# Stratigraphy of the Cretaceous/Paleogene (K/Pg) boundary at the Global Stratotype Section and Point (GSSP) in El Kef, Tunisia: New insights from the El Kef Coring Project

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**ABSTRACT**

The Cretaceous/Paleogene (K/Pg) boundary is marked by one of the largest mass extinctions in Earth's history, with geological evidence for this event being expressed in hundreds of locations worldwide. An extensively studied section located near El Kef (northwestern Tunisia), is characterized by the classic iridium-rich K/Pg boundary layer, abundant and well-preserved microfossils, and apparently continuous sedimentation throughout the early Danian with no previously described structural complication. These features led to its designation in 1991 as the Global Stratigraphic Section and Point (GSSP) for the base of the Danian (i.e., the K/Pg boundary). However, the outcrop section has become weathered and the 'golden spike' marking the GSSP is difficult to locate. The El Kef Coring Project therefore aimed to provide a continuous record of unweathered sediments across the K/Pg transition in cores recovered from five rotary-drilled holes located close to the El Kef GSSP. Here we present new, high-resolution lithologic, biostratigraphic, and geochemical data from these cores. We find that the recovered stratigraphic successions of each hole (all drilled within ~75 m of one another) are unexpectedly different, and identify a formerly unknown unconformity within planktic foraminiferal biozone P1b. Our results provide evidence that sedimentation at El Kef was not as continuous or free from structural complication as previously thought. Despite these challenges, we present a new composite section from the five El Kef holes and an age model correlated to the orbitally tuned record at Walvis Ridge (South Atlantic Ocean), critical in placing the paleoenvironmental and paleoecological records from El Kef in a global context.

## INTRODUCTION

The mass extinction event at the Cretaceous/Paleogene (K/Pg) boundary (~66.02 Ma) eradicated more than 75% of marine species on Earth, and is almost universally believed to have been caused by the asteroid impact that formed the Chicxulub crater off the modern-day Yucatán Peninsula in southern Mexico (e.g., Jablonski, 1991; Schulte et al., 2010; Hull et al., 2020). In addition to the demise of all non-avian dinosaurs, marine reptiles such as the mosasaurs, and many groups of invertebrates including the ammonites (e.g., Buffetaut, 1990; Sheehan and Fastovsky, 1992; Jablonski, 1994; Marshall and Ward, 1996), the K/Pg impact led to the extinction of over 90% of calcifying plankton (calcareous nannoplankton and planktic foraminifera), likely due to a combination of global cooling, decreased light availability, and possibly acidification of the surface ocean (e.g., D'Hondt et al., 1994; Bown, 2005; Ohno et al., 2014; Vellekoop et al., 2014; 2015; 2016; Kaiho et al., 2016; Henehan et al., 2019). These environmental perturbations led to substantial ecological reorganization throughout the marine food web as well as fundamental changes in ocean carbon cycling that lasted for millions of years following the impact. This is particularly true in open-ocean depositional settings (e.g., D'Hondt et al., 1998; Coxall et al., 2006; Birch et al., 2016; Lowery et al., 2021), although neritic and bathyal regions closer to continental margins appear to have been more resilient (Sepúlveda et al., 2009; 2019; Rosenberg et al., 2021).

Geological evidence for the impact is recorded in hundreds of studied K/Pg sections worldwide, but is expressed differently with distance from the Chicxulub crater (Claeys et al., 2002; Schulte et al., 2010; Lowery et al., 2018). In sections proximal to the crater, the K/Pg boundary can be recognized by ejecta- and spherule-rich clastic event beds 1 to >80-meters-thick that were likely deposited by tsunamis and/or high energy gravity flows (e.g., Bourgeois et al.,

1988; Sigurdsson et al., 1991; Ocampo et al., 1996; Smit et al., 1992, 1996; Urrutia-Fucugauchi et al., 1996; Bralower et al., 1998; Alegret et al., 2005; Arenillas et al., 2006; Goto et al., 2008; Schulte et al., 2010; 2012; Gulick et al., 2019). The thicknesses of these complex clastic event beds generally decrease with increasing distance from the crater. In distal sections (>5000 km from the Chicxulub crater), the K/Pg boundary is typically expressed by a distinctive mm- to cm-thick clay layer (e.g., Molina et al., 2009), enriched in rare platinum-group elements (most notably iridium), shocked minerals, ejecta spherules, and Ni-rich spinels (e.g., Alvarez et al., 1980; Norris et al., 1999; Smit, 1999; Claeys et al., 2002; Schulte et al., 2010).

One of the most extensively studied distal sections is at the Global Stratotype Section and Point (GSSP) for the base of the Danian (i.e., the K/Pg boundary), located near the town of El Kef in northwest Tunisia (Molina et al., 2006; Figure 1). Here, the K/Pg boundary 'clay layer' is unusually thick in comparison to other stratigraphically complete marine sections (50 cm versus a few cm), which has allowed for numerous high-resolution studies over the past decades (e.g., Perch-Nielsen et al., 1982; Smit and Romein, 1985; Brinkhuis and Zachariasse, 1988; Keller and Lindinger, 1989; Arenillas et al. 2000; 2004; Molina et al., 2006). The stratigraphically expanded sections at El Kef and other nearby outcrops (e.g., Elles and Aïn Settara; Figure 1) contain well-preserved microfossils, which have provided a wealth of information about ecological, environmental, and climatological changes across the K/Pg boundary, including extinction and recovery patterns (e.g., Brinkhuis and Zachariasse, 1988; Speijer and Van der Zwaan, 1996; Arenillas et al., 2000; 2004; Rodríguez-Tovar et al., 2016; Alegret et al., 2022), carbon cycling and productivity (Sepúlveda et al., 2019), and global climate change (e.g., Galeotti et al., 2004; Vellekoop et al., 2015; Macleod et al., 2018). However, the El Kef outcrop is heterogeneously weathered (Molina et al., 2009; Rodríguez-Tovar et al., 2016), and the 'golden spike' placed to

mark the exact position of the GSSP (Molina et al., 2006) is now either absent or very difficult to locate. The aim of the El Kef Coring Project was therefore to provide a continuous, expanded, and unweathered record across the K/Pg transition for future scientific analyses, especially using novel stratigraphic and geochemical techniques that require pristine material and were developed long after initial studies of the El Kef outcrop began.

Here, we present lithostratigraphic, biostratigraphic, bulk geochemical and isotopic records from five sediment cores recovered between 2013 and 2015 during the El Kef Coring Project. These data provide the framework for an orbital age model that can be used to correlate the El Kef GSSP to other K/Pg boundary sections with unprecedented stratigraphic detail. The results of this study are therefore essential for placing future paleoceanographic, paleoecologic, and paleoclimatologic reconstructions from El Kef into a global context, and for providing the time control needed to determine the rates of biological and biogeochemical processes occurring in the aftermath of the Chicxulub impact.

## BACKGROUND

### Stratigraphy of the K/Pg boundary at El Kef

The El Kef stratotype section is located approximately 5 km southwest of the town of El Kef in northwestern Tunisia (Figures 1, 2A). Here, Upper Maastrichtian to lower Paleogene strata are well- and continuously exposed, providing one of the most expanded and stratigraphically complete K/Pg boundary sections in the world (Keller, 1996; Molina et al., 2006). The boundary itself is included within the upper Maastrichtian – Thanetian El Haria Formation, a 700-m thick unit that is predominantly composed of grey marls and clays intercalated with thick argillaceous limestone beds (Burollet, 1956; Zaghbib-Turki et al., 2000; Karoui-Yaakoub et al., 2002). The El Haria Formation lies conformably on the Campanian –

lower Maastrichtian Abiod Formation, which is composed of fine-grained chalky limestones with abundant macrofossils (inoceramids, bivalves, and echinoderms), ichnofossils, and microfossils (planktic foraminifera and calcareous nannofossils) (Negra, 1994).

The K/Pg boundary at El Kef is defined by a 'classic' 1-3 mm thick rust-colored ferruginous layer that comprises the iridium anomaly and contains hematite, goethite, pyrite, and less than 1% wt. percent $CaCO_3$ (Smit and Ten Kate, 1982; Keller and Lindinger, 1989; Robin and Rocchia, 1998; Molina et al., 2006). Below the K/Pg boundary, the upper Maastrichtian sediments are represented by a 4.5 m series of white-grey marls with floating burrows (Keller, 1988a). Immediately overlying the K/Pg boundary is a 50-cm-thick dark grey clay layer containing very few specimens of Cretaceous species (Smit, 1982; Keller, 1988a) and further impact materials, including Ni-rich spinels (Robin et al., 1991) and spherules of sanidine and hematite interpreted as altered microtektites (Smit, 1982; Robin et al. 1991). These dark grey clays grade into a lighter grey layer (50 cm thick), which progressively transition into more carbonate-rich clays and eventually white-grey marls ~3 m above the K/Pg boundary, associated with the diversification and increasing abundance of pelagic fauna and flora (Smit, 1982; Keller, 1988a; Pospichal, 1994).

**Depositional environment**

During the late Maastrichtian — early Paleogene, El Kef was located on the outer continental shelf/upper slope (~200 to 300 m water depth; e.g., Keller, 1988b; Speijer and Van der Zwaan, 1996; Alegret, 2003) of the Kasserine-Sidi Bouzid Island at a paleolatitude of ~20 ºN, on the southern margin of the "shallow" Tethys Sea that extended over much of northern Tunisia (Negra, 1994; Kadri et al., 2015; Negra et al., 2016; Negra and Jaballah, 2020) (Figure 1). The relatively high sedimentation rates (~1.1 to 3.5 cm/kyr) within this outer shelf-upper

bathyal environment during the latest Maastrichtian and early Danian (e.g., Cande and Kent, 1995; Adatte et al., 2002; Macleod et al., 2018), indicate that the K/Pg transition and early Danian at El Kef is more stratigraphically expanded (>9 m in thickness) and complete than at pelagic sites, where it tends to be stratigraphically condensed (generally <1 m in thickness), and/or can contain short hiatuses or periods of non-deposition (Salaj, 1980; Zachos and Arthur, 1986; Pospichal, 1994; Adatte et al., 2002; Keller et al., 2002; Karoui-Yaakoub et al., 2002; Molina et al., 2009; Giron, 2013).

Although the sediments at El Kef were generally deposited in an oxic, open-marine environment, the dark color of the boundary clay layer and its relatively high pyrite and total organic carbon content (TOC; ~0.5%) may indicate a brief interval when conditions at the sediment/water interface became less oxygen-rich (Keller and Lindinger, 1989; Speijer and Van der Zwaan, 1996). Oxygen-deficient environments during the first 10 to 15 kyr of the Danian at El Kef are supported by the ostracod faunas (Peypouquet et al., 1986) and depauperate benthic foraminiferal assemblages, which contain higher abundances of opportunistic taxa adapted to lower oxygen conditions (Alegret, 2003; Alegret, 2008). Furthermore, a 1-2‰ enrichment in $\delta^{15}N$ above the K/Pg boundary may indicate enhanced bacterial denitrification (and thus lower oxygenation) and phytoplanktonic nitrate assimilation in response to elevated surface ocean productivity (Sepúlveda et al., 2019). Intensively bioturbated sediments and the sequential re-appearance of many species of benthic foraminifera that had temporarily disappeared (due to the Lazarus effect) at the K/Pg boundary (Speijer and Van der Zwaan, 1996; Alegret et al. 2022), indicate well-oxygenated bottom waters following deposition of the boundary clay.

**Tectonic and eustatic history of northwestern Tunisia**

159 The stratigraphy in northwest Tunisia is structurally complex, with active tectonism
160 affecting sediments deposited from the Late Cretaceous to the Neogene. Extensional tectonic
161 activity with a WNW-ESE strike direction was first initiated in the Campanian-Maastrichtian, and
162 affected the entire North African margin (Bey et al., 2012) (Figure 2). These extensional processes
163 led to the creation of a NW-SE to NNW-SSE conjugate normal fault system, which cross-cut and
164 formed syn-depositional features within the carbonates of the Campanian Abiod Formation in the
165 folded Atlasic domain (Bouaziz et al., 2002; Bey et al., 2012). Intervals of extensional tectonics
166 were often followed by reverse or thrust faulting, leading to structural inversion. In addition to
167 active tectonism, northwest Tunisia was also influenced by a complex eustatic history during the
168 Late Cretaceous, with the Campanian experiencing sea level transgression, followed by sea level
169 regression and relative cooling during the late Maastrichtian (Stüben et al., 2002). Therefore, both
170 tectonic and eustatic factors strongly controlled sediment deposition during the late Maastrichtian
171 in Tunisia.

172 Extensional tectonic plate movements were also active during the K/Pg boundary interval,
173 and gave rise to instabilities that widely affected continental platforms and ramps in the
174 Mediterranean Tethyan region (Bey et al., 2012; Negra et al., 2016). Evidence for this intense
175 tectonic activity is observed in Tunisian outcrop sections as numerous faults and fractures with a
176 dominant NW-SE to NNW-SSE trend (Figure 2A), interpreted as representing reactivated Late
177 Cretaceous faults. Normal fault motions initially gave rise to horst-graben structures followed by
178 strike-slip movements, causing horizontal displacements of hundreds of meters. This faulting
179 along with relative sea-level changes, greatly impacted sedimentation during the Late Cretaceous
180 and the Paleogene (Negra et al., 2016). Tectonic and eustatic processes have therefore caused
181 structural complexity within the K/Pg boundary strata at El Kef that have generally been

overlooked in previous studies, but which must be considered when investigating the stratigraphy of this section.

**History of studies at El Kef**

As the K/Pg boundary section at El Kef provides one of the most stratigraphically complete and expanded records in the world, it has been the subject of numerous high-resolution studies over nearly half a century. Initially studied by Salaj (1974), the El Kef section was subsequently analyzed by a diverse suite of macro- and micropaleontologists and geochemists, including for nannoplankton (Verbeek, 1977; Perch-Nielsen et al., 1982; Pospichal, 1994), planktic foraminifera (Keller, 1988a; Keller et al., 1996; Arenillas et al. 2000), benthic foraminifera (Keller, 1988b; 1992; Speijer and Van der Zwaan, 1996; Alegret, 2003; Alegret, 2008; Alegret et al., 2022), dinoflagellates (Brinkhuis and Zachariasse, 1988; Brinkhuis et al., 1998; Vellekoop et al., 2015), palynoflora (Méon, 1990), ostracods (Donze et al., 1982; Peypouquet et al., 1986), ammonites (Goolaerts et al., 2004), ichnology (Rodríguez-Tovar et al., 2016), bulk rock chemistry (Keller and Lindinger, 1989), carbon, oxygen, nitrogen, and strontium isotopes (Keller and Lindinger, 1989; Vonhof and Smit, 1997; Sepúlveda et al., 2019), and platinum group elements (Smit and Ten Kate, 1982; Robin and Rocchia, 1998).

In 1989, the section was officially proposed as the GSSP for the base of the Danian (i.e., the K/Pg boundary) at the 28$^{th}$ International Geological Congress in Washington D.C. (US). In 1991, the International Commission on Stratigraphy ratified the proposal to define the GSSP at the base of the boundary clay at El Kef, after which the “golden spike” was placed at the section (Arenillas et al., 2000). Molina et al. (2006) published the official proposal, including the original definition and a proposition to define the K/Pg boundary as the moment of the asteroid impact, implying that all sediments generated by the impact belong to the Danian; a definition

that is now generally accepted. Additional outcrops in close proximity to the El Kef GSSP provide other well-preserved high-resolution K/Pg boundary sections (Figure 1), especially at Elles (75 km southeast of the El Kef outcrop), which has one of the most expanded orbitally calibrated K/Pg boundary records (Thibault et al., 2016) and has thus been proposed as a parastratotype of the K/Pg boundary (Zaghbib-Turki et al., 2001).

## METHODS

### Drilling operations

The El Kef Coring Project initially planned to drill four holes, offset by ~25 to 50 m, near the El Kef GSSP outcrop section (36°09’13.2”N, 8°38’54.8”E; Molina et al., 2016; Figure 2). A preliminary field survey conducted in 2011, was unable to locate the ‘golden spike’ marking the exact position of the GSSP outcrop. However, a 0.5 m-deep trench located ~15 m NE of the GSSP (36° 9'13.66"N, 8°38'55.16"E) uncovered fresh outcrop across the K/Pg boundary (Macleod et al., 2018), and was used as a reference point for drilling operations (Figure 2B). During December 2013, the first hole (Hole T) was rotary drilled to a depth of 60 meters below surface (mbs) by the Laboratoire de sol Geoconseil, Tunisia. Hole T was designed to be an exploratory hole to determine the depth of the K/Pg boundary and therefore guide the drilling strategy for the subsequent three holes. For this reason, the cores from Hole T were not drilled in core liners and were later cut into 1 m core sections. Between December 2013 and January 2014, the remaining three holes (Holes A, B, and C) were each rotary drilled to a depth of ~36 m and the cores recovered in 1.5 m plastic core liners. The holes were drilled along a transect with Hole A (36° 9'13.30"N, 8°38'56.02"E) located ~2 m to the south of Hole T, Hole B (36° 9'12.66"N, 8°38'55.40"E) ~25 m to the southwest of Hole A, and Hole C (36° 9'11.57"N, 8°38'54.44"E) ~40 m to the southwest of Hole B (Figure 2B; Supplementary Figure 1).

Following completion of drilling operations, the cores recovered from all four holes were sent to the IODP Bremen Core Repository at the MARUM-Center for Marine Environmental Sciences, University of Bremen, where core splitting and sampling was conducted in November 2014. The preliminary nannofossil biostratigraphy conducted during this initial sampling indicated that the K/Pg boundary was preserved in Hole A, but that Holes B and C only contained the post-impact (Danian) sediments and not the boundary itself (see Results and Discussion). For this reason, it was decided that two further holes (Holes D and E) would be drilled in close proximity to Hole A to provide more sediment for scientific analyses immediately at and around the K/Pg boundary.

Hole D (36° 9'13.30"N, 8°38'55.91"E) and Hole E (36° 9'13.33"N, 8°38'56.01"E) were rotary drilled in March 2015 by the Laboratoire de sol Geoconseil, very close to Hole A (see Figure 2B; Supplementary Figure 1). The drilling of both holes was destructive from 0 to 4 mbs, with sediment cores being recovered in 1.5 m plastic core liners between 4 and 26 mbs. All cores were sent to the core repository at the MARUM, University of Bremen where they were sampled in September 2017.

**Split core analyses**

Following their transportation to the MARUM core repository, all cores were kept refrigerated at +4ºC until the sampling party, when they were split into archive and working halves. To aid in core correlation, non-destructive X-ray fluorescence (XRF) scanning and digital line scan imaging was conducted on the archive halves of each split core at the MARUM, University of Bremen. The methodology for each of these technical analyses is outlined below.

***Non-destructive XRF***

XRF Core Scanner data were collected every 1 cm down-core over a 1 $cm^2$ area directly at the split core surface of the archive half with down-core slit size of 10 mm using generator settings of 10, 30, 50 kV, a current of 1.0, 1.0, 0.2 mA, and a sampling time of 15 seconds using an XRF Core Scanner II (AVAATECH Serial No. 2). The split core surface was covered with a 4 μm-thin SPEXCerti Prep Ultralene1 foil to avoid contamination of the XRF measurement unit and desiccation of the sediment. The reported data were acquired by a Canberra X-PIPS Silicon Drift Detector (SDD; Model SXD 15C-150-500) with 150eV X-ray resolution, the Canberra Digital Spectrum Analyzer DAS 1000, and an Oxford Instruments 50W XTF5011 X-Ray tube with rhodium (Rh) target material. Raw data spectra were processed by the analysis of X-ray spectra by Iterative Least square software (WIN AXIL) package from Canberra Eurisys.

***Line scan imaging***

In addition to the XRF data, digital line scan images of the split cores were also obtained using the AVAATECH XRF Core Scanner III. This XRF core scanner has an option for line scan camera and linear light source. The line scanner produces high-resolution color images and outputs accurate color data in RGB and Commission Internationale d'Eclairage (CIE) L (lightness), a (green to red chromaticity), and b (blue to yellow chromaticity) units (L*a*b*) using individual CCD pixel calibration. The line scan program uses the Stemmer Common Vision Blox (CVB) platform to acquire and process color images. The camera system contains a 3-CCD camera using 3 × 2048 pixels with a beam splitter and a manually controlled Pentax 50 mm lens. The image resolution is ~150 pixel/cm (70 μm/cm) in the cross-core and downcore directions. With an exposure time of 5 ms, a scan speed of 125 mm/s was achieved. Added to this time is the initialization time and camera repositioning after a scan. The image coverage is ~13.5 cm cross core and a maximum of 153 cm in the downcore direction. All split cores were

measured using an aperture setting of 6.7 and 11 to account for the strong light to dark color changes in the cores.

**Discrete sample analyses**

Numerous geochemical and biostratigraphic analyses were performed on discrete samples from the El Kef cores to constrain the depth of the K/Pg boundary in Holes A, D, and E, and to aid in stratigraphic correlation and the generation of an orbitally tuned age model. The methodologies employed for these analyses are outlined below.

***Total Organic Carbon (TOC) and weight percent calcium carbonate (% $CaCO_3$)***

Approximately 10 $cm^3$ of sediment was freeze-dried and ground to a fine powder using an agate mortar at the MARUM, University of Bremen. Total carbon (TC) and total organic carbon (TOC) were measured using a LECO CS-200 carbon-sulfur analyzer. Approximately 65 mg of the homogenized sample was weighed in a ceramic cup and burnt in an induction furnace. The evolved $CO_2$ was measured with a nondispersive infrared detector to provide a measure of the sedimentary TC content. To determine the TOC content, ~65 mg of powdered sample was decalcified using 12.5% HCl to remove carbonate species and analyzed as described above. Total inorganic carbon (TIC) was determined by subtracting TOC from TC. All data are reported in weight percent (wt%) dry sample, with an analytical precision of <3 % based on replicate sample analysis.

***Bulk organic $\delta^{13}C$***

Powdered sample was obtained by crushing freeze-dried sample using a benchtop IKA-WERKE grinder. $CaCO_3$ was removed by reacting ~ 2 g powdered sample with 40% HCl for 24 hours, diluting with de-ionized water and centrifuging until the samples attained a neutral pH. The carbon isotopic composition of the organic fraction ($\delta^{13}C_{org}$) was then measured using an

296 Isotope Ratio Mass Spectrometer coupled with an Elemental Analyzer (EA-IRMS) at the School
297 of Ocean and Earth Science, University of Southampton, with USGS-40 and USGS-41a as the
298 international reference standards used to calibrate the data with an analytical precision of 0.01
299 ‰.

300 ***Bulk carbonate $\delta^{13}C$ and $\delta^{18}O$***

301 For El Kef A and a sub-set of samples from El Kef E (see Table A5), the bulk carbonate
302 was sonicated in MeOH and dried for 24 hours at 50ºC. They were then reacted with 106.2%
303 phosphoric acid in a Thermo Finnigan Kiel-IV carbonate device at the University of
304 Southampton, National Oceanography Centre, Southampton, UK. Purified $CO_2$ was analyzed on
305 a Thermo Finnigan MAT 253 isotope ratio mass spectrometer. Carbon and oxygen stable isotope
306 ratios were normalized using a two-point calibration with GS1 (in house material previously
307 calibrated to NBS 18 and NBS 19) and NBS 18 (International Atomic Energy Agency, Vienna,
308 Austria). An in-house reference material (SC1) was used as an independent QC with an overall
309 precision of 0.01 and 0.04 ‰ for $\delta^{13}C$ and $\delta^{18}O$ respectively.

310 For El Kef C, D and a sub-set of samples from El Kef E (see Table A5), additional bulk
311 carbonate C and O isotope measurements were made at the Yale Analytical and Stable Isotope
312 Centre (YASIC), Yale University, also on a Thermo-Finnigan MAT 253 mass spectrometer
313 coupled to a Thermo Finnigan Kiel-IV carbonate device. Analytical precision of replicates of
314 standard measurements was typically better than 0.06 and 0.08 ‰ for carbon and oxygen,
315 respectively. To verify consistency between laboratories, the University of Southampton in-
316 house reference materials (GS1 and SC1) were measured at YASIC, with both labs agreeing
317 within accepted standard error (instrument and material) of 0.1 ‰ ($\delta^{18}O$) for both reference
318 materials.

### *Nannofossil biostratigraphy*

Nannofossil biostratigraphy was performed on at least one sample per core in Holes B, C, and D and at least five samples per core in Holes A and E with the frequency increasing close to the boundary in Hole A. Smear slides were prepared for biostratigraphy by disaggregating a small chip of sediment in distilled water. An aliquot of this mixture was applied to a cover slip, dried on a hot plate and adhered to a microscope slide using Norland Optical Adhesive, which was then cured under ultraviolet light. All smear slides were examined at 1600 x magnification under cross-polarized light using a Zeiss Imager.A2m (Penn State University) or an Olympus BX51 polarization microscope (MARUM, University of Bremen). Age-diagnostic nannofossil specimens were imaged using a Zeiss Axiocam 305 Color camera (Penn State University) or an Olympus DP22 camera and associated software (MARUM, University of Bremen), to help identify specimens to species level and to allow for internal taxonomic consistency. The nannofossil biostratigraphy utilized largely follows the CP zonation of Okada and Bukry (1980) and the additional CNP biozones proposed by Agnini et al. (2014).

### *Planktic foraminiferal biostratigraphy*

For the uppermost Maastrichtian and lower Danian, planktic foraminiferal biostratigraphy was conducted on 58 samples from Hole A, 34 samples from Hole C, and 52 samples from Hole E. Holes B and D were not sampled for planktic foraminifera. All samples were oven-dried at 40 °C, weighed to obtain bulk dry sample weight, and soaked and disaggregated in a cold sodium hexametaphosphate ($Na_6(PO_3)_6$) solution, then washed with tap water or deionised water over 38 μm or 63 μm wire mesh sieves, in accordance with each laboratory's standard protocols. The residue was oven-dried at 40 °C and weighed. Presence/absence data were recorded for each split sample by picking ~300 specimens, which were identified to species level using the taxonomic

concepts in the Paleocene Atlas of Olsson et al. (1999). The remainder of the sample was then quickly scanned to check for rare species. Planktic foraminiferal biostratigraphy follows the Pardo et al. (1996) biozonation scheme for the Cretaceous and the Wade et al. (2011) biozonation scheme for the Paleocene.

Below the K/Pg boundary, 25 additional samples were examined from Hole A (Cores 21 through Core 26; 26.88 to 36.32 mbs) to determine the first occurrence (FO) of *Plummerita hantkeninoides*, which marks the base of the uppermost Maastrichtian planktic foraminiferal biozone (Pardo et al., 1996). Samples were sieved to >106 μm, and multiple splits of ca. 500 particles were examined to determine the presence or absence of *Plummerita hantkeninoides* following the taxonomic concepts of Brönnimann (1952). After initial screening, more detailed treatment (up to 19 splits) was given to samples around the provisional FO.

***Paleomagnetism***

Paleomagnetic analyses were conducted at the University of Bremen on 54 samples from Hole A (18), Hole B (19) and Hole C (17), collectively spanning the entire recovered stratigraphic range. Each sample was demagnetized for natural remanent magnetization (NRM) in 2.5 mT increments to 10 mT AF, at which the sensitivity of the magnetometer was reached. Unfortunately, magnetic intensities were weak throughout the section such that consistent and reliable polarity could not be reconstructed from the inclination and declination data. For this reason, it was not possible to generate a paleomagnetic record for the El Kef cores.

**RESULTS**

Following data collection, our first aim was to constrain the position of the K/Pg boundary in Holes A, D, and E to provide a basic stratigraphic frame of reference. The boundary was initially identified by observed lithological changes on the split core surfaces and by

preliminary nannofossil biostratigraphy, specifically the abrupt decline in Cretaceous species and the replacement by an assemblage dominated by disaster species. The K/Pg boundary depth interval was subsequently confirmed with geochemistry, namely the sharp decline in $\%CaCO_3$ and the abrupt decrease in bulk carbonate $\delta^{13}C$ (Figure 3).This combination of nannofossil biostratigraphy and geochemistry shows nearly identical changes in the outcrop section (e.g., Keller and Lindinger, 1989; Pospichal, 1994) where shifts also correspond to traditional boundary markers including iridium and Ni-rich spinels (Kruslys and Krahenbuhl, 1983; Robin et al, 1991; Robin and Rocchia, 1998), validating the boundary definition in the cores. Once the position of the K/Pg boundary had been constrained, we then conducted more detailed lithostratigraphic, biostratigraphic, and geochemical analyses on the rest of the Maastrichtian and Danian sediments, the results of which are outlined below.

**Lithostratigraphy**

The El Kef cores consist predominantly of grey marls (carbonate-rich mudstones) that have been moderately to intensively bioturbated (Plate 1G), except for immediately above the K/Pg boundary. Structural complexity at this site is evidenced by abundant microfractures and, less commonly, larger fractures filled with sparry calcite cement or pyrite (Plate 1C-1E). At least one unconformity is also present during the lower Paleocene (Plate 1B). In addition to the inherent structural complexity of these cores, rotary drilling disturbance including common biscuiting (artificial layering created when the formation is fractured during coring and drilling mud is injected in between layers) and flow-in after coring (Plate 1I) affected the sediments to a varying extent. Moreover, the top three to four cores (~4.5-6 m) from each hole are strongly weathered (Plate 1F), obscuring many of the features that would otherwise be visible on the split core surfaces. Although these confounding factors complicate the stratigraphic reconstruction of

this section, many critical sedimentological features are nevertheless observed and described in the El Kef cores. Below, we separate our detailed lithostratigraphic findings into two sections: Holes A, D, and E; and Holes B and C, which – based on the biostratigraphic results – represent the earlier and later parts of the recovered stratigraphic interval, respectively.

***Holes A, D, and E***

At El Kef, the K/Pg boundary can be recognized by a transition from lighter grey, carbonate-rich Cretaceous sediments to darker grey Paleocene marls in Hole A (Core 16R-1, ~108 cm; 20.03 mbs), Hole D (Core 10R-1, ~73 cm; 18.31 mbs), and Hole E (Core 10R-1, ~121 cm; 19.15 mbs) (Plate 1A; Figure 3). The distinctive 1-3 mm rust-colored layer enriched in rare earth elements that is characteristic of the K/Pg boundary in the El Kef outcrop is noticeably absent from the El Kef cores. This is most likely a product of the rotary drilling process, which either completely removed this very thin layer or "smeared" it into the over- and/or underlying sediments.

The upper Maastrichtian sediments below the K/Pg boundary at El Kef generally consist of dark grey marls containing visible foraminifera. Darker-colored sediment layers were observed between El Kef A 20R-1A, 0 cm and El Kef A 21R-1A, 65 cm (~25.28 to 27.53 mbs) and from El Kef A 22R-1A, 100 cm to El Kef A 25R-1A, 150 cm (~29.32 to 34.72 mbs) (Figure 3). Large burrows and other evidence for moderate to intense bioturbation were observed throughout the uppermost Cretaceous, including immediately below the K/Pg boundary (Plate 1A). Fracturing is relatively uncommon throughout the Maastrichtian at El Kef, especially when compared to the Paleocene cores (see below).

Immediately above the K/Pg boundary, the marls are much darker in color than in the uppermost Cretaceous and there is little evidence for bioturbation (Plate 1A). Intervals

411 containing abundant pyrite are also common (e.g., El Kef A 15R-1A, 0-69 cm; 17.68 to 18.37
412 mbs). Above the base of Core 14 in Hole A (17.6 mbs) and the base of Core 9 in Holes D and E
413 (17.48 mbs and 17.84 mbs, respectively), the sediments become lighter in color and there is a
414 slight increase in bioturbation. However, bioturbation remains low until approximately 14R-1A,
415 76 cm in Hole A (17.51 mbs), 8R-1A, 135 cm in Hole D (15.67 mbs), and 8R-1A, 148 cm in
416 Hole E (16.22 mbs), above which there is a visible increase in bioturbation including the
417 reappearance of small, bedding-parallel burrows (Plate 1G). The exact depth level at which this
418 increase in bioturbation occurs is difficult to determine due to the presence of common rotary
419 drilling marks and other effects of drilling disturbance such as heavy biscuiting and flow-in
420 (especially in Hole A; Plate 1I), and abundant microfractures that obscure other primary and
421 secondary structural features on the split core surfaces (Plate 1C to 1E). These microfractures are
422 rare in the upper Maastrichtian sediments but are common throughout the lowermost Danian
423 (especially in Hole E), suggesting that they were not caused by drilling disturbance. Typically,
424 the fractures are thin, infilled with a white mineral (likely sparry calcite), and are bedding-
425 parallel or low-angle oblique (Plate 1D). It is also common for fractures to abruptly switch from
426 being bedding-parallel to low-angle oblique (and vice versa) (e.g., El Kef E 9R-1A, 122-128 cm;
427 17.56 to 17.62 mbs), or for the low-angle fractures to change strike direction (e.g., El Kef E 8R-
428 1A, 88-89 cm; 15.62 to 15.63 mbs). Although intermittent fracturing was observed throughout
429 the entirety of the lower Danian at El Kef, extended intervals of heavy fracturing generally occur
430 closer to the K/Pg boundary (e.g., El Kef E 8R-1A, 58-148 cm (15.32 to 16.22 mbs), and El Kef
431 E 9R-1A, 122-140 cm (17.56 to 17.74 mbs). In addition to these thin microfractures, some
432 larger, high-angle fractures that cross-cut bedding direction were observed (e.g., El Kef E 9R-

1A, 84-97 cm; 17.18 to 17.31 mbs), one of which contained partially oxidized material and/or pyrite (El Kef E 6R-1A, 49-67 cm; 11.96 to 12.14 mbs; Plate 1D).

At a depth of ~14.8 mbs in Hole D (8R-1A, 48 cm) and ~10.08 mbs in Hole E (5R-1A, 21 cm), there is a sharp transition from lightly bioturbated, dark grey-colored marls to more heavily bioturbated, lighter-colored sediments (Plate 1B). It is likely that this lithologic boundary represents an unconformity, which is supported by both the nannofossil and planktic foraminiferal biostratigraphic datums (see Biostratigraphy section). The unconformity is observed at a lower depth in Hole D (~14.8 mbs) than in Hole E (~10.08 mbs), suggesting that an offset exists between the two holes, potentially caused by a reactivated minor fault (Figure 2B; see Discussion for further detail). Unfortunately, the contact between the older, darker-colored marls, and the younger, lighter-colored sediments is partially obscured by drilling disturbance in both Holes D and E so its exact nature cannot be described in detail. Similar drilling disturbance is also observed at the top of Core 14 in Hole A (14R-1A, 0-29 cm; 16.75 to 17.04 mbs; Plate 1I), suggesting that the unconformity is present in this hole but has been completely obscured by cave-in.

Above the unconformity in Hole E, the drilling disturbed, lighter-colored sediments continue until El Kef E 4R-1A, ~81 cm (9.05 mbs), above which the cores start to become heavily weathered and/or oxidized (Plate 1F). In Hole D, the sediments above the unconformity are heavily fractured and intensely bioturbated, with intervals that contain concentrated small, bedding-parallel burrows (e.g., El Kef D 7R-1A, 110-114 cm; 13.79 to 13.82 mbs) and others that contain larger, elongated burrows which cross-cut bedding planes (El Kef D 7R-1A, 15 cm; 12.84 mbs). Most of the fractures (especially throughout El Kef D, 6R-1A; 11.05 to 12.59 mbs) are longer and wider than those observed lower in the Danian, and generally cross-cut bedding

456 planes in a NW-SE direction. Above El Kef D, 5R-1A, ~44 cm (9.86 mbs), the sediments are
457 still heavily bioturbated but there is reduced fracturing. Weathering and oxidation begin to affect
458 the sediments in Hole D from the base of 3R-1A (7.89 mbs), although it only obscures
459 sedimentary features on the split core surfaces in Cores 1 and 2.

460 Overall, the sharp facies transitions and intense fracturing/micro-fracturing observed in
461 the cores confirm the effect of tectonics on sedimentation during the earliest Danian. The larger
462 microfractures appear to be associated with the movement of the regional NW-SE trending faults
463 (Figure 2A). These structures are also possibly responsible for the offset in the depth of the
464 identified unconformity between Holes D and E.

465 ***Holes B and C***

466 Higher in the Danian, the lighter grey-colored marls observed above the unconformity in
467 Holes D and E continue. These sediments are generally more intensely bioturbated and less
468 heavily fractured than lower in the Danian, although there are sporadic, restricted intervals where
469 more severe microfracturing occurs (e.g., El Kef B 23R-1A, 118-149 cm; 35.28 to 35.59 mbs
470 and El Kef C 21R-1A, 53-67 cm; 31.33 to 31.47 mbs; Plate 1C, D). Extended intervals of intense
471 microfracturing are rarer than in Holes D and E, but can also be observed in El Kef B 13R-1A,
472 105 cm to 15R-1A, 123 cm (19.16 to 22.53 mbs) and El Kef C 8R-1A, 99 cm to 9R-1A, 146 cm
473 (11.09 to 13.16 mbs). These concentrated microfractures are usually low-angled and SW-NE
474 trending, but often become more parallel. In addition to microfractures, larger NW-SE or SW-
475 NE trending fractures filled with sparry calcite cement were observed. These fractures are not as
476 common as the microfractures (which they cross-cut), and are confined to restricted stratigraphic
477 intervals (e.g., El Kef B 11R-1A, 0-25 cm; 14.9 to 15.15 mbs and 52-75 cm; 15.42 to 15.65 mbs
478 and El Kef C 19R-1A, 76-93 cm; 28.36 to 28.53 mbs).

Pyrite nodules are sporadically observed throughout Holes B and C, particularly in the deeper cores. Two of these pyrite nodules (El Kef B, 18R-1A, 116-117 cm; 27.26 to 27.27 mbs and 119-120 cm; 27.29 to 27.30 mbs) were observed immediately below a SW-NE trending contact that may represent a microfault (EL Kef B 18R-1A, 115-120 cm; 27.25 to 27.5 mbs) (Plate 1D). Pyrite was also observed lining the edges of burrows (El Kef B 18R-1A, 49 cm; 26.59 mbs) (Plate 1G) and completely replacing them (e.g., El Kef C 23R-1A, 46 cm; 34.46 mbs). Burrows themselves are a common feature throughout El Kef B and El Kef C, and are generally larger (El Kef C 23R-1A, 21-23 cm; 34.21 to 34.23 mbs) and more complex (El Kef B 17R-1A, 115-117 cm; 25.65 to 25.67 mbs, and El Kef B 13R-1A, 55-60 cm; 18.65 to 18.7 mbs) than those observed in the lower Danian sediments of Holes A, D, and E (Plate 1G). Ichnofossils become more diverse and increase in abundance up-section, especially long, cylindrical, bedding-parallel forms (e.g., El Kef B 8R-1A, 12-23 cm; 10.22 to 10.33 mbs; Plate 1G).

Within El Kef B 11R-1A and El Kef C 14R-1A, parallel laminations of alternating darker and lighter sediments develop (Plate 1H) and become low-angled within El Kef B 5R-1A and El Kef C 13R-1A, 76-79 cm (18.86 to 18.89 mbs; Plate 1H). These laminae are continuously present near the top of Hole B, but temporarily disappear in Hole C between El Kef C 7R-1A, 41 cm and El Kef C 10R-1A, base; 8.91 to 14.8 mbs. Cores 1 through 4 in Holes B and C are intensely weathered so meaningful lithological observations cannot be made.

**Biostratigraphy**

High-resolution calcareous nannofossil biostratigraphy was predominantly conducted on samples from Hole E, which was discovered to contain the thickest succession of lowermost Danian sediments (Figure 3). Lower-resolution nannofossil biostratigraphy (at least one sample per core) was performed on sediments from all other holes. In contrast, planktic foraminiferal

biostratigraphy was only conducted in Holes A, C, and E, and not in Holes B or D. Both the calcareous nannofossil and planktic foraminiferal biostratigraphy for all the El Kef holes was complicated by clear evidence for local faulting and fracturing (Plate 1C-E), which causes some biozone markers to disappear only to reappear again further up-section. The effects of primary faulting on the biostratigraphy are further complicated by frequent drilling disturbance and drill mud contamination (Plate 1I; see Lithostratigraphy for further information).

***Calcareous nannofossil biostratigraphy***

The uppermost Maastrichtian observed in El Kef Holes A, D, and E, is characterized by well-preserved nannofossils with moderate amounts of etching and overgrowth (Plate 2). Assemblages are highly diverse and are comprised of typical latest Cretaceous taxa including *Watznaueria barnesiae*, *Prediscosphaera cretacea*, *Prediscosphaera stoveri*, *Micula murus*, *Micula prinsii*, *Lithrapidites quadratus*, *Cribrosphaerella ehrenbergii, Eiffellithus turriseiffelii*, and *Arkhangelskiella cymbiformis*, all of which are commonly reworked into the overlying earliest Danian sediments. *Micula prinsii* extends to the base of Hole A, indicating that this section lies within the uppermost Maastrichtian and is within 0.25 Myr of the K/Pg boundary (Henricksson, 1993).

The K/Pg boundary can be recognized in nannofossil smear slides by the extinction of nearly all Cretaceous species and the increased abundance of calcareous dinoflagellate cysts (Plate 2, 19 and 25). Using these criteria, the K/Pg boundary was found to be expressed in three of the five holes drilled at El Kef (Holes A, D, and E; Table 1). Nannofossil preservation above the K/Pg boundary is generally moderate to good with abundant complete cell coverings (coccospheres) throughout (Plate 2, 15) and abundant fragile specimens of *Neobiscutum* in the lowermost Danian (Plate 2, 13-14). Within each hole, we identified the first occurrences (FOs) of

525 *Cruciplacolithus primus* (base of the *Cr. primus* subzone; Bernaola and Monechi, 2007),
526 *Coccolithus pelagicus* (Base CNP2; Agnini et al., 2014), and *Cruciplacolithus intermedius*
527 (Bernaola and Monechi, 2007) (Table 1), all of which are illustrated in Plate 2. Despite intensive
528 and detailed biostratigraphic work, the exact placement of these datums was complicated by
529 several factors. Firstly, many of the earliest 'primitive' specimens of incoming Paleocene taxa
530 (e.g., *Cr. primus*) look very different from their fully evolved counterparts both in size and form
531 (see Plate 2, 5-9), and this poses a particular challenge for correlation to more stratigraphically
532 condensed deep-sea sections where such primitive forms have not been described. Moreover, as
533 the cores are stratigraphically expanded, nannofossil specimens that are transitional in form
534 between two species are common. For example, it is often difficult to differentiate *Cr. primus*
535 from *Cr. intermedius* at El Kef as these two species are generally separated by size (smaller or
536 larger than 7 µm for *Cr. primus* and *Cr. intermedius* respectively), which is particularly
537 problematic when there is any evidence for calcite overgrowth. Other than size, some
538 nannofossil paleontologists use additional, and somewhat variable, criteria to differentiate
539 between *Cruciplacolithus* species, and there has been considerable discussion as to which of
540 these described forms and taxonomic classifications are best used as datums or biozone markers
541 (e.g., Bernaola and Monechi, 2007; Agnini et al., 2014; Thibault et al., 2018). Applying the
542 traditional 7 µm "cut-off" between *Cr. primus* and *Cr. intermedius* in our study, the FO of *Cr.*
543 *intermedius* occurs immediately above the unconformity that is present in Holes A and D, and ~1
544 m below the unconformity in Hole E (see Lithostratigraphy; Plate 1B; Figure 3). Similarly, it
545 was not possible to reliably identify the base of CNP3 (Agnini et al., 2014), which is defined by
546 the FO of the *Prinsius dimorphosus* group (including *Praeprinsius tenuiculus*). Very small (~1-2
547 µm) *Praeprinsius* specimens (*Praeprinsius* cf. *vegrandis*; Kim, 2020) originate shortly above the

548 K/Pg boundary at El Kef (El Kef E 10R-1W, 81 cm), and appear to gradually evolve into *Pr.*
549 *tenuiculus* throughout the early Danian (Plate 2, 16-18). It is therefore challenging to determine
550 the FO of 'true' *Praeprinsius tenuiculus* in the El Kef cores without extensive morphometric
551 work beyond the scope of this contribution.

552 Holes B and C, which do not preserve the K/Pg boundary and represent a later part of the
553 Danian post-extinction interval, did not contain any of the usual age-diagnostic nannofossil taxa
554 such as *Chiasmolithus danicus* (Base CP2; Okada and Bukry, 1980), *Prinisus martinii* (Base
555 CNP4; Agnini et al., 2014), and *Toweius pertusus* (Base CNP5; Agnini et al., 2014), or contain
556 the last occurrence (LO) of the *Praeprinsius dimorphosus* group (Agnini et al., 2014). Extremely
557 rare primitive specimens of *Cruciplacolithus tenuis* (Base NP2; Martini 1971) that lack the fully-
558 developed 'feet' diagnostic of this species, are observed in only two samples (El Kef C 7R-1W,
559 61cm and El Kef C 3R-1W, 1 cm; Plate 2, 1,2); however, a true FO or stratigraphic range cannot
560 be determined. Therefore, it was not possible to constrain the biostratigraphic age of Holes B and
561 C using nannofossil datums.

562 ***Planktic foraminiferal biostratigraphy***

563 High-resolution planktic foraminiferal biostratigraphy was conducted on the
564 Maastrichtian sediments from Hole A and on the early Danian sediments (including the K/Pg
565 boundary when present) from Hole A (up until the cave-in at the top of Core 14; ~17.05 mbs),
566 Hole C, and Hole E (Supplementary Figure S2). Planktic foraminiferal biostratigraphy was not
567 conducted on Holes B and D. In the uppermost Maastrichtian, planktic foraminifera are
568 moderately preserved, although with pervasive infilling from secondary carbonate. Assemblages
569 are diverse, consisting of typical Maastrichtian *Globotruncana, Globotruncanella,*
570 *Globotruncanita, Hedbergella, Heterohelix, Pseudoguembelina, Racemiguembelina,*

571 *Pseudotextularia* and *Rugoglobigerina* species. The species *Plummerita hantkeninoides* is
572 present throughout the examined Maastrichtian cores, down through sample El Kef A 25R-1W,
573 75-77 cm (33.88 mbs) in which two individuals were observed. *P. hantkeninoides* is absent in the
574 next deepest sample examined (El Kef A 25R-1W, 103-107 cm; 34.17 mbs) and in all the
575 samples below this depth interval. Although a transitional form was observed in sample El Kef A
576 25R-1W, 127-130 cm (34.405 mbs), this single specimen more closely resembles
577 *Rugoglobigerina reicheli* and was therefore not considered a true *P. hantkeninoides*. For this
578 reason, the base of the *P. hantkeninoides* biozone is placed at the midpoint between sample El
579 Kef A 25R-1W, 75-77 cm and El Kef A 25R-1W, 103-107 cm (34.025 mbs; Table 1).
580 The K/Pg boundary (i.e., base of planktic foraminiferal zone P0) can be recognized by
581 the extinction of almost all Cretaceous taxa (*e.g., Globotruncana, Rugoglobigerina,* and
582 *Globigerinelloides*; Wade et al., 2011). The placement of the K/Pg boundary using planktic
583 foraminiferal biostratigraphy is consistent with the nannofossil biostratigraphy in Hole A, but
584 shows a +~35 cm offset in Hole E (Table 1). Above the K/Pg boundary, planktic foraminifera are
585 poorly preserved and assemblages are less diverse than at open ocean sites. The FO of *P.*
586 *eugubina* (base Pα) occurs at a depth of 19.39 mbs in Hole A and 18.72 mbs in Hole E (Figure 3;
587 Table 1). However, these earliest specimens are non-typical (containing only 4 ½ to 5 chambers),
588 with classic 6-7-chambered forms not appearing until sample El Kef A 16R-1W, 8-9 cm (~19.07
589 mbs) and not being observed at all in El Kef E, although this may be because only the 38-63 μm
590 size fraction was examined in most samples from this hole. This depth level is coincident with an
591 increase in the abundance of biserial planktic foraminifera, which occurs at ~19 mbs and ~16.05
592 mbs in Holes A and E, respectively. At the very top of their stratigraphic range (between El Kef
593 E 7R-1W, 65-67 cm (13.77 mbs) and El Kef E 7R-1W, 125-127 cm (14.37 mbs)), *P. eugubina*

specimens are very rare. Despite this, we were still able to reliably identify the LO of this taxon (base biozone P1a) within both Holes A and E (Table 1). Overall, the stratigraphic range of *P. eugubina* (i.e., the 'thickness' of Pα) spans ~2 m of sediment in Hole A and >4.5 m of sediment in Hole E (Figure 3; Supplementary Figure 2), confirming that Hole E contains a thicker succession of earliest Danian sediments than Hole A despite the fact that the two holes were drilled within ~5 m of each other.

The FO of *Subbotina triloculinoides* (base biozone P1b) was recognized immediately above the unconformity in Hole E (~12.38 mbs), but was not observed in Hole A (Table 1) as planktic foraminiferal biostratigraphy was not conducted above ~17.13 mbs in this hole. At the base of Hole C, which lies further above the unconformity, planktic foraminiferal assemblages contain *Globanomalina compressa,* placing these sediments firmly within biozone P1c. As the P1b/P1c boundary was not observed in any of the three holes examined (Holes A, C, and E), it is possible that this time slice (spanning <1.2 Myr) was not preserved in any of the cores recovered, or that it is contained within the weathered cores at the top of Hole E (Cores 2 to 4) which were not sampled for planktic foraminiferal biostratigraphy due to poor preservation. Alternatively, this stratigraphic boundary might be preserved at El Kef but not expressed in our recovered cores due to the same local or regional tectonic processes (e.g., faulting) that led to each of our drilled holes containing slightly different parts of the upper Maastrichtian and/or lower Danian. The presence of a second unconformity above the one located at El Kef E 5R-1W, 21 cm (~10 mbs) is also possible, and is explored in further detail within the Discussion.

The base of biozone P2 was tentatively placed between samples El Kef C 14R-1W, 73-76 cm (~20.45 mbs) and El Kef C 14R-1W, 123-126 cm (20.95 mbs; midpoint ~20.7 mbs; Table 1), at the first occurrence of *Praemurica uncinata*. Very rare *P. uncinata* specimens were also

observed in sample El Kef C 20R-1W, 93-96 cm (30.15 mbs). However, this taxon was noticeably absent from the next nine samples examined above this depth level (i.e., between samples El Kef C 14R-1W, 123-126 cm and El Kef C 20R-1W, 38-41 cm; 20.95 to 28.65 mbs), suggesting that its isolated presence at a sample depth of 30.15 mbs is a product of downhole drilling contamination. Furthermore, if the P1c/P2 biozone boundary were to be placed as far down as ~30.15 mbs in Hole C, the FOs of near-contemporary nannofossil taxa such as *Chiasmolithus danicus*, *Cruciplacolithus tenuis, Prinsius martinii,* and *Toweius pertusus* would be observed at similar or lower depths (e.g., within El Kef C 20R-1W or below). In addition, *Praeprinsius tenuiculus* should be absent from almost all Hole C samples. However, *P. tenuiculus* is present in high abundances throughout the entirety of Hole C and the FOs stated above were not observed in any of the nannofossil samples from this hole. We therefore consider the consistent presence of *P. uncinata* starting at ~20.7 mbs as its true first occurrence.

**Geochemistry**

***Total organic carbon (TOC)***

The oldest part of the Maastrichtian that was recovered at El Kef (between ~29.40 and 36.04 mbs; Hole A) is characterized by relatively stable TOC contents (~0.75 weight percent) (Figure 3d). Above this interval in Hole A and above the bottom-most sample analyzed in Hole E (~27.73 mbs), TOC values gradually decrease to ~0.5 wt. % up until the K/Pg boundary. Above the extinction horizon (~20 mbs; Hole A and ~19.4 mbs; Hole E), TOC content begins to increase up to a maximum of 1.13 wt. % at 17.26 mbs (Hole A) and up to a maximum of 1.3 wt. % at 17.05 mbs (Hole E). TOC values in Hole E then remain at ~1% until ~13.77 mbs, where there is a sharp, transient increase to TOC values exceeding 1.5 wt. %. Between 13.37 and 12.08 mbs in Hole E, TOC decreases back down to ~0.7 wt. % and remains at a relatively stable value

until the unconformity at ~10.08 mbs, above which TOC content decreases further (<0.5 wt. %). In Hole A, the decrease to similarly low TOC values occurs further down than in Hole E (~17.15 mbs). This is consistent with our previous suggestion that cave-in obscures the unconformity within Hole A, Core 14 (see Lithostratigraphy). Further above the unconformity (i.e., in Holes B and C, and the upper part of Hole A), TOC content remains low, generally ranging between 0.3 and 0.7 wt. % (Figure 4c). The decrease to very low values (~0.1 wt. %) at the top of each hole is most likely a product of weathering.

***Calcium carbonate content***

In the Maastrichtian, the weight percent calcium carbonate content ranges between ~10 and 50% and averages ~37.5% (Figure 3e). At ~20.025 mbs in Hole A and 19.175 mbs in Hole E, $CaCO_3$ content sharply decreases to <10 wt. %, representing the 'carbonate crash', which is characteristic of the K/Pg mass extinction. However, although the depth level of the $CaCO_3$ decrease is consistent with the last occurrence of Cretaceous calcareous nannoplankton taxa in both Holes A and E, the LO of Cretaceous planktic foraminifera is observed 20 cm higher than the carbonate crash in Hole A and ~30 cm lower than it in Hole E. The depth discrepancy between the extinction of planktic foraminifera and the decrease in $CaCO_3$ values in Hole E can likely be explained by the fact that only planktic foraminiferal samples from the 38 to 63 μm size fraction were examined from this hole. Therefore, some of the larger Cretaceous species may only have been present in sediments from the > 63 μm size fraction and thus not observed in our study. In contrast, the depth discrepancy in Hole A may be due to the short-term persistence of some smaller planktic foraminiferal species into biozone P0, as previously recognized in other stratigraphically expanded K/Pg sections (e.g., Strong, 2000; Arenillas et al., 2004; Keller, 2004; Rasmussen et al., 2005).

Above the K/Pg boundary in El Kef A (~20.025 mbs), $CaCO_3$ content remains relatively low (average 13-14 wt. %) up to ~18.25 mbs. Between 18.25 and ~17 mbs, % $CaCO_3$ values then increase gradually to just over 40% (Figure 3e). Higher up-section, a further increase to even higher $CaCO_3$ contents (~60 wt. %) occurs over the hypothesized, obscured unconformity near the top of El Kef A, Core 14. Post-extinction $CaCO_3$ content also remains low in El Kef E up to a depth of ~17.9 mbs. Above this, % $CaCO_3$ values briefly increase to up to ~40 wt. % at 17.73 mbs, before gradually decreasing back down to lower values (~10 wt. %) between 17.73 and 16.15 mbs (Figure 3e). Above 16.15 mbs, $CaCO_3$ content abruptly increases once more to ~40 wt. %, and consistently averages around this value up ~11.5 mbs. $CaCO_3$ declines to ~20 wt. % until ~10.08 mbs, then sharply increases to >60 wt. % across the unconformity, similarly to El Kef A.

At the base of El Kef B and C, which are also above the unconformity, % $CaCO_3$ fluctuates at ~55 wt. % (Figure 4d). Above 15.52 mbs in El Kef B, average % $CaCO_3$ values increase to 70 wt. %, and remain consistently high until the top of the hole. This increase in $CaCO_3$ content occurs meters below the weathering horizon and is also observed at a depth of ~11.5 mbs in El Kef A, but is not recorded in El Kef C.

***Bulk organic $\delta^{13}C$***

During the earliest part of the upper Maastrichtian at El Kef (Figure 3f), $\delta^{13}C_{org}$ values average ~ -27.2 ‰. Between 26.8 mbs and 22.2 mbs in El Kef A, $\delta^{13}C_{org}$ increases by ~1 ‰. A similar increase is also observed in El Kef E between 27.7 mbs and 22 mbs, but is more gradual and not as large (~0.5 ‰), likely because El Kef E was not drilled as deeply as Hole A so the earliest part of this positive excursion was not recovered. Between 22.2 mbs and 22.0 mbs in El Kef A, $\delta^{13}C_{org}$ values decrease back down to ~-27 ‰ and remain low until the K/Pg boundary.

This same decrease is not observed at a similar depth in El Kef E, where $\delta^{13}C_{org}$ values continue to average ~-26.7 ‰. At the K/Pg boundary in El Kef A (~20.06 mbs), $\delta^{13}C_{org}$ values are variable (Figure 3f). However, approximately 5 to 20 cm above the boundary, (~19.98 to 19.8 mbs), there is a sharp but transient ~0.7 ‰ increase to average $\delta^{13}C_{org}$ values of -25.9 ‰, followed by a decrease back to average values of ~-26.5 ‰. In El Kef E, this positive $\delta^{13}C_{org}$ spike is not observed at the K/Pg boundary. Instead, there is a ~1 ‰ transient decrease in $\delta^{13}C_{org}$ between ~19.2 and 19.0 mbs, above which average values return to ~-26.5 ‰. Following the transient changes in $\delta^{13}C_{org}$ immediately above the K/Pg boundary, bulk organic $\delta^{13}C$ values are relatively stable until the unconformity at ~17.15 mbs (El Kef A) and ~10.12 mbs (El Kef E), above which there is 1 ‰ decrease in $\delta^{13}C_{org}$ (Figure 3f). The subsequent increase in bulk organic $\delta^{13}C$ above ~9.55 mbs in El Kef E, is coincident with the onset of weathering and thus is not considered a primary signal.

Above the unconformity at the base of El Kef B, and El Kef C (Figure 4e) and the upper part of El Kef A (Figure 3f), bulk organic $\delta^{13}C$ values are relatively invariable and remain consistently low (average ~-27.5 ‰). A slight ~0.5 ‰ decrease in $\delta^{13}C_{org}$ is observed between 10.2 and 5.47 mbs in El Kef B, but not in El Kef A and C. As in El Kef E, the increase to more positive $\delta^{13}C_{org}$ values near the tops of El Kef A, El Kef B and El Kef C is likely a product of weathering.

***Bulk carbonate $\delta^{13}C$ and $\delta^{18}O$***

Throughout the uppermost Maastrichtian at El Kef (~36 to 20 mbs; El Kef A, ~28.11 to 18.68 mbs; El Kef D and 27.7 to 19.2 mbs; El Kef E), bulk carbonate $\delta^{13}C$ gradually increases by 1 ‰, reaching a maximum of 1.41 ‰, 1.18 ‰ and 1.72 ‰ just below the K/Pg boundary in El Kef A, D and E, respectively (Figure 3g). At approximately 5 cm above the K/Pg boundary,

709 $\delta^{13}C_{carb}$ values abruptly decrease by ~1.4 ‰. The higher resolution isotope record of El Kef E
710 shows that this decrease in bulk carbonate $\delta^{13}C$ to a minimum value of -2 ‰ occurs over a ~1 m
711 stratigraphic interval (19.2 to 18.2 mbs). Two slight $\delta^{13}C_{carb}$ enrichments then occur in El Kef E
712 between 18.2 and 17.5 mbs and between 16.4 and 15.7 mbs (Figure 3g). However, $\delta^{13}C$ values
713 fluctuate during both depth intervals, making it uncertain whether these transient enrichments
714 reflect any meaningful environmental or stratigraphic changes. Indeed, similar enrichments are
715 not observed at the same depths in Hole D, although the isotope records from this hole are at a
716 much lower resolution than from Hole E. Above 15.7 mbs in Hole E, $\delta^{13}C_{carb}$ values remain
717 relatively constant, fluctuating around an average value of ~0 ‰. At ~10.08 mbs in Hole E, bulk
718 carbonate $\delta^{13}C$ increases by ~3 ‰ (Figure 3g) further supporting the presence of an
719 unconformity at this depth level. Above the unconformity (i.e., from the base to the top of El Kef
720 C; Figure 4f), bulk carbonate $\delta^{13}C$ gradually increases from ~0.6 ‰ to 2.5 ‰, without any major
721 excursions. Overall, we are confident that the trends in our bulk carbonate $\delta^{13}C$ record are
722 predominantly a primary signal, as similar $\delta^{13}C$ values were measured from an overlapping
723 stratigraphic interval in two separate labs (Figure 3g).

724 The bulk carbonate $\delta^{18}O$ record for the El Kef cores (Supplementary Figures 3 and 4) is
725 variable with values often fluctuating greatly. This variability is likely the result of diagenetic
726 calcite, which was commonly observed infilling planktic foraminifera tests and has likely
727 overprinted the primary $\delta^{18}O$ signal, as recently shown in samples from the El Kef GSSP outcrop
728 (Sepúlveda et al., 2019). For this reason, we decided to omit the bulk carbonate $\delta^{18}O$ data from
729 our interpretations. Although the bulk carbonate $\delta^{13}C$ record is likely to have been similarly
730 affected, it is generally more resilient to diagenetic alteration than $\delta^{18}O$ (Margolis et al., 1987). In
731 our $\delta^{13}C$ record, this is supported by the fact that clear paleoenvironmental trends are observed

(e.g., at the K/Pg boundary and the unconformity) in concurrence with changes in e.g., lithology, wt. % $CaCO_3$ and wt. % TOC, which is not the case in the $\delta^{18}O$ record. Furthermore, our bulk carbonate $\delta^{13}C$ record is generally much less variable than our $\delta^{18}O$ record, especially in Hole C (Supplementary Figure 4). Nonetheless, although the trends in our $\delta^{13}C$ record appear to be paleoenvironmentally significant, the absolute $\delta^{13}C$ values should be interpreted with caution, especially when directly comparing to bulk carbonate $\delta^{13}C$ records from other sites, as complex sedimentological, source-related, and diagenetic processes can affect the bulk carbonate $\delta^{13}C$ record (e.g., Minoletti et al., 2005; Sepúlveda et al., 2019).

## DISCUSSION

### El Kef composite section

A composite stratigraphic section ('splice') for the five holes drilled at El Kef was constructed using the biostratigraphic datums, coulometry (wt. percent TOC and $CaCO_3$), stable isotopic records and scanning XRF data (iron (Fe) and zircon (Zr) total counts) (Figure 5). To construct a composite record, the individual cores from each hole were first offset with respect to the drill depth so that prominent features in the data could be correlated. The splice was then defined using the highest-resolution, fullest-coverage dataset available within a given stratigraphic interval. The scanning XRF data were therefore particularly critical for constraining the splice, as these data were generated for every core section in each hole and often at a higher resolution and signal/noise ratio than the other data types. This meant that general patterns and large amplitude variations in Fe and Zr (including at the K/Pg boundary) could be finely and reliably matched between cores from different holes. Once the best core sections from parallel holes were spliced together (composite section), offsets were calculated for every core so that the

754 data plotted separately for each individual hole (drilling depth in meters below surface; mbs)
755 could all be plotted on the same depth scale (meters composite depth; mcd).
756 Overall, our presented splice represents a stratigraphic record of the entire K/Pg boundary
757 section at El Kef (Figure 5), including the uppermost Maastrichtian (61.44 to 78 mcd), the K/Pg
758 extinction horizon (61.44 mcd), the lower Danian (52.5 to 61.44 mcd) and the mid to upper
759 Danian (0 to 52.5 mcd). Whilst core correlation is robust in the upper Maastrichtian and lower
760 Danian (including the K/Pg boundary), the upper Danian section (i.e., in Holes B and C) is more
761 challenging to correlate in detail in all records, partly due to the lack of calcareous nannofossil
762 biostratigraphic datums within this interval. Furthermore, intense coring disturbance and
763 weathering can sometimes hinder high-resolution correlation, causing slight mismatches between
764 data from adjacent holes even after applying the offsets. This, coupled with the fact that each of
765 the El Kef holes reveal a structurally complex and distinct stratigraphic succession despite their
766 proximity to one another, makes core correlation challenging. Nevertheless, we provide here a
767 best possible composite record reflecting the stratigraphic succession recovered from all five
768 holes, allowing for future integration and fine-tuning of detailed paleontological and
769 geochemical records at El Kef.
770 **Construction of an age model: correlation of the El Kef composite core section to Ocean**
771 **Drilling Program (ODP) Site 1262 (Walvis Ridge, S. Atlantic)**
772 To establish an age model for the El Kef drill cores we first formed a basic age model
773 based on biostratigraphy. The planktic foraminiferal and nannofossil biostratigraphic datums
774 (Figure 6; Table 1) do not provide a consistent basis for the Danian part of the record as there are
775 several stratigraphic conflicts between the two taxonomic groups within the El Kef cores (e.g.,
776 the FO's of the nannofossil taxa *Coccolithus pelagicus, Cruciplacolithus intermedius, and*

*Cruciplacolithus tenuis* vs. the placement of the P1a, P1b, and P2 planktic foraminiferal datums respectively; Supplementary Figure 2). Thus, we formed one age model using only planktic foraminiferal datums (shown in Table 2) and an alternative age model using only calcareous nannofossil datums (shown in Table 3) for the Danian interval. The K/Pg boundary and base of the Maastrichtian planktic foraminiferal *Plummerita hantkeninoides* biozone were then used to complete the biostratigraphic age model framework. To test both age models and potentially improve them, we correlated our $\delta^{13}C$ bulk carbonate record, the XRF core scanning Fe elemental data and biostratigraphic datums (in Tables 2 and 3) to the ODP Site 1262 (Walvis Ridge) record in the equatorial South Atlantic (Figures 7 and 8), which currently has the best-constrained orbital age model for the latest Cretaceous and early Paleocene (Westerhold et al., 2020). As the Walvis Ridge age model is directly correlated to the Laskar2010b curve (Laskar et al., 2011), it reports calcareous nannofossil and planktic foraminferal datums down to 3 decimal places (i.e., 1000 years). Therefore, in this study, we also report our El Kef biostratigraphic datums down to 1000 years to maintain consistency with the Walvis Ridge age model and to allow for high-precision correlation of the El Kef and Walvis Ridge records. Reducing the precision of the reported ages to 1 or 2 decimal places has the potential to introduce artefacts that could be falsely interpreted as phase lags or a delay in the biotic response.

The upper Maastrichtian part of the El Kef record from the base of the *Plummerita hantkeninoides* biozone (~75.5 mcd) to the K/Pg boundary, reveals five well-defined precession-related Fe cycles (Figure 5b; Supplementary Figures 5 and 6). This is consistent with a recent study on the K/Pg outcrop section in Zumaia (Spain), which also found five precession cycles (representing ~100 kyr) between B. *P. hantkeninoides* and the K/Pg boundary (Gilabert et al., 2022). In addition, the Fe cycles in our El Kef cores are correlated to the prominent precession-

controlled Fe cycles present at Walvis Ridge (Figures 7 and 8). Therefore, to provide a more detailed chronology for the upper Maastrichtian El Kef section, we modified the age model for Site 1262 from Westerhold et al. (2020) for the cycles in the Maastrichtian, assuming they represent precession cycles (Table S1). We then correlated the precession-related cycles for El Kef (Maa tie points 1 to 5; Table S2; Figure 5b) aligning maxima in Fe intensity to those at Site 1262. Bulk carbonate $\delta^{13}C$ records confirm this phase relationship (Figure 9) and the correlation.

Spectral analysis was also attempted for the Paleocene part of the record at El Kef. However, clear cycles were not visible during the earliest Danian (~55 to 61.5 mcd) and potential ~2 m cyclicity in the XRF Fe data above this (0 to ~55 mcd) cannot be reliably interpreted due to faulting disturbance and uncertainties in the biostratigraphy. This makes the Danian interval at El Kef more challenging to correlate to the Walvis Ridge record. Despite this, we tested two correlation options based on the biostratigraphy (tie points given in Table S2). Our results reveal that the $\delta^{13}C$ bulk carbonate record for El Kef generally shows a much better correlation to the $\delta^{13}C$ bulk carbonate record for Walvis Ridge when using Option 1 (planktic foraminifera-based biostratigraphy; Figure 9A) than when using Option 2 (calcareous nannofossil-based biostratigraphy; Figure 9B). Although the magnitude of changes in the $\delta^{13}C$ bulk carbonate record are not expected to be identical at continental shelf/slope sites such as El Kef and pelagic sites such as Walvis Ridge due to the different biogeochemical processes operating in these disparate depositional systems (see Sepúlveda et al., 2019 for detailed discussion), trends in our Option 2 $\delta^{13}C_{carb}$ curve clearly mismatch those in the Walvis Ridge record. This is particularly evident at ~65.95 Ma, where the $\delta^{13}C_{carb}$ values in the Walvis Ridge and El Kef Option 1 records continue to decline, whereas $\delta^{13}C_{carb}$ values in the El Kef Option 2 record begin a steady and consistent increase (Figure 9). A similar increase in $\delta^{13}C_{carb}$ values does not occur until ~65.825

823 Ma in both the Walvis Ridge and the planktic foraminifera-based records, indicating that the
824 Option 1 correlation is more parsimonious; especially during the earliest Danian.

825 The higher reliability of the planktic foraminifera-based age model is further revealed in
826 Figure 6. Here, several of the nannofossil datums, especially those from Holes A and D, more
827 closely conform to the planktic foraminiferal age-depth plot than the nannofossil age-depth plot,
828 the latter of which is largely based on datums from Hole E. This is puzzling, especially
829 considering that nannofossil biostratigraphy was conducted at much higher resolution in Hole E
830 than in Holes A and D. However, as the earliest Danian succession is thicker in Hole E compared
831 to Holes A and D, it is likely that the higher abundance of transitional nannofossil specimens in
832 Hole E made the precise designation of biozone datums within this hole more challenging (see
833 further discussion within section "Resolving the discrepancy between planktic foraminiferal and
834 calcareous nannofossil biostratigraphy").

835 Taking all these factors into account, we currently consider the planktic foraminifera-
836 derived age model (Figure 7) to be more reliable than the nannofossil-derived age model (Figure
837 8). Overall, this preferred age model is robust at and immediately above the K/Pg boundary.
838 However, its reliability decreases during the later Danian where potential tie points such as
839 biostratigraphic datums and geochemical data are scarcer. Although future intensive
840 biostratigraphic and geochemical work will likely improve the resolution of the later part of the
841 age model, our current composite section still provides a unique record of the K/Pg GSSP, which
842 can be correlated to other sites with orbital age control. This will help to constrain the rate of
843 ecosystem recovery following the K/Pg mass extinction at El Kef and allow its direct comparison
844 to global sites that sample different depositional environments.

845 **Sedimentation rates at El Kef**

846 Both our planktic foraminifera- and nannofossil-based age models indicate that the
847 uppermost Maastrichtian is stratigraphically expanded at El Kef, with high sedimentation rates
848 averaging ~11 cm/kyr (Figure 6). At the K/Pg boundary, the sedimentation rate drops
849 substantially to ~1 cm/kyr and ~5 cm/kyr in the planktic foraminifera- and nannofossil-based age
850 models, respectively (Figure 6). In the planktic foraminiferal age model, the sedimentation rate
851 remains consistently at ~1 cm/kyr throughout the rest of the Danian. In contrast, the nannofossil-
852 based age model shows more fluctuation in sedimentation rates, which decline from ~ 4 to 1
853 cm/kyr at approximately 30 kyr post-impact. Sedimentation rates then increase to up to 7 cm/kyr
854 (at ~250 kyr post-impact), before declining to ~4 cm/kyr at ~380 kyr post-impact. Due to
855 differences in the estimated early Danian sedimentation rates in the two models, the
856 unconformity observed in Holes D and E (Plate 1B) occurred either ~1 Myr (planktic
857 foraminiferal age model) or ~0.5 Myr (calcareous nannofossil age model) after the mass
858 extinction event. When using the favored planktic foraminiferal age model, the duration of the
859 unconformity is estimated to be ~600 kyr.
860 Overall, the higher sedimentation rates predicted by the nannofossil-based age model
861 indicate that the post-extinction sediments in the El Kef cores represent ~1.25 Ma of the early
862 Paleocene, whereas the planktic foraminifera-based age model suggests that the same depth
863 interval represents >2 Ma of the Danian. Although sedimentation rates are expected to be
864 relatively high at outer shelf/upper slope sites such as El Kef, the early Danian sedimentation
865 rates of >4 cm/kyr predicted by the nannofossil age model greatly exceed all prior estimates
866 based on the El Kef outcrop section (e.g., Cande and Kent, 1995; Adatte et al., 2002; Stüben et
867 al., 2002). In contrast, the lower Danian sedimentation rates in the planktic foraminifera-based
868 age model are more consistent with previous time-averaged estimates for El Kef (~1.1 to 2.5

cm/kyr; Cande and Kent, 1995; Adatte et al., 2002; Macleod et al., 2018), and with lower estimates for sedimentation rates at nearby Elles, Tunisia (~2 to 4 cm/kyr; Galeotti et al., 2005), which is more proximal to the shoreline than El Kef and would therefore be expected to have slightly higher sedimentation rates (e.g., Adatte et al., 2002; Stüben et al., 2002; Vellekoop et al., 2015). The fact that sedimentation rates in the calcareous nannofossil-based aged model fluctuate greatly and are much higher than previous estimates for El Kef, provides further evidence that the planktic foraminifera-based age model is a more reliable option.

**Confounding issues that complicate interpretation of the K/Pg stratigraphy at El Kef**

As mentioned previously, a combination of structural and stratigraphic complexity, and drilling disturbance explain several apparent inconsistencies in our composite section and in core correlation, including the different depth levels of the unconformity in Holes A, D and E, and discrepancies in the placement of some planktic foraminiferal biostratigraphic datums between holes along the composite depth scale (e.g., the placement of biozones Pα and P1a in Hole A vs. Hole E). Below, we discuss in greater detail how these processes might have impacted our interpretations of the K/Pg stratigraphy at El Kef and its implications.

***Structural complexity***

Our multi-hole coring approach has revealed that the K/Pg stratigraphy in the El Kef region is more structurally complex than previously revealed by the prior outcrop studies. This is especially apparent when considering the unique stratigraphic signature of each of the holes. In particular, Hole B recovers a stratigraphic succession that is similar to Hole C, but different from both the K/Pg GSSP outcrop section (Keller and Lindinger, 1989; Molina et al., 2006) and Holes A, D, and E, which are located only ~25 m away (Figure 2B). Although the K/Pg boundary would likely have been recovered in Holes B and C if coring had continued deeper, the K/Pg

892 boundary was present in Holes A, D, and E, which were drilled to the same or lesser depths as
893 Holes B and C (Figures 3; 4). In addition, there are clear local variations in the stratigraphic
894 thickness of the lower Danian successions recovered in Holes A, D, and E (Figure 3), which
895 were drilled within only a few meters of one another (Figure 2B). Although it could be argued
896 that cave-in near the inferred unconformity in Hole A (~58.5 mcd; Figure 5) indicates
897 incomplete core recovery during drilling, there is no similar evidence showing that drilling
898 disturbance also caused differences in the early Danian stratigraphic thicknesses observed in
899 Hole D vs. Hole E. For this reason, we suggest a strong tectonic influence (i.e., syn-depositional
900 faulting) on our recovered sediment cores. In particular, we propose a small-offset NW-SE or
901 WNW-ESE normal fault between Hole B and Holes A, D and E that lacks surficial expression
902 due to the argillaceous lithology and thick deposits of Quaternary to recent sediments. This
903 makes the inference of its exact orientation and location imprecise. However, we suggest that
904 this hypothetical fault is in close proximity to Holes D and E (due to the particularly intense
905 (micro)fracturing within these holes), and is likely associated with the main fault located ~200 m
906 to the NE of the drill site (Figure 2). If this fault was active at the time of deposition it would
907 have resulted in an uneven seafloor topography and variable accommodation space that can
908 possibly explain the minor differences in depths to the K-Pg boundary and varied stratigraphic
909 thicknesses of the boundary interval in the closely-spaced Holes A, D and E. Alternatively these
910 variations may be a result of a network of microstructures that could have offset the
911 biostratigraphic datums and resulted in thickness differences on a local scale.
912 Although minor faulting at El Kef has previously been recognized (Negra et al., 2016),
913 evidence for tectonic activity is not readily observed in the outcrop section, which has been
914 described as “free from structural complication”: one of the factors that led to its designation as

915 the GSSP for the K/Pg boundary (Molina et al., 2006). However, in our sediment cores, we
916 documented abundant fractures and micro-faults (Plate 1, Figures C-E), many of which have the
917 NW-SE dominant trend typical of reactivated regional Late Cretaceous-Paleogene fault systems
918 (Bey et al., 2012; Negra et al., 2016; Figure 2A). Therefore, it is possible that the weathered
919 marl and shale in the outcrop masks the microstructures that are clearly observed in the cores.
920 This highlights the utility of sediment cores in gaining a deeper and more comprehensive
921 understanding of the underlying geology at a given site, especially those that are designated as
922 reference sections and GSSPs.

923 ***Stratigraphic complexity***

924 The El Kef outcrop, including the GSSP section, preserves what is traditionally thought
925 to be a stratigraphically complete and continuous K/Pg section from the uppermost Maastrichtian
926 to the lower Danian up to planktic foraminiferal biozone P1b (Molina et al., 2006). The
927 biostratigraphic datums and geochemical trends shown in our El Kef composite section are
928 broadly consistent with previous studies of the El Kef outcrop section (e.g., Keller and
929 Lindinger, 1989; Sepúlveda et al., 2019) including a characteristic ~3 ‰ decrease in $\delta^{13}C_{carb}$ and
930 a sharp decline in weight percent calcium carbonate at the K/Pg boundary (Figure 5), caused by
931 the extinction of >90% pelagic marine calcifiers (e.g., Bown, 2005; Jiang et al., 2010; Alegret et
932 al., 2012). However, our lithologic and biostratigraphic data indicates an unconformity between
933 ~63.84 and 64.41 Ma (based on the planktic foraminifera-derived age model) within planktic
934 foraminiferal zone P1b (e.g., Plate 1B) that has not previously been recognized in the El Kef
935 outcrop, but which might be related to that recently observed in a nearby outcrop section at Elles,
936 Tunisia (Arenillas et al., 2021).

937 It is also possible that a second unconformity exists within planktic foraminiferal biozone
938 P1c. This is suggested due to a +~1‰ offset in $\delta^{13}C_{carb}$ values and a +~2‰ offset in $\delta^{13}C_{org}$
939 values at the top of Hole E compared to the base of Hole C, despite their apparent stratigraphic
940 overlap in the composite section (i.e., between ~49 and 52 mcd; Figure 5f, g). Although the
941 positive $\delta^{13}C_{org}$ excursion at the top of Hole E is likely related to weathering (Figure 5f), a
942 weathering-induced enrichment of $\delta^{13}C_{carb}$ at the top of Hole E is unlikely and is not observed
943 within the weathered upper cores of any of the other holes (e.g., Hole C; Figure 5g). In addition,
944 other geochemical parameters (such as the XRF Fe and Zr area counts) that would also be
945 affected by weathering, maintain similar values at the top of Hole E vs. the base of Hole C, and
946 are in fact used in stratigraphic core correlation (Figure 5b, c). Therefore, it is unlikely that the
947 offset in $\delta^{13}C_{carb}$ values between the top of Hole E and base of Hole C can be completely
948 explained by weathering. Alternatively, the presence of a second unconformity and/or faulting
949 activity are plausible explanations for the $\delta^{13}C_{carb}$ discrepancy. Unfortunately, the presence of a
950 second unconformity cannot be confirmed at this time as the top four cores of Hole E were not
951 sampled for planktic foraminifera due to poor preservation. However, a resurgence of intense
952 micro-fracturing within the weathered core tops of Holes D and E, suggests that syn-depositional
953 faulting was active during this interval and may represent renewed displacement along the
954 previously hypothesized fault (Figure 2B). Thus, we conclude that the offset between $\delta^{13}C_{carb}$
955 values at the top of Hole E and the base of Hole C, can at least partially be explained by faulting.
956 Overall, our new data indicate that the K/Pg stratigraphy at El Kef may not be as
957 complete and continuous as previously thought. This has important implications regarding
958 recently raised questions concerning the completeness of the K/Pg geological record at high time
959 resolution, which might be the cause, at least in part, of the apparent geographic variability of

post-extinction fauna (Alegret et al., 2022). As a result, sections traditionally considered to be continuous, such as El Kef, due to the presence of all biozones, might be incomplete in detail, requiring re-evaluation of paleoenvironmental interpretations (Alegret et al., 2022).

Stratigraphic complexity at El Kef is further revealed when comparing our bulk carbonate $\delta^{13}C$ core records to one collected from the El Kef outcrop section (Keller and Lindinger, 1989; Figure 10). Based on these data, the K/Pg stratigraphy of the outcrop section is most similar to that recorded in our Hole E sediment cores, especially during the lower Danian. Although the early Danian succession in the outcrop section appears thicker than contemporaneous intervals in Hole E, especially during planktic foraminiferal biozones P0 and P1a (Arenillas et al., 2018), this is likely due to different paleontologists conducting the biostratigraphic and taxonomic work on outcrop vs. core samples. However, higher up in the Danian (~2 m above the boundary), the bulk carbonate carbon isotope records obtained from the outcrop becomes dissimilar from our Hole E $\delta^{13}C$ data (Figure 10). Planktic foraminiferal biostratigraphic studies have also yielded contradictory results during this interval (e.g., Keller, 1988a; Keller et al., 1996; Arenillas et al., 2000), potentially because they were conducted on multiple different outcrop sections, although this was poorly documented prior to the official establishment of the 'golden spike' GSSP (Molina et al., 2006). Although variations in biostratigraphy can at least partially be explained by the use of differing taxonomic concepts, the dissimilarities in the bulk carbonate $\delta^{13}C$ records of our cores compared to the outcrop section, especially in the later Danian, provide further evidence that the K/Pg stratigraphy at El Kef is locally complex; likely a direct result of the structural complications described previously.

***Drilling disturbance***

For Holes A, D, and E, which were drilled at approximately the same location (Figure 2B), the stratigraphic differences between holes can partially be explained by the rotary drilling process. Drilling disturbance and incomplete stratigraphic recovery is particularly likely at and around the lower Danian unconformity at ~52 mcd, which can be recognized by an increase in $\delta^{13}C_{carb}$ and weight percent calcium carbonate, and a decrease in $\delta^{13}C_{org}$ and weight percent TOC (Figure 5). In Hole E, this lithologic boundary is recognized by a sharp transition from darker- to lighter-colored sediments at ~22 cm in Core 5, with a relatively minor amount of drilling disturbance evident between ~25 and 42 cm within the same core (Plate 1B). In comparison, the same lithologic boundary in Hole D has clearly been more affected by drilling disturbance (Plate 1B) and is not observed at all in Hole A due to cave-in (Plate 1I). Drilling disturbance around the unconformity, in the immediate vicinity of the K/Pg boundary (especially in Hole E; Figure 5) and during other intervals within the El Kef cores; Plate 1I), often make the correlation of lithologic features challenging, leading to irreconcilable inconsistencies in the composite section.

**Implications concerning designation of El Kef as the K/Pg GSSP**

The El Kef outcrop was designated as the GSSP for the K/Pg boundary according to several criteria including its apparent freedom from structural complication and unconformities (Molina et al., 2006). However, our study provides strong evidence that faulting has had a profound impact on the K/Pg stratigraphy at El Kef, and reveals one potentially significant unconformity within planktic foraminiferal biozone P1b. Although these problems do not directly affect the sediments at or below the K/Pg boundary, the stratigraphic signatures of Holes A, D, and E start to become disparate less than 1 m above the boundary, suggesting that structural complications begin to affect the sediments within planktic foraminiferal biozone Pα (i.e., within 200 to 300 Kyr post-impact; Figure 5; Supplementary Figure 2). In addition to the

apparent lack of structural complexity, El Kef was also chosen as the K/Pg GSSP due to the 'abundance and diversity of well-preserved fossils' (Molina et al., 2006). Although calcareous nannofossils are generally moderately preserved and dinoflagellate cysts are moderately to well-preserved within the Danian at El Kef, planktic foraminifera are often poorly preserved and infilled with secondary carbonate. As well as hampering taxonomic identification for planktic foraminiferal taxonomy, the presence of diagenetic carbonate has also clearly affected our bulk carbonate $\delta^{18}O$ record, and to a lesser extent, our bulk carbonate $\delta^{13}C$ record. As these three data types are typically used in the correlation of stratigraphic sections, the correlation of El Kef to other sections will also likely be challenging as evidenced by our attempted correlation to Walvis Ridge.

Overall, we maintain that our unique composite record from El Kef provides a valuable contribution for better understanding the K/Pg stratigraphy in a global context. However, it is also a cautionary tale that structural and stratigraphic complications are not always obvious within outcrop sections, especially those composed of shale and marlstone. Therefore, our study reopens previous debates as to whether the El Kef outcrop, with its many challenges, really fulfills the criteria of the K/Pg GSSP, especially given the many auxiliary sections available in Tunisia and the greater Tethys area (Molina et al., 2009).

**Resolving the discrepancy between planktic foraminiferal and calcareous nannofossil biostratigraphy**

This study highlights significant discrepancies between the early Danian planktic foraminiferal and nannofossil datums at El Kef, the exact reasons for which are difficult to ascertain. Compared to the early Danian calcareous nannofossil biozones, the Paleogene planktic foraminiferal biozones have been more recently updated and calibrated to the Geological Time

Scale GTS (Wade et al., 2011), and most of the early Danian marker species are considered to be robust, reliable, and taxonomically easy to identify. Although planktic foraminiferal biozonation schemes continue to be refined and further developed (e.g., Arenillas et al., 2021), the standardized Wade et al. (2011) biozonation scheme is currently widely used within the planktic foraminifera community, allowing for consistency between different studies. In contrast, several alternate nannofossil biozonation schemes continue to be used during the early Danian (e.g., Martini, 1971; Okada and Bukry, 1980; Agnini et al., 2014), none of which have been as precisely calibrated to the GTS (Wade et al., 2011). In addition, each of the nannofossil biozonation schemes suffer from their own specific taxonomic challenges. These challenges are predominantly caused by the presence of abundant 'transitional' forms: specimens that represent intermediate morphologies between two closely-related species. Transitional forms are particularly common immediately above the K/Pg boundary due to the very high speciation and diversification rates that followed the mass extinction event (Bown et al., 2004), and are more readily observed in relatively stratigraphically expanded sections like El Kef. Although this aspect has exciting implications for examining the evolution of calcareous nannoplankton lineages following the K/Pg mass extinction event in future studies, it makes it challenging to pinpoint potential early Danian biozone marker species that can be consistently and reliably identified taxonomically and morphometrically throughout the nannofossil community.

Within this study, we encountered issues with each of the nannofossil biozonation schemes that we attempted to apply to the El Kef cores. For example, the biozonation schemes of Martini (1971) and Okada and Bukry (1980) rely heavily on the first occurrences of certain species within the *Cruciplacolithus* - *Chiasmolithus* lineage. As this lineage evolved very rapidly during the early Danian, there are many transitional forms that likely represent different species

or morphotypes, the identification of which has caused controversy and inconsistency in taxonomic concepts for this group (see e.g., Van Heck and Prins, 1987, Fornaciari et al., 2007; Agnini et al., 2014; and Thibault et al., 2018 for discussion). Taxonomic inconsistencies are particularly troubling when attempting to identify biostratigraphically important '*sensu stricto (s.s.)' Cruciplacolithus*/*Chiasmolithus* species including *Cr. primus*, *Cr. intermedius*, *Cr. tenuis,* and *Ch. danicus,* all of which are commonly used as biozone markers. Indeed, the taxonomy applied here for most of these species differs from that applied at Site 1262 (Bernaola and Monechi, 2007), and the first occurrences of the *Cr. primus* and *Cr. intermedius* markers are previously noted as being diachronous (by up to 25 to 30 kyr) between Walvis Ridge and Shatsky Rise (Schueth et al., 2015). In addition, at El Kef, we observed many specimens with morphologies that were intermediate between *Cr. primus* and *Cr. intermedius*, and very early forms of probable (but not *s.s.*) *Cr. tenuis* (similar to specimens observed at Bidart, France; Galbrun and Gardin, 2004), making it difficult to precisely constrain these datums. The possible evolutionary response of the *Cruciplacolithus* lineage to ecosystem recovery following the K/Pg mass extinction events hinders their biostratigraphic utility further (Thibault et al., 2018). The absence of *Cr. tenuis* (*s.s*.) and *Ch. danicus* at El Kef during a depth interval in which the planktic foraminiferal datums suggests they should be present, could be explained if *Cr. tenuis* and *Ch. danicus* originated chronologically later in shelf environmental settings than in pelagic environments as a result of slower nannoplankton recovery at shallower sites (e.g., Thibault et al., 2018; Jones et al., 2019). This hypothesis should be more rigorously tested at other K/Pg sites so that the utility of *Cr. tenuis* and *Ch. danicus* as useful biostratigraphic markers can continue to be critically assessed.

1073 The challenges of using *Cruciplacolithus* species as biostratigraphic markers have
1074 previously been recognized, and an alternate 'CNP' biozonation scheme has been recommended
1075 to resolve these issues (Agnini et al., 2014). However, we also encountered issues when applying
1076 this biozonation scheme to the El Kef cores, especially concerning the base common (Bc)
1077 *Praeprinsius dimorphosus* group datum (base CNP3), which includes the acme-forming taxa
1078 *Praeprinsius tenuiculus*. In the description of this biozone, 'common' is defined as "the initial
1079 increase in the abundance of this taxon" after which it shows "a continuous presence with
1080 abundance values >10 specimens/mm$^2$" (Agnini et al., 2014). As the method used in Agnini et al.
1081 (2014) to quantify the abundance of nannofossils is somewhat user-dependent, we did not apply
1082 it here. Therefore, we could not determine the depth at which *Pr. tenuiculus* reached a consistent
1083 abundance of >10 specimens/mm$^2$. However, *Pr. tenuiculus* continues to increase in abundance
1084 over several meters of sediment at El Kef and, as with *Cruciplacolithus*, the *Prinsius* lineage
1085 experienced rapid evolutionary rates during the early Danian. At El Kef, this is evidenced by the
1086 presence of many small, transitional forms with morphologies that are intermediate between
1087 *Praeprinsius* cf. *vegrandis* (the first *Prinsius* species to appear immediately above the K/Pg
1088 boundary; Kim (2020)) and *Praeprinsius tenuiculus*. This, coupled with the possibility that
1089 *Praeprinsius tenuiculus* may have formed geographically or environmentally asynchronous
1090 acmes (Jones et al., 2019), implies that we cannot accurately assign the CNP3 biozone at El Kef.
1091 Further taxonomic subjectivity and user-dependency in the designation of other CNP biozones,
1092 and significant age deviations for the bases of biozone CNP2 and biozone CNP4 further
1093 complicate the application of the Agnini et al. (2014) biozones (Kim, 2020). In fact, Kim (2020)
1094 showed that the age discrepancies are substantially less profound when using the traditional

nannofossil biozonation model of Martini (1971), which is still predominantly used within the nannofossil community despite its own issues during the early Danian.

In summary, the discrepancy between our nannofossil and planktic foraminiferal datums and age models at El Kef is presumably largely a product of taxonomic subjectivity and inconsistency within the commonly used nannofossil biozonation schemes. This is particularly problematic when attempting to correlate datums at two different sites, especially when disparate biozonation schemes or taxonomic concepts are used for each. In contrast, user subjectivity was diminished for our planktic foraminiferal biostratigraphy, as the same paleontologist collected these data at both El Kef and Walvis Ridge. In addition to taxonomic inconsistency, it is possible that the first occurrences of some of the traditional calcareous nannofossil marker species are environmentally controlled, similar to the *Micula prinsii* biozone marker in the late Maastrichtian (Henriksson, 1993), or possibly impacted by ecological interactions between species (e.g., Schueth et al., 2015), which would call into question their biostratigraphic utility. High-resolution studies from a range of depositional environments and geographic locations are required to critically assess whether this is the case. Finally, our study highlights the role of transitional nannofossil morphologies in complicating interpretations of the K/Pg stratigraphy at El Kef, but also likely at other stratigraphically expanded early Paleocene sites. As the cores from El Kef contain abundant transitional taxa, we suggest that it as an ideal candidate for conducting detailed morphometric work to better define and constrain the taxonomy of potential early Danian nannofossil markers. This future work would be an important first step in improving and/or developing a calcareous nannofossil biozonation scheme that can be consistently and universally applied to K/Pg sections worldwide.

## CONCLUSIONS

The sediment cores recovered from five new holes drilled close to the GSSP for the base of the Danian (i.e., the K/Pg boundary) near El Kef (Tunisia) provide over 100 m of unweathered, accessible material for future high-resolution analyses. Our new composite section and age model, based on biostratigraphic data as well as correlation of the XRF Fe and bulk carbonate $\delta^{13}C$ data to the orbitally-tuned Walvis Ridge record, confirm that the El Kef cores are stratigraphically expanded relative to other contemporaneous sections, but most importantly, indicate that they preserve an apparently continuous record of the last ~250 kyr of the Maastrichtian, the K/Pg boundary itself, and the earliest Danian (planktic foraminiferal biozones P0 to P2; ~3.5 Myr post-extinction), except for a <600 kyr-long unconformity near the top of Danian planktic foraminiferal biozone P1b (~1.7 Myr post-impact). Overall, we consider our El Kef age model to be robust for the upper Maastrichtian as the cores preserve precessional orbital rhythms that allow a high-resolution time scale to be constructed. Although these orbital cycles are not as prominent during the Danian, the planktic foraminiferal biozone datums below the inferred unconformity at ~52 mcd are well-constrained, leading to reasonable correlation of the El Kef and Walvis Ridge records and thus a relatively reliable age model. However, the age model becomes less reliable above the P1b unconformity as there is only one planktic foraminiferal datum as a tie point.

Another challenge in constructing the Danian part of the age model, and one of the most significant findings of our study, is the influence of tectonic processes on the local stratigraphy at El Kef. This is exemplified by the fact that two of the cored sections (Holes B and C), which were drilled within 75 meters of the other three sections (Holes A, D and E), preserve a different stratigraphic portion of the lower Danian. Moreover, Holes A, D and E each show different depths to the K/Pg boundary and P1b unconformity, as well as variable stratigraphic thicknesses

of the earliest Danian interval. These differences are likely a result of syn-depositional faulting that resulted in uneven seafloor topography. In addition, many of the microstructural features revealed within our El Kef cores were not observed in outcrop, indicating that a combination of sediment core and outcrop data should be used to gain a more comprehensive understanding of the stratigraphy of this site, especially considering its designation as a GSSP. Despite these caveats, and the attendant challenges in core correlation, the age model contained herein is far more detailed and complete than existing ones based on the El Kef outcrop, and can be used to reliably place paleoceanographic, paleoenvironmental and paleoecological work on the K/Pg boundary GSSP into a global context.

**ACKNOWLEDGEMENTS**

We would like to thank Thomas Frederichs, University of Bremen, Germany for his attempted paleomagnetic analyses on the El Kef cores and Marwa Baroumi for her assistance in the field during both drilling seasons. Drilling and core shipment was supported by NASA Exobiology NNX12AD83G (to TB). HB acknowledges support from the ERC grant PAst Links in the Evolution of Ocean's Global ENvIronment and Ecology (PALEOGENiE). JS acknowledges support from the MIT International Science and Technology Initiative (MIT-MISTI Spain) Seed Grant, the University of Colorado Boulder, and NSF awards 2037750 and 2021648. JV acknowledges support from the Research Foundation Flanders (FWO) grant 12Z6618N. JHW acknowledges financial support from Annual Adventures in Research award and Megan Wilding and Bastian Hambach for laboratory assistance. LA acknowledges support from Grant PID2019-105537RB-I00 funded by MCIN/AEI/ 10.13039/501100011033 and by "ERDF A way of making Europe", and the Government of Aragon (Reference Group E33_17R). MH acknowledges financial support from the Yale Peabody Museum, and laboratory

assistance from Jule Hoysagk. JvD acknowledges financial support from the Swiss National Science Foundation. Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany´s Excellence Strategy – EXC-2077 – 390741603 ("The Ocean Floor – Earth´s Uncharted Interface ", research unit RECORDER). Last (but not least), we would like to thank Philippe Claeys and another anonymous reviewer for their helpful comments and suggestions, which helped to greatly improve the quality of this manuscript.

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**FIGURE CAPTIONS**

Figure 1. A. Paleogeographic map of the late Maastrichtian to early Paleogene created using PALEOMAP (Scotese, 2001), showing the location of the El Kef section in relation to other K/Pg sites. B. Simplified paleogeographic map of northwest Tunisia during the late

Maastrichtian to early Danian showing the depositional setting of the El Kef section (star) and other Tunisian K/Pg sections. Isolines indicate depth in meters. Modified after Burrolet, 1967.

Figure 2. A. Location of the K/Pg GSSP outcrop section (yellow star) within context of the regional geology (modified from Lindinger, 1988) showing NW-SE to NNW-SSE faults that appear to have impacted sedimentation. The major fault that runs along and approximately parallel to the closest road (northern part of map) is represented by a thicker black dashed line. B: Google Maps image showing the exact location of the holes drilled during the El Kef Coring Program in relation to the GSSP outcrop section (yellow star) and the new auxiliary outcrop section that was used to guide drilling (labelled 'Survey site'; Macleod et al., 2018). A possible minor fault between Hole B and Holes A, D and E is shown as a red dashed line. A more detailed Google Earth map is shown in Supplementary Figure 1.

Figure 3. Line scan images for (a) El Kef A, (b) El Kef D and (c) El Kef E with core numbers and key planktic foraminiferal and calcareous nannofossil datums shown to the right of each hole. The relative position of the K/Pg boundary as determined biostratigraphically in each hole is shown by a red line, and the relative position of the unconformity in each hole is shown by a yellow dashed line. Panels d through g show associated geochemical data from El Kef A (black lines), El Kef D (orange lines), and El Kef E (blue lines) — (d) weight percent total organic carbon (TOC), (e) weight percent calcium carbonate ($CaCO_3$), (f) bulk organic $\delta^{13}C$ and g) bulk carbonate $\delta^{13}C$. The dark blue open triangles in panel g indicate additional stable isotope data that were collected at Yale University; all other data in this panel were collected at the National

Oceanography Centre, University of Southampton. Data is plotted against meters below surface (mbs), explaining the mismatch in data between holes.

Figure 4. Line scan images for (a) El Kef B and (b) El Kef C, with core numbers shown to the right of each hole. The *Praemurica uncinata* planktic foraminiferal datum is also displayed next to panel (b). Panels c through f show associated geochemical data from El Kef B (green lines) and El Kef C (gray lines) — (c) weight percent total organic carbon (TOC), (d) weight percent calcium carbonate ($CaCO_3$), (e) bulk organic $\delta^{13}C$ and (f) bulk carbonate $\delta^{13}C$. Data is plotted against meters below surface (mbs) for each hole.

Figure 5. Composite section derived from the splice for El Kef. The K/Pg boundary is marked by the red dashed line. (a) Line scan images for El Kef A to El Kef E, with core numbers to the right of the images. The white spaces in-between core images signify stratigraphic gaps. The yellow dashed lines in Holes A, D, and E represent the inferred position of the unconformity based on lithological, biostratigraphic, and geochemical observations. Panels (b) through (g) show the compiled geochemical data colored by hole: El Kef A (black), El Kef B (green), El Kef C (gray), El Kef D (orange) and El Kef E (blue). (b-g): (b) Iron (Fe) X-ray diffraction (XRD) data, with numbered arrows marking the Maastrichtian precessional cycles as defined by spectral analysis (Supplementary Figures 5 and 6), (c) Zircon (Zr) XRD data, (d) Weight percent total organic carbon (TOC), (e) Weight percent calcium carbonate ($CaCO_3$), (f) bulk organic $\delta^{13}C$, (g) bulk carbonate $\delta^{13}C$. The right-hand side of the figure shows the planktic foraminiferal biozones from Hole E. Nannofossil datums (based on the Hole E biostratigraphy) are shown to the right.

1610 Figure 6. Age-depth model for El Kef.

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1612 Figure 7. Correlation of the XRF data (red) and bulk carbonate $\delta^{13}C$ records (black) at the El Kef
1613 composite section (this study; bottom red and black lines) and at ODP Site 1262 Walvis Ridge
1614 (Westerhold et al., 2020; top red and black lines) using only planktic foraminiferal
1615 biostratigraphic datums in the Danian. Tie points are shown as blue lines.

1616 Figure 8. Correlation of the XRF data (red) and bulk carbonate $\delta^{13}C$ records (black) at the El Kef
1617 composite section (this study; bottom red and black lines) and at ODP Site 1262 Walvis Ridge
1618 (Westerhold et al., 2020; top red and black lines) using only calcareous nannofossil
1619 biostratigraphic datums in the Danian. Tie points are shown as blue lines.

1620 Figure 7. Correlation of the XRF data (red) and bulk carbonate $\delta^{13}C$ records (black) at the El Kef
1621 composite section (this study; bottom red and black lines) and at ODP Site 1262 Walvis Ridge
1622 (Westerhold et al., 2020; top red and black lines) using only planktic foraminiferal
1623 biostratigraphic datums in the Danian. Tie points are shown as blue lines.

1624

1625 Figure 8. Correlation of the XRF data (red) and bulk carbonate $\delta^{13}C$ records (black) at the El Kef
1626 composite section (this study; bottom red and black lines) and at ODP Site 1262 Walvis Ridge
1627 (Westerhold et al., 2020; top red and black lines) using only calcareous nannofossil
1628 biostratigraphic datums in the Danian. Tie points are shown as blue lines.

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1630 Figure 9. Correlation of the bulk carbonate $\delta^{13}C$ record from Walvis Ridge (red line) to the
1631 composite bulk carbonate $\delta^{13}C$ record from El Kef (black line; top and gray line; bottom) using

(A) only the planktic foraminiferal biostratigraphic datums for the Danian (Option 1) and (B) only the calcareous nannofossil biostratigraphic datums for the Danian (Option 2).

Figure 10. Plot comparing bulk carbonate $\delta^{13}C$ records from our El Kef drill cores (Hole D; orange line and Hole E; blue line) with those from the El Kef outcrop, using data from Keller and Lindinger, 1989 (green line). We also compare our planktic foraminiferal biostratigraphy from Hole E to the El Kef outcrop (modified from Arenillas et al., 2000).

Plate 1. Line scan images showing important lithostratigraphic features within the El Kef cores. Most of the core images shown were taken with a 6.7 x aperture, as these camera settings generally made the desired features and structures on the split core surfaces more visible. Core sections denoted with an asterisk (*) indicate images taken with an 11 x aperture.

Plate 2. Common calcareous nannofossil taxa observed in the El Kef cores. 1, 2. *Cruciplacolithus* "*pretenuis*", 1. Hole C-7R-1, 61cm; 2. Hole C-3R-1, 1 cm. 3, 4. *Cruciplacolithus intermedius*, 3. Hole C-2R-1, 100 cm; 4. Hole C-5R-1, 10 cm. 5-9. *Cruciplacolithus primus*, 5. Hole E-9R-1, 30 cm; 6. Hole E, 4R-1, 50 cm; 7. Hole E, 5R-1, 30 cm; 8. Hole E, 8R-1, 130 cm (early morphotype); 9. Hole E, 8R-1, 90 cm (early morphotype). 10-12. *Coccolithus pelagicus*, 10. Hole E, 7R-1, 149 cm (early morphotype); 11. Hole E, 9R-1, 50 cm; 12. Hole D, 8R-1, 60 cm. 13-15. *Neobiscutum parvulum*, 13. Hole E, 5R-1, 110 cm; 14. Hole E, 6R-1, 110 cm; 15. Hole E, 8R-1, 10 cm (coccosphere). 16-18. *Praeprinsius* cf. *vegrandis*, 16. Hole E, 4R-1, 50 cm; 17. Hole E, 4R-1, 50 cm; 18. Hole E, 4R-1, 50 cm. 19, 25. *Cervisiella* spp., 19. Hole A, 15R-1, 29 cm; 25. Hole E, 8R-1, 10 cm. 20, 26. *Braarudosphaera*

1655 *bigelowii*. 20. Hole E, 8R-1, 10 cm; 26. Hole E, 10R-1, 10 cm. 21-22. *Futuyania petalosa*, 21.
1656 Hole E, 4R-1, 50 cm; 22. Hole E, 4R-1, 50 cm. 23, 24. *Prinsius tenuiculus*, 23. Hole C, 3R-1, 20
1657 cm; 24. Hole C, 4R-1, 16 cm. 27. *Micrantholithus* cf. *entaster.* 27. Hole C, 23R-1, 147 cm.
1658 Scale bars are 5 μm, all images are same scale except for 1 and 2 which are slightly less enlarged
1659 than the remainder of the images.
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1661 [1]GSA Data Repository item 201Xxxx, Additional data tables, is available online at
1662 www.geosociety.org/pubs/ft20XX.htm, or on request from editing@geosociety.org.