact between the R1 and the R2m members of the Scaglia Rossa indicated at meter level 137. (D) Partial road-cut exposure of the R2m unit in the FUR section. Note soft-sediment deformation within the marly unit.

plete and continuous Lower Campanian sections throughout the Umbria-Marche paleobasin. The search was facilitated by the fact that the K1/early Campanian event interval is located in the transition between the chert-bearing R1 and the chert-free R2 lithologic members of the Scaglia Rossa Formation, which can be recognized easily in the field (Fig. 2). Ultimately, two workable sections were identified at Furlo (Alvarez et al., 1985), and near Apiro, some 50 km east from Gubbio (Mitchell et al., 2021), and these were chosen for a high-resolution integrated stratigraphic analysis, including biostratigraphy, magnetostratigraphy, stable isotope, and ^3He analyses, to identify the relationship between the extraterrestrial K1 event and the isotopic excursion of the early Campanian event.

GEOLOGIC AND STRATIGRAPHIC SETTING

Scaglia Rossa Paleobasin

The pelagic carbonates of the Scaglia Rossa Formation of the Umbria-Marche paleobasin were initially deposited in the earliest Turonian following the resumption of tectonic activity after an ~ 30 -m.y.-long period of tectonic quiescence (Fig. 2). This activity consisted of the reactivation of buried normal faults under a regional regime of crustal extension, which caused some parts of the paleobasin to subside to form intrabasinal depocenters such as the Furlo Basin and the Genga Basin (Fig. 1B). It was in these depocenters that biocalcarenic seismo-turbidites made up of remobilized pelagic ooze were deposited in thickening-upward sequences culminating in the Danian (earliest Paleocene), whereas the unstable margins of these depocenters, bounded by active normal faults, generated soft-sediment slumps (Alvarez and Lowrie, 1984; Alvarez et al., 1985; Chan et al., 1985; Montanari, 1988; Montanari et al., 1989; Bice et al., 2007; Tognaccini et al., 2019; Alvarez, 2019, and references therein). In contrast, other areas surrounding these depocenters, such as the Umbria Basin and the Marche Basin, remained practically unaffected by this seismogenic activity, and they continued to collect pelagic sediment essentially made up of coccoliths and planktonic foraminifera with a minor component of eolian terrigenous material (e.g., Sinnesael et al., 2016), with no influx of calcarenitic turbidites.

The first thickening-upward turbiditic cycle culminated in the early Campanian (~ 80 m.y. ago; e.g., Bice et al., 2007), and it is marked by a distinctive marly unit called R2m (Montanari et al., 1989), which is often associated with soft-sediment deformation and synsedimentary faulting, even in areas of the paleobasin that lack

turbidites (e.g., Gubbio; Fig. 3A). The K1 ^3He anomaly of Farley et al. (2012) and the early Campanian isotopic event of Sabatino et al. (2018) occur in correspondence with this R2m unit. However, the classic Bottaccione section at Gubbio is affected by a stratigraphic discontinuity right at the base of the R2m unit due to a synsedimentary fault, and the marly unit itself exhibits soft-sediment deformation features (Fig. 3A).

Furlo Sections

The Furlo Upper Road (FUR) section is almost continuously exposed along a limestone quarry road, which merges with a zig-zag mountain road of the State Natural Reserve of the Furlo Gorge just above the village of Furlo (Fig. 4A). The FUR section spans from the Upper Cenomanian Scaglia Bianca Formation to the lowermost Danian R3 member of the Scaglia Rossa Formation, and it was first studied by Alvarez and Lowrie (1984), who defined a detailed magnetostratigraphy from the middle of chron C34n to upper chron C31n, which permitted a correlation to be made with the biostratigraphic-magnetostratigraphic reference section of the Bottaccione Gorge at Gubbio (Alvarez et al., 1977). The portion of the section on which we concentrated (indicated in Fig. 4A) stretched from 308 m to 360 m based on some still-visible meter marks painted with light blue enamel on the outcrop by Alvarez and Lowrie (1984). The Furlo Strada al Monte (FSM) section, instead, started at meter level 100, right at the second switchback down the road from FUR (indicated in Fig. 4A), in correspondence with a 15-cm-thick bentonite layer (Mattias et al., 1989; Galeotti et al., 2002), which yielded a U-Pb zircon age of 81.4 ± 0.3 Ma (Bernoulli et al., 2004). In the FSM section, the marly R2m unit is well exposed high up on the face of a small abandoned quarry (Fig. 4B), and its base crops out along a road cut just outside the quarry (Fig. 4C). In the FUR section, the R2m unit is exposed from ~ 315 m to 322.4 m (Fig. 4D), but it is displaced by a few synsedimentary faults, which put it in contact with the underlying R1 member, whereas the upper part contains soft-sediment deformation features up to 325 m. Correlation between the two sections was only possible on the basis of lithology, i.e., by recognizing turbidite markers, whether amalgamated, thick or thin, or associated with chert nodules, as shown in the lithologic logs in Figure 5.

Apiro Dam Section

The Scaglia Rossa Formation is almost continuously exposed along the provincial road that runs along the Castreccioni Reservoir, a few kilometers southeast of the town of Apiro (for

location, see Figs. 1A, 1B, and 6A). A detailed biostratigraphic-magnetostratigraphic characterization of this section (APD) was determined by Mitchell et al. (2021), who recognized the chronal boundary C33r-C33n precisely at 110 m within the upper part of the planktonic foraminiferal *Globotruncanita elevata* zone (Fig. 6B). This section is characterized by massive beds of the typically pink, homogeneous limestones, which are free of the plane-parallel pressure-solution stylolites that normally define a characteristic "pseudobedding" (Alvarez et al., 1985; Sinnesael et al., 2016, 2019). This turbidite- and slump-free section is devoid of faults, and it lacks the marly interval R2m, which is otherwise present in the Gubbio and Furlo sections.

MATERIALS AND METHODS

Planktonic Foraminiferal Biostratigraphy

Bulk-rock samples of ~ 200 g were collected through the Furlo Upper Road (FUR) section from 315.00 m to 363.00 m with an average spacing of ~ 1 m for planktonic foraminifera biozonation, which was carried out following the methods and techniques described in Cocconi et al. (2022).

Carbon Isotopes

Bulk-rock samples were collected from: (1) the Furlo Strada al Monte (FSM) section from 114.00 m to 132.25 m with an average spacing of $\sim 50 \pm 25$ cm but with a nonsampled interval of ~ 12 m from 117.00 m to 129.52 m, (2) the Furlo Upper Road (FUR) section continuously from 315.00 m to 363.00 m with an average spacing of ~ 1 m, and (3) the Apiro Dam (APD) section from 101.04 m to 115.76 m across the C33r-C33n chronal boundary located at 110 m, with an average spacing of $\sim 70 \pm 50$ cm, for a total of 22 samples.

Stable isotope measurements of $\delta^{13}\text{C}$ (in permil [‰] relative to Vienna Peedee belemnite [VPDB]) and $\delta^{18}\text{O}$ (‰, VPDB) were carried out on bulk-rock samples for sample series FUR16 and FSM16 at the Vrije Universiteit Brussel using a dual-inlet Nu Perspective isotope ratio mass spectrometer (IRMS) interfaced with a Nu Carb automated carbonate device for highly sensitive, ultraprecise isotopic measurements in an automated, high-throughput workflow. Acidification of the samples occurred at a temperature of 70 °C. Corrections were carried out using the in-house standard MAR-2, which is made of Marbella limestone and has been calibrated against the international standard NBS-19. On the basis of replicate measurements on standards and sampled material, the reproducibility of the

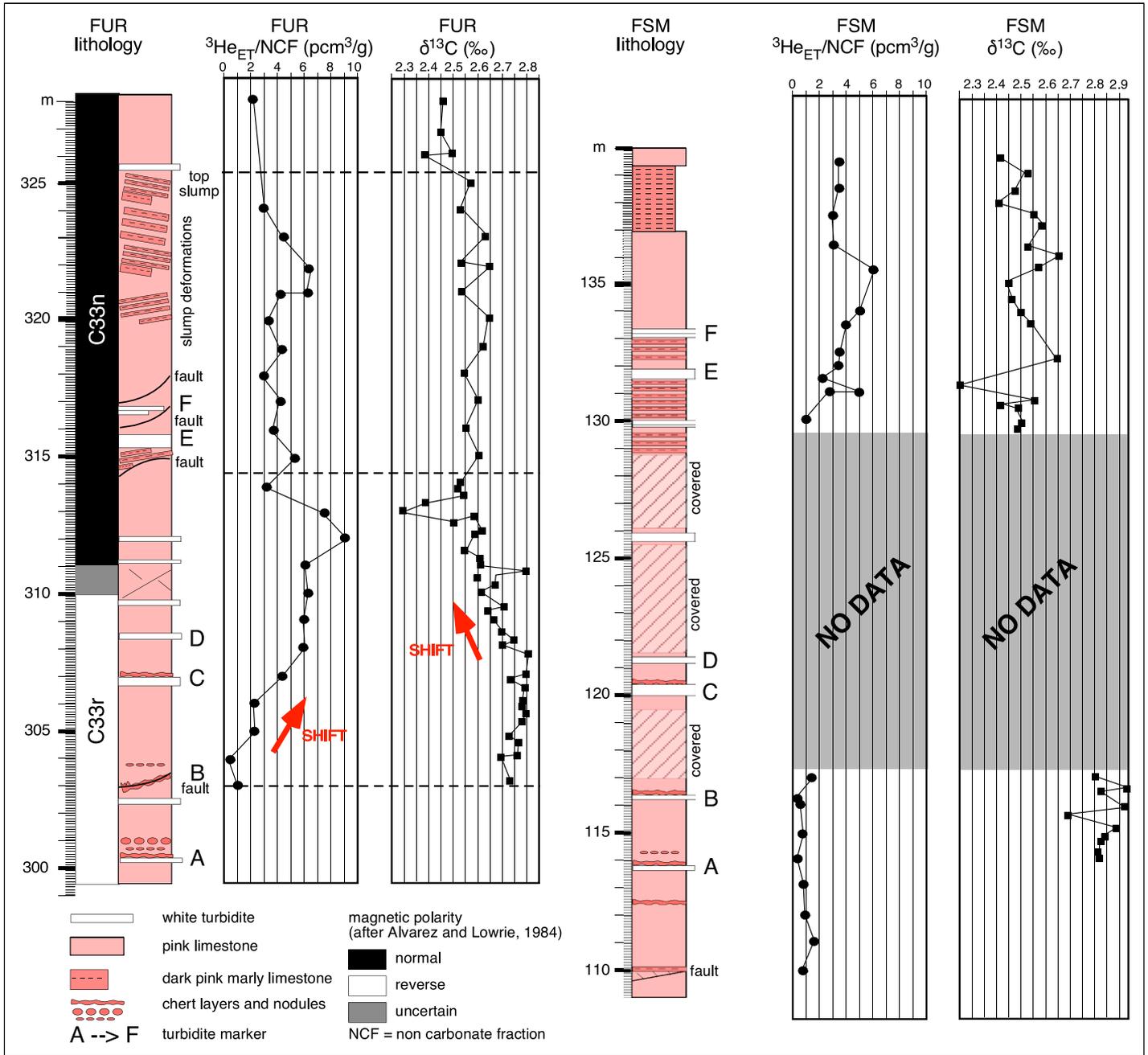


Figure 5. Correlation between the Furlo upper road (FUR) and Furlo Strada al Monte (FSM) sections based on lithology, extraterrestrial ³He, and carbon isotopes.

carbon isotope measurements was estimated at 0.05‰ (1σ). Results are shown in Table S1 in the Supplemental Material¹.

Bulk carbonate stable isotope analyses for the APD section were carried out with an automated continuous-flow carbonate preparation

GasBench II device (Spötl and Vennemann, 2003) and a Thermo Electron Delta V mass spectrometer at the Istituto per lo Studio degli Impatti Antropici e Sostenibilità in Ambiente Marino–Consiglio Nazionale delle Ricerche (IAS-CNR; Capo Granitola) isotope geochemistry laboratory. Acidification of samples was performed at 60 °C. An internal standard (Carrara marble with δ¹³C = +2.43‰ versus VPDB) was run every six samples. Reproducibility of replicate standards was better than 0.06 for carbon

isotope measurements. All the isotope data are reported in per mil versus VPDB. The analytical results are shown in Table S1 in the Supplemental Material.

Helium Isotopes

Helium isotope analyses on bulk-rock samples from the Furlo sections FSM and FUR and the APD section were performed at the California Institute of Technology (Pasadena, Califor-

¹Supplemental Material. Tables S1 and S2. Please visit <https://doi.org/10.1130/GSAB.S.23638836> to access the supplemental material, and contact editing@geosociety.org with any questions.



Figure 6. (A) Aerial photograph of the town of Apiro and its Castreccioni reservoir, with location of the Apiro Dam (APD) section indicated ($43^{\circ}22'51''\text{N}$; $13^{\circ}09'17''\text{E}$; 360 m above sea level). (B) Fisheye photograph of the APD section with the lithostratigraphic boundary between the Scaglia Rossa members R1 and R2 and the boundary between chrons C33r and C33n indicated. Note the absence of the marly unit R2m.

nia) following the method of Mukhopadhyay et al. (2001). The analytical results are shown in Table S2.

Cyclostratigraphic Analysis

Previous studies on the Scaglia sequence of pelagic limestones throughout the Umbria-Marche basin have shown that magnetic susceptibility (or biogenic carbonate as its inverse proxy) is a reliable recorder of Milankovitch orbital cycles (Brown et al., 2009; Husson et al., 2014; Galeotti et al., 2015; Sinnesael et al., 2016, 2018; Batenburg et al., 2016; Coccioni et al., 2022). For the present study of the Lower Campanian sections of Scaglia Rossa limestones at

Furlo, we used a portable masonry drill to collect powdered samples every 5 cm. Magnetic susceptibility measurements were then carried out at the Osservatorio Geologico di Coldigioco on a Bartington MS2B dual-frequency sensor at low frequency (0.465 kHz) and $0.1\times$ sensitivity. Samples were measured at a constant volume, and their masses were noted. Air measurements were made between samples to correct for thermally induced drift.

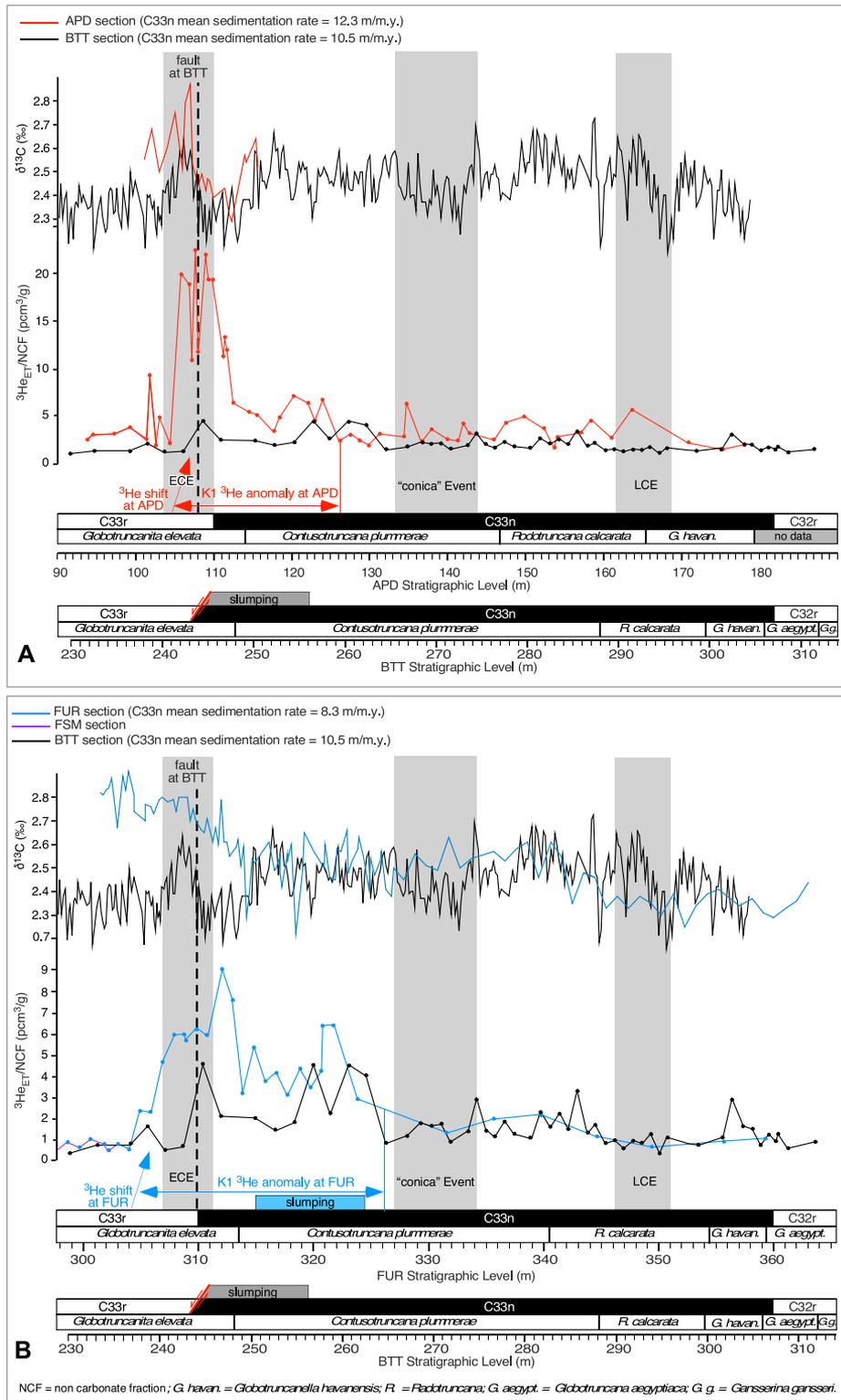
In some areas of the Umbria-Marche basin, and in particular at Furlo (Fig. 1B), the Scaglia Rossa pelagic limestones contain a series of calcarenitic turbidites related to episodic syndimentary seismic events (Montanari et al., 1989; Bice et al., 2007). These turbidites are intraba-

sinal in origin, i.e., derived from slope failure of the Scaglia Rossa unconsolidated calcareous ooze. The fluidization, transport, and deposition of these turbidites resulted in a sorting of the pelagic carbonates, with the sand-sized foraminifera comprising the A through D Bouma divisions and the coccolith mud forming the Bouma E division. The A–D parts of the turbidites are readily visible in outcrop, since they are essentially devoid of the fine hematite grains that give the Scaglia Rossa its characteristic salmon-pink color, but the E parts of the turbidites are more subtle and can only be recognized by their lack of foraminifera. These turbidites present a challenge for cyclostratigraphic analysis because they represent essentially instantaneous additions of sediment to the sequence. The turbidites must be excised before undertaking any kind of time-series analysis, but these turbidites may also have involved some amount of erosion just before the deposition—many of them have flute casts on the bottom, suggesting some amount of erosion.

Our method for dealing with the turbidites began with careful analysis of each turbidite in the field to identify the Bouma E divisions and then subtraction of these thicknesses from the overall sequence. Then, we experimented with varying amounts of erosion for each turbidite. This amounted to adding thickness to the section, ranging from 0 to the full thickness of the turbidite. When we added material that may have been eroded, the MS data were simply interpolated between the top and bottom of the turbidite.

If we assume that the magnetic susceptibility faithfully records Milankovitch cycles, then when we properly restore the section by removing the turbidites and adding eroded material, we should see the Milankovitch cycles clearly represented in the spectral analysis. For each of the three sections we studied at Furlo, we iterated through all combinations of eroded thicknesses until we found the best spectral representation of Milankovitch cycles. The lower FSM section had just one turbidite, while the upper FSM section had two, and the FUR section had six turbidites.

For the spectral analyses presented here, we used a set of Matlab algorithms and routines modified from Muller and MacDonald (2000) that essentially calculate a periodogram (after detrending and padding with zeros) with normalized spectral power. This approach has been shown to precisely detect weak signals embedded in noise (Bice et al., 2012). We evaluated the statistical significance of the spectral peaks by calculating a 95% confidence level from a Monte Carlo noise simulation. In this approach, 1000 random number sets with the same dimensions as the magnetic susceptibility data were gener-



rising above this 95% confidence level were considered to be statistically significant. We also used band-pass filters with Gaussian windows to extract the signal components corresponding to the Milankovitch cycles in order to compare them with the raw data.

RESULTS

Carbon Isotope Geochemistry

Carbon isotope values for the FUR and APD sections are reported in Table S1 and shown in Figures 5 and 7. In the FUR section (Figs. 5 and 7B), the $\delta^{13}\text{C}$ values oscillate around a mean value of $\sim 2.5\text{‰}$. In its lower part, the early Campanian event is not as well defined as in the Bottaccione section. Then, the $\delta^{13}\text{C}$ profile shows a slight negative trend from 307 m to 317 m. Small oscillations around a mean value of 2.5‰ persist throughout the interval between 318 m and 363 m. In the APD section, the $\delta^{13}\text{C}$ values of the studied interval reproduce the signature of the early Campanian event obtained in the Bottaccione section by Sabatino et al. (2018).

Extraterrestrial Helium

The ^3He values for the FUR and APD sections are reported in Table S2 and shown in Figures 5 and 7. In the FUR section, the extraterrestrial ^3He ($^3\text{He}_{\text{ET}}$) profile shows higher values (up to $9.05 \text{ pcm}^3/\text{g}$) in the stratigraphic interval between 307 m and 324 m. Small oscillations around a mean value of 1.67‰ persist throughout the interval between 324 m and 360 m. In the APD section, the $^3\text{He}_{\text{ET}}$ background values oscillate between $1.4 \text{ pcm}^3/\text{g}$ and $9.0 \text{ pcm}^3/\text{g}$, with a prominent peak up to $22.6 \text{ pcm}^3/\text{g}$ in the stratigraphic interval between 105.86 m and 111.74 m.

Milankovitch Cyclostratigraphic Analysis

Lower FSM Section

The mean sedimentation rate for the whole 430-m-thick Scaglia Rossa limestone at Furlo, from the Bonarelli Level (oceanic anoxic event 2) up to the Cretaceous-Paleogene boundary, is $\sim 10 \text{ m/m.y.}$ (Alvarez and Lowrie, 1984). The section designated here as lower FSM spans $\sim 7 \text{ m}$, and with an approximate sedimentation rate of 10 m/m.y. , it represents roughly 700 k.y. of time before the onset of the K1 extraterrestrial ^3He pulse, which is not clearly visible in this section. This section contained just one turbidite (Fig. 8), and we experimented with varying amounts of eroded material, up to the entire thickness of the turbidite. Figure 9 shows four representative FFTs of the magnetic susceptibil-

Figure 7. Extraterrestrial (ET) ^3He and $\delta^{13}\text{C}$ isotopic records of the (A) Apiro Dam (APD) section and (B) Furlo upper road (FUR) section, as compared with the Bottaccione (BTT) section. ECE—early Campanian event; LCE—late Campanian event.

ated and then run through a fast Fourier transform (FFT) to find the spectral power at each frequency. The 95% confidence level was estimated

from these 1000 spectral results by calculating three times the mean power value for each frequency (Muller and MacDonald, 2000). Peaks

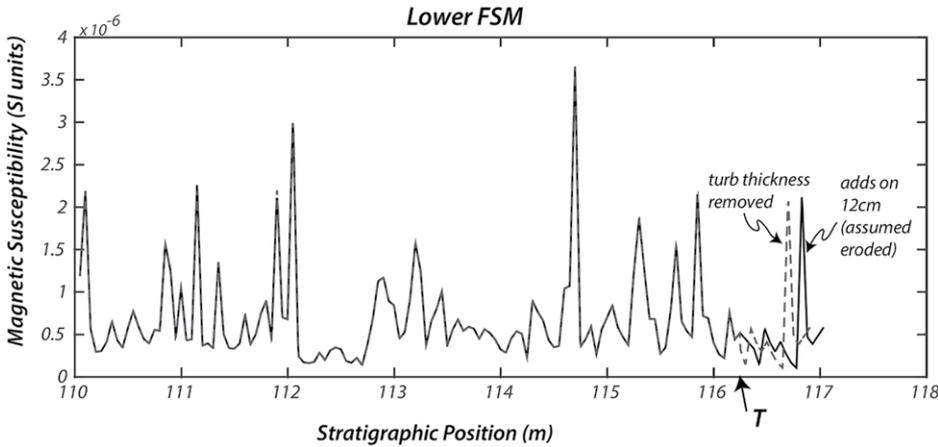


Figure 8. Magnetic susceptibility (MS) data from the lower Furlo Strada al Monte (FSM) section showing the location of a turbidite (T) at about meter level 116.3. Dashed line shows the remaining data if we simply cut out the turbidite thickness; this implies that no erosion accompanied the emplacement of the turbidite. Solid line extending above the turbidite shows a model case where we assume that 12 cm of material was eroded during the emplacement of the turbidite, so we restore this eroded material, which pushes the remaining data to higher stratigraphic levels. Magnetic susceptibility data are interpolated across this new 12 cm of section.

ity data from this section, each of which represents an assumption about how much material was eroded: 0 cm, 2 cm, 8 cm, and 12 cm (the turbidite is 15 cm in thickness). We selected the best version based on how well the significant spectral peaks matched the expected periods or orbital variations, which, according to Laskar et al. (2004), are 124 k.y. and 95 k.y. for short eccentricity, 38 k.y. for obliquity, and 23 k.y. and 20 k.y. for precession. As can be seen in Figure 9, the model with 12 cm of eroded material does the best in terms of matching these expected spectral peaks and minimizing some of the other peaks (the ones with periods of 0.48 m, 0.29 m, and 0.25 m) that do not correspond to orbital cycles.

We used a series of band-pass filters to isolate the components that best corresponded to the Milankovitch cycles and then added these together for the purpose of comparing them with the raw magnetic susceptibility data (Fig. 10). In this experiment, the band-passed data closely matched the raw data with very few mismatches in the peaks and troughs, suggesting that this section records the orbital cycles with good fidelity.

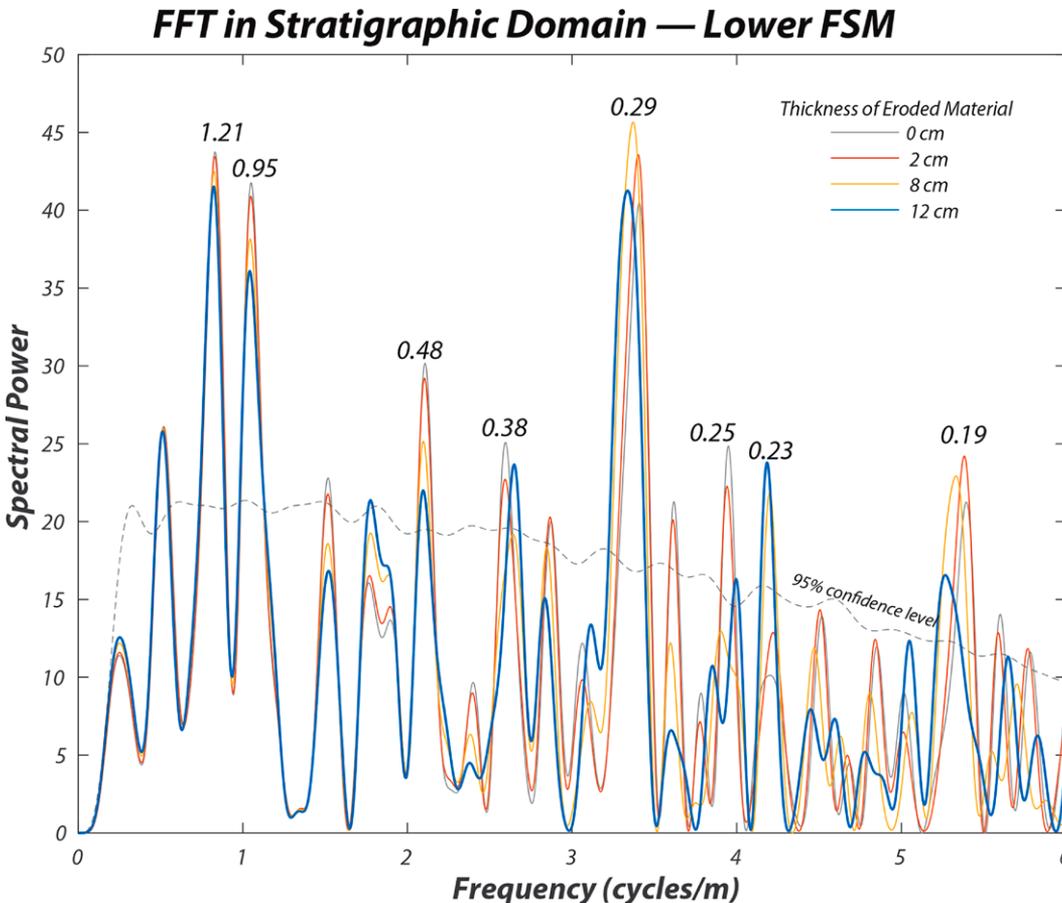


Figure 9. Fast Fourier transform (FFT) spectra for the lower Furlo Strada al Monte (FSM) magnetic susceptibility (MS) data using different erosion assumptions or models of how much erosion accompanied the emplacement of the turbidite; just a few of the spectra are shown here to illustrate how we chose the best model. Also shown is the 95% confidence level based on a Monte Carlo noise simulation. These spectra are in the stratigraphic domain, so the frequency is in cycles/m; prominent peaks are labeled with their periods (really wavelengths), which are in meters. The expected sedimentation rate for this section is ~ 10 m/m.y., which means that a spectral peak with a wavelength of 0.95 m would have a period of 95 k.y. The preferred model is the one with 12 cm of erosion because its spectrum has significant peaks with the periods expected for Milankovitch cycles (1.21, 0.95, 0.38, 0.23, and 0.19 m, correspond-

ing to 121, 95, 38, 23, and 19 k.y.), and it minimizes the spectral peaks at the unexpected periods (0.48, 0.29, 0.25 m).

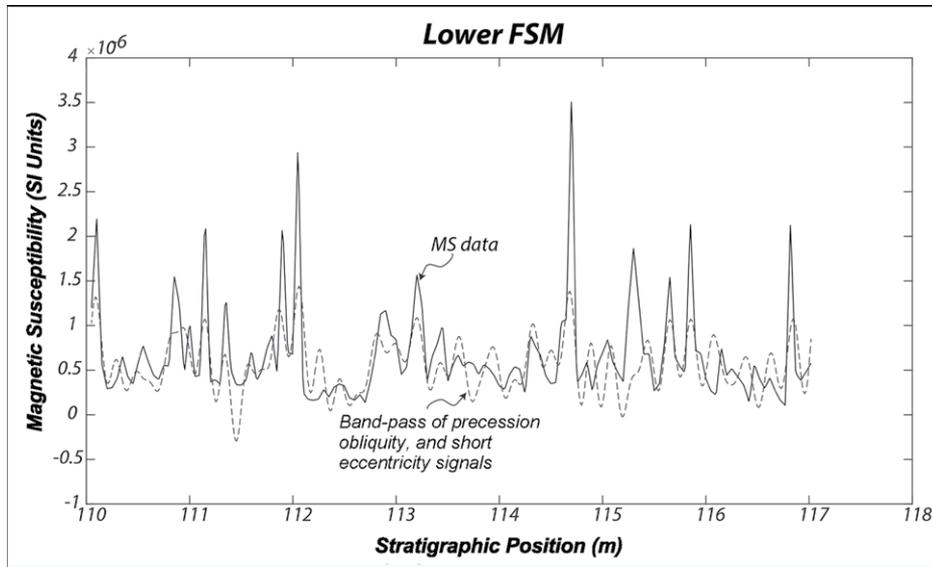


Figure 10. Lower Furlo Strada al Monte (FSM) magnetic susceptibility (MS) data, in solid black, compared with a band-passed composite representing the short eccentricity, obliquity, and precession signals. The MS data include an assumed 12 cm of erosion associated with the one turbidite in this section. The very close agreement between the band-passed signal and the raw data indicate that during this time period, the MS data closely record the orbital cycles.

Upper FSM Section

The upper FSM section spans ~ 3 m, and with an approximate sedimentation rate of 10 m/m.y., it represents roughly 300 k.y. of time that presumably postdates the K1 extra-

terrestrial ^3He shift. This section contained two turbidites, designated as T1 (25 cm thick) and T2 (35 cm thick) in Figure 11. We experimented with varying amounts of eroded material, up to the entire thickness of each turbidite. Figure 12

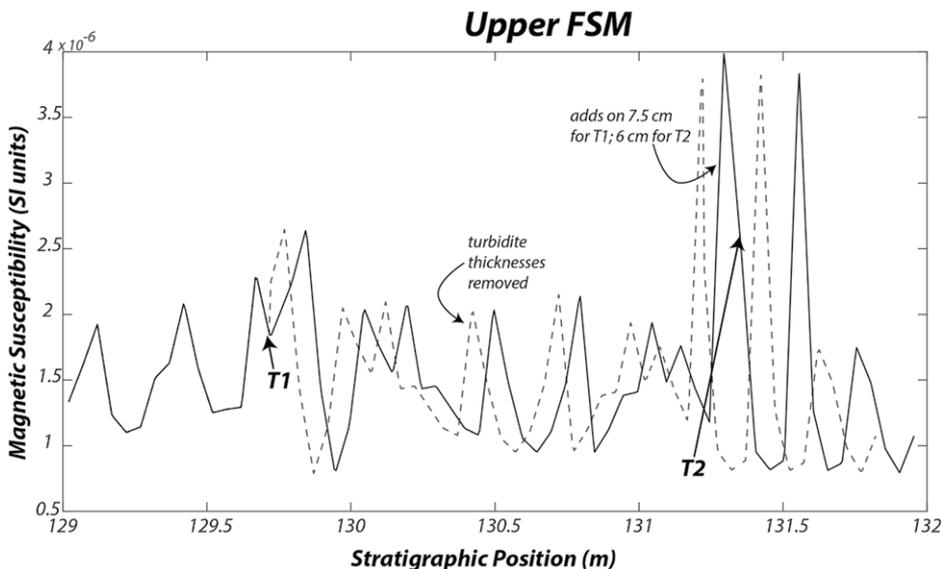


Figure 11. Magnetic susceptibility (MS) data from the upper Furlo Strada al Monte (FSM) section, showing the locations of two turbidites (T1 and T2). Dashed line shows the MS data if we simply cut out the turbidite thicknesses; this implies that no erosion accompanied the emplacement of the turbidite. Solid line extending above T1 shows a model where we assume that 7.5 cm of material was eroded during the emplacement of T1 and 6 cm of erosion was associated with T2. Spectra for both of these models are shown in Figure 12.

shows two FFTs of the magnetic susceptibility data from this section; one represents an assumption of no erosion, and the other assumes 7.5 cm of erosion for T1 and 6 cm of erosion for T2 (the turbidite is 15 cm in thickness). This second version was selected as the best version based on how well the significant spectral peaks matched the expected periods or orbital variations, which, according to Laskar et al. (2004), are 124 k.y. and 95 k.y. for short eccentricity, 38 k.y. for obliquity, and 23 k.y. and 20 k.y. for precession for this period of time. As can be seen in Figure 12, the model with the addition of eroded material does better in terms of matching these expected spectral peaks. In particular, the obliquity spectral peak is closer to its expected frequency, and the precession peaks are enhanced. The model with eroded material added showed an enhanced spectral peak at 1.34 m, which could be the short eccentricity, but we would expect it to be closer to 1.2 m or 0.95 m for it to convincingly correspond to the short eccentricity. It is worth noting that with an approximate time span of just 300 k.y., this section is not really long enough to properly resolve the short eccentricity signal.

We used two band-pass filters to isolate the components that we presumed to correspond to the precession and obliquity and then added these together for the purpose of comparing them with the raw magnetic susceptibility data (Fig. 13). As can be seen, the band-passed data closely match the raw data with very few mismatches in the peaks and troughs, giving us confidence that this section, like the lower FSM section, appears to record the orbital cycles with good fidelity.

FUR Section

The FUR section is the longest of these sections, and it was chosen because it spans the onset and possibly the full duration of the K1 extraterrestrial ^3He anomaly. The section (Fig. 14) covers 10 m, representing ~ 1 m.y., assuming a mean sedimentation rate for the Furlo Scaglia Rossa limestone of ~ 10 m/m.y. (Alvarez and Lowrie, 1984), and it contains six turbidites (designated T1–T6) ranging in thickness from 10 cm to 25 cm. We performed FFTs on more than 400 models with varying amounts of erosion for each turbidite, looking for the model that best matched the expected Milankovitch peaks and that avoided strong peaks at unexpected frequencies. Of the models we explored, we found the best results from a model that involved no eroded material for each of the six turbidites; a few of these are illustrated in Figure 14. Our preferred model (A of Fig. 15) has spectral peaks at the expected frequencies and relatively few peaks at unexpected frequen-

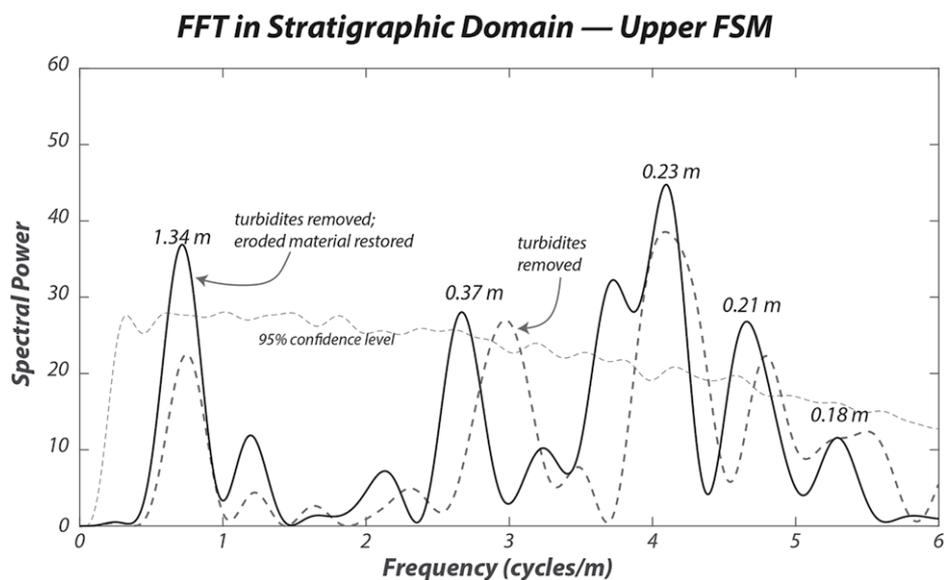


Figure 12. Fast Fourier transform (FFT) spectra for the upper Furlo Strada al Monte (FSM) magnetic susceptibility (MS) data using two different assumptions or models of how much erosion accompanied the emplacement of the turbidite; just a few of the spectra are shown here to illustrate how we chose the best model. Also shown is the 95% confidence level based on a Monte Carlo noise simulation. These spectra are in the stratigraphic domain, so the frequency is in cycles/m; prominent peaks are labeled with their periods (really wavelengths), which are in meters. The expected sedimentation rate for this section is ~ 10 m/m.y., which means that a spectral peak with a wavelength of 0.37 m would have a period of 37 k.y. The model represented by the solid curve is the one involving erosion because its spectrum has significant peaks with the periods expected for Milankovitch cycles (0.37, 0.23, 0.21, and 0.18 m, corresponding to 37, 23, 21, and 18 k.y.). The spectral peak with a wavelength of 1.34 m could be the short eccentricity signal, but it should be more in the range of 1.2–0.95 m; however, this section only represents ~ 300 k.y., which is not sufficiently long to resolve cycles with periods in the range of 100 k.y.

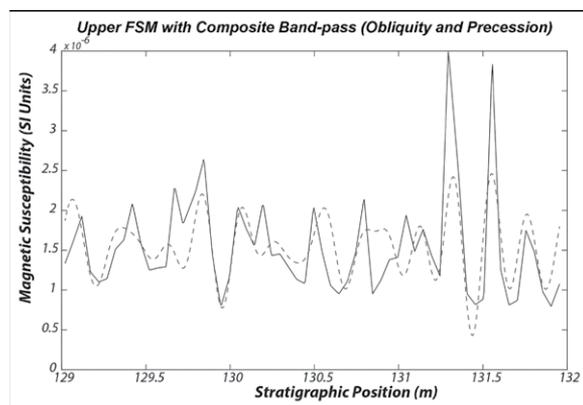


Figure 13. Upper Furlo Strada al Monte (FSM) magnetic susceptibility (MS) data, in solid black, compared with a band-passed composite representing the obliquity and precession signals added together. MS data include an assumed 7.5 cm of erosion for T1 and 6 cm for T2. There is a fairly good correspondence between the data and the band-passed signal, indicating that the MS data did record the orbital cycles during this time span, but not with the

same fidelity as seen in the lower FSM section (see Fig. 10).

cies. Of these peaks, only the short eccentricity (0.95 m) clearly rises above the 95% confidence level; the 4.6 m peak could correspond to the 405 k.y. long eccentricity signal, but the section is too short to convincingly record that signal. The obliquity signal (0.38 m period) and pre-

cession signal (0.22–0.18 m periods) barely rise above the noise level.

We combined three band-pass filters to isolate the eccentricity, obliquity, and precession signals and then compared them with the data to see how closely these orbital signals matched the

data (Fig. 16). We have indicated with a series of arrows the time periods where the band-passed signal does not closely match that actual data. Also shown in Figure 16 is the extraterrestrial ^3He signal, which begins to rise at meter level 304 and tapers off at meter level 313. As can be seen in Figure 16, the misfits between the data and the orbital signals begin right where the helium ratio begins to rise and continue intermittently to about meter level 312.2, at the point where the He ratio begins to fall off.

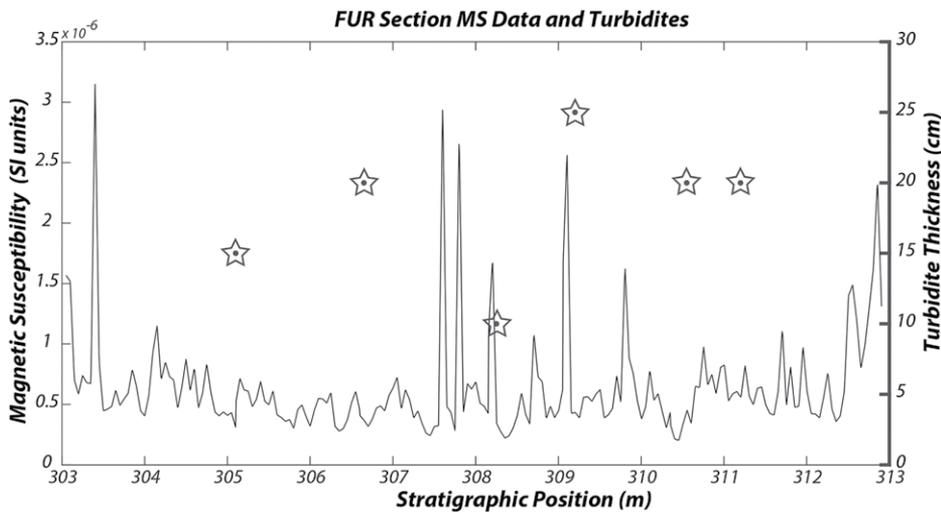
DISCUSSION AND CONCLUSIONS

Aware of the close coincidence of the K1 extraterrestrial ^3He event with the negative $\delta^{13}\text{C}$ shift known as the early Campanian event in the Bottaccione section at Gubbio, as respectively documented by Farley et al. (2012) and Sabatino et al. (2018), we confirmed such a coincidence in the complete and continuous coeval sections of Scaglia Rossa pelagic limestones at Apiro (APD) and Furlo (FUR-FSM) (see Fig. 7). This led us to hypothesize that the two events, the extraterrestrial K1 on one hand and the terrestrial environmental early Campanian event on the other hand, may have been linked by a cause-and-effect relationship. Practically, an asteroidal breakup or, in any case, a collision in the asteroid belt could have been responsible for producing a cascade of cosmogenic ^3He -rich interplanetary dust particles on Earth, perhaps accompanied by a bombardment of small and larger meteorites, which, by altering the transparency of the atmosphere, would have caused a climatic change that affected the carbon cycle in the oceans. On the other hand, a negative $\delta^{13}\text{C}$ shift was found to precede, by a few hundred thousand years, the K3 extraterrestrial ^3He event in the mid-Turonian (ca. 91 Ma) interval of the Bottaccione section, as was recognized by Farley et al. (2012) (see also Fig. 2). This apparent paradox, in view of the expectation that the extraterrestrial event was the cause of the $\delta^{13}\text{C}$ shift and not the other way around, was explained by Montanari et al. (2017, p. 1375) as follows:

“... it can be envisioned that the cascade of comminuted asteroidal matter initiated immediately after the [asteroidal] breakup but prior to the arrival of an interplanetary dust particle mass large enough to leave a global ^3He signature. This initial cascade would contain a myriad of larger particles, from ‘shooting star’-size grains to larger, several-tens-of-meters-sized objects (similar to Chelyabinsk or Tunguska; cf. Fari-nella et al., 2001; Brown et al., 2013; Povinec et al., 2015), which, vaporizing in the atmosphere or upon impacting on the surface of Earth, would exhale their volatile ^3He content back to outer space and would not be massive enough to leave

Figure 14. Magnetic susceptibility (MS) data from the Furlo upper road section (FUR), showing the locations of the six turbidites found in this section, which spans ~10 m or ~1 m.y. After exploring the fast Fourier transform (FFT) spectra of more than 400 possible combinations of eroded thickness associated with each turbidite, we found that a model with no erosion for each turbidite was the best.

Whatever the dynamics of the influx of extraterrestrial matter onto Earth, in the case of the early Campanian K1 event, in both the APD and FUR sections, the negative $\delta^{13}\text{C}$ shift followed the inception of the extraterrestrial ^3He excursion by ~500 k.y. (Figs. 7A and 7B). The question remains: Did the increased influx of extraterrestrial matter (i.e., the interplanetary dust particles) effectively cause a climate change event, which is expressed, in the stratigraphic record, by a negative $\delta^{13}\text{C}$ shift? This question was challenged by Brown et al. (2009), who performed a high-resolution multiproxy cyclostratigraphic analysis through the GSSP section for the Eocene-Oligocene boundary at Massignano. This section records multiple late Eocene impact events (LEMIE in Fig. 2), first documented by Montanari et al. (1993) and subsequently found to record a 1.3-m.y.-long extraterrestrial ^3He anomaly by Farley et al. (1998), who attributed three iridium-rich layers and the coincidental ^3He excursion to a comet shower. The rationale presented by Brown et al. (2009) was that in a pelagic rhythmite such as the Eocene Scaglia Variegata Formation or the Oligocene Scaglia Cinearea Formation, both exposed at Massignano, which neatly record Milankovitch cycles (e.g., Hyland et al., 2009), a random extraterrestrial event such as a long-lasting comet shower or an asteroidal bombardment may interfere with the regular orbitally driven climate changes by obscuring or blurring the record of Milankovitch cycles, which are normally expressed by periodic excursions of climate proxies such as oxygen and carbon isotopes, biogenic calcium carbonate, or magnetic susceptibility. Brown and coworkers were successful in demonstrating that this climate-forcing interference did occur through the late Eocene multiple impact events, while the same was found by Montanari et al. (2017) in the Monte dei Corvi Beach section, which records the breakup of the Veritas asteroid (8.5 Ma) with an 800-k.y.-long ^3He excursion. Therefore, following the methodological approach suggested by Brown et al. (2009) and Montanari et al. (2017), we performed a high-resolution cyclostratigraphic



a detectable PGE signature worldwide. However, they may have been capable of causing an alteration of the atmosphere transparency, pos-

sibly triggering a climate change, which would be recorded [in the stratigraphic record] by the $\delta^{18}\text{O}$ [or the $\delta^{13}\text{C}$] proxy with a short trend shift."

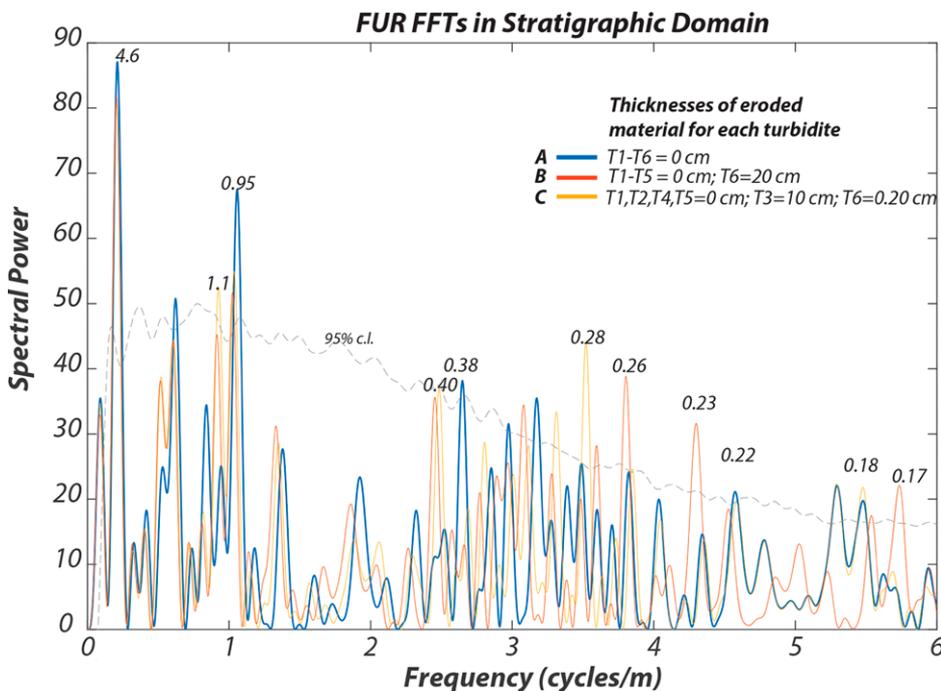


Figure 15. Fast Fourier transform (FFT) spectra for the Furlo upper road section (FUR) magnetic susceptibility (MS) data showing three different assumptions or models of how much erosion accompanied the emplacement of the turbidites (out of a total of more than 400 versions). Also shown is the 95% confidence level (c.l.) based on a Monte Carlo noise simulation. These spectra are in the stratigraphic domain, so the frequency is in cycles/m; prominent peaks are labeled with their periods (really wavelengths), which are in meters. The expected sedimentation rate for this section is ~10 m/m.y., which means that a spectral peak with a wavelength of 0.95 m would have a period of 95 k.y. The model represented by the blue curve involving no erosion is preferred because its spectrum has significant peaks with the periods expected for Milankovitch cycles (0.95, 0.38, 0.22, and 0.18 m, corresponding to 95, 38, 22, and 18 k.y.). The spectral peak with a wavelength of 4.6 m could be the long eccentricity signal (405 k.y.), but given that this section only represents ~1 m.y., it is not really long enough to resolve cycles with periods in the range of 400 k.y.

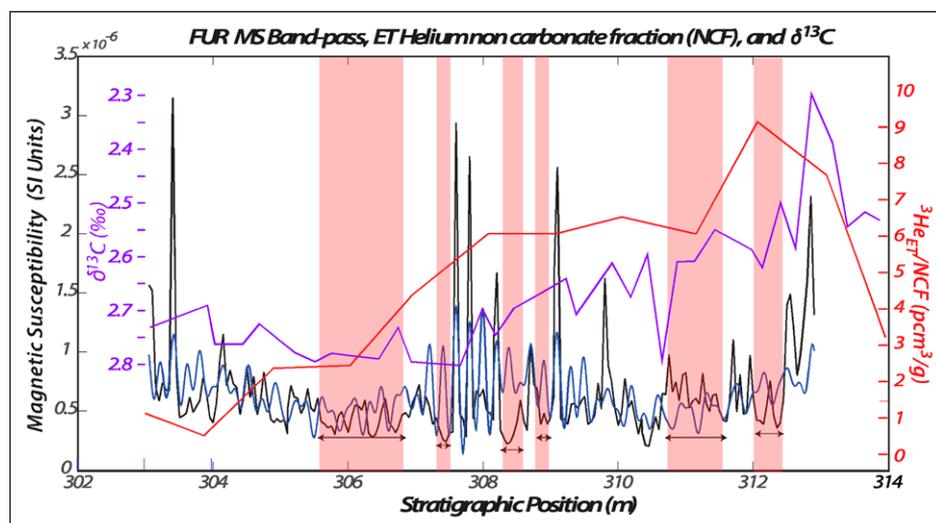


Figure 16. Magnetic susceptibility (MS) data from the Furlo upper road (FUR) section (solid black), along with the band-passed data combining the short eccentricity, obliquity, and precession signals in blue, as well as the ^3He data that represent the rise and fall of the K1 extraterrestrial ^3He ($^3\text{He}_{\text{ET}}$) event. The horizontal black arrows highlighted with the pink vertical bands indicate time periods where there is a mismatch between the band-passed orbital signals and the data. The longer of these periods begins with the rise of the $^3\text{He}_{\text{ET}}$ signal and persists, at least intermittently, through the part of the section with elevated $^3\text{He}_{\text{ET}}$ /NCF values.

analysis, using magnetic susceptibility as a climate proxy, through the early Campanian K1 event in the FSM and FUR sections.

While the presence of turbidites in the Furlo sections posed a challenge to high-resolution cyclostratigraphic analysis, we believe we found a way to overcome that obstacle by exploring a wide range of models that included different assumptions about the amount of material that may have been removed by erosion during the deposition of the turbidites. This approach was limited by a couple of facts: (1) We cannot know the magnetic susceptibility of the removed material, and so we had to just interpolate to fill the missing gap, and (2) there is always going to be noise added to the orbitally driven climate changes recorded by a proxy like magnetic susceptibility.

In conclusion, we think that the Scaglia Rossa sections at Furlo support the hypothesis that the influx of additional extraterrestrial material during the K1 event disrupted the signal of orbitally driven climate changes and caused a climate change event known as the early Campanian event, which is expressed by a negative shift in $\delta^{13}\text{C}$ in the deep marine stratigraphic record.

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