CLIMATE AND SEA-LEVEL CHANGES ACROSS A SHALLOW MARINE CRETACEOUS–PALAEOGENE BOUNDARY SUCCESSION IN PATAGONIA, ARGENTINA

by JOHAN VELLEKOOP[1,2] (iD), FEMKE HOLWERDA[3,4], MERCEDES B. PRÁMPARO[5], VERONICA WILLMOTT[6,10], STEFAN SCHOUTEN[6,7], NESTOR R. CÚNEO[8], ROBERTO A. SCASSO[9] *and* HENK BRINKHUIS[1]

[1]Marine Palynology & Palaeoceanography, Laboratory of Palaeobotany & Palynology, Department of Earth Sciences, Faculty of Geosciences, Utrecht University, Budapestlaan 4, Utrecht, 3584 CD, The Netherlands

[2]Division Geology, Department of Earth & Environmental Sciences, KU Leuven, Celestijnenlaan 200E, Leuven, 3001, Belgium; johan.vellekoop@kuleuven.be

[3]Staatliche Naturwissenschaftliche Sammlungen Bayerns (SNSB), Bayerische Staatssammlung für Paläontologie und Geologie, Richard-Wagner-Strasse 10, München, 80333, Germany

[4]GeoBioTec, Faculdade de Ciências e Tecnologia (FCT), Universidade Nova de Lisboa, Campus da Caparica, Caparica, 2829-516, Portugal

[5]Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA), CCT-CONICET, CC 330, Mendoza, 5500, Argentina

[6]Department of Marine Microbiology & Biogeochemistry and Utrecht University, Royal Netherlands Institute for Sea Research, Texel, The Netherlands

[7]Faculty of Geosciences, Utrecht University, Budapestlaan 4, Utrecht, 3584 CD, The Netherlands

[8]Museo Paleontológico Egidio Feruglio – CONICET, Avenida Fontana 140, Trelew, Chubut, 9100, Argentina

[9]Instituto de Geociencias Básicas, Aplicadas y Ambientales de Buenos Aires (IGeBA), Departamento de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires-CONICET, Ciudad Universitaria, Pabellón II, Buenos Aires, C1428, Argentina

[10]*Current address:* Alfred Wegener Institute, Helmoltz Centre for Polar and Marine Research, Am Handelshafen 12, Bremerhaven 27570, Germany

Abstract: Upper Maastrichtian to lower Paleocene, coarse-grained deposits of the Lefipán Formation in Chubut Province, (Patagonia, Argentina) provide an opportunity to study environmental changes across the Cretaceous–Palaeogene (K–Pg) boundary in a shallow marine depositional environment. Marine palynological and organic geochemical analyses were performed on the K–Pg boundary interval of the Lefipán Formation at the San Ramón section. The palynological and organic geochemical records from the San Ramón K–Pg boundary section are characteristic of a highly dynamic, nearshore setting. High abundances of terrestrial palynomorphs, high BIT-index values and the occasional presence of plant fossils are indicative of a large input of terrestrial organic material. The organic-walled dinoflagellate cyst (dinocyst) assemblage is generally dominated by *Senegalinium* and other peridinioid dinocyst taxa, indicative of high-nutrient conditions and decreased salinities, probably associated with a large fluvial input. The reconstructed sea surface temperatures range from 25°C to 27°C, in accordance with the tropical climate inferred by palynological and megafloral studies. As in the Bajada del Jagüel section, ~500 km north-north-east of San Ramón, peaks of *Senegalinium* spp. were recorded below and above the K–Pg boundary, possibly related to enhanced runoff resulting from more humid climatic conditions. The lithological, palynological and organic geochemical records suggest the occurrence of a sea-level regression across the K–Pg boundary, resulting in a hiatus directly at the boundary in both sections, followed by a transgression in the Danian.

Key words: Cretaceous, Palaeogene, Argentina, climate, sea level, dinocysts.

T H E Cretaceous–Palaeogene (K–Pg) boundary mass extinction (~66 Ma) has been shown to be related to global environmental perturbations as the result of the impact of a large extraterrestrial body (e.g. Schulte *et al.* 2010 and references therein). This impact is likely to have led to exceptionally rapid and profound global climate change (e.g. Galeotti *et al.* 2004; Kring 2007; Vellekoop *et al.* 2014, 2015, 2016) superimposed on a latest Maastrichtian cooling trend (Olsson *et al.* 2002; Habib & Saeedi 2007; Vellekoop *et al.* 2016). High-resolution reconstructions of short- and long-term environmental changes across the K–Pg boundary interval are based

mostly on ancient shallow marine sections, as these are generally characterized by higher sedimentation rates and therefore provide a high temporal resolution (e.g. Brinkhuis *et al.* 1998; Vellekoop *et al.* 2014, 2016; Alegret *et al.* 2015; Woelders & Speijer 2015). However, the expression and stratigraphical completeness of these marginal marine K–Pg successions typically is highly variable (MacLeod & Keller 1991; Adatte *et al.* 2002; Hart *et al.* 2012) complicating accurate dating and complete portrayal of climatic and biotic changes across the K–Pg boundary. Some studies have suggested that, at least regionally, the late Maastrichtian to early Paleocene was marked by relatively long-term changes in relative sea level, on timescales in the order of hundreds of thousands of years (MacLeod & Keller 1991; Habib *et al.* 1992; Adatte *et al.* 2002; Miller *et al.* 2005; Schulte *et al.* 2006; Kominz *et al.* 2008). However, while such changes have been documented across the K–Pg boundary on a regional scale on the northern hemisphere, very few records exist from the southern hemisphere because of the scarcity of outcrops of sediments of this age (Kiessling & Claeys 2002). This emphasizes the need for additional studies on K–Pg boundary sections in the southern hemisphere. The upper Maastrichtian to lower Paleocene, coarse-grained, tidally dominated deposits of the Lefipán Formation (Chubut Province, Patagonia, Argentina; see Spalletti 1996; Barreda *et al.* 2012; Scasso *et al.* 2012) provide an opportunity to study climate and sea level changes across the K–Pg boundary in a very shallow-marine depositional environment. These deposits present an ideal record to investigate the interaction between local shallow-marine sedimentary systems, and regional and global sea level changes.

However, the acquisition of a reliable age-model can be challenging in such settings, as planktic foraminiferal stratigraphic marker taxa are often absent or very rare (e.g. Woelders *et al.* 2017). Fortunately, organic-walled dinoflagellate cysts (dinocysts) are often abundantly present in very shallow-marine settings (e.g. Elliot *et al.* 1994; Brinkhuis & Schiøler 1996; Prámparo & Papú 2006; Vellekoop *et al.* 2016) and can provide powerful biostratigraphical age constraints across the K–Pg boundary (e.g. Schiøler *et al.* 1997; Brinkhuis *et al.* 1998; Prámparo & Papú 2006; Açikalin *et al.* 2015; Vellekoop *et al.* 2015, 2016). In addition, dinoflagellates are highly sensitive to changes in environmental parameters such as nutrient loading and salinity (Sluijs *et al.* 2005; Vellekoop *et al.* 2015). Therefore, dinocysts provide an excellent tool for both biostratigraphy and the reconstruction of palaeoenvironmental changes in the coastal setting of the Lefipán Formation. In such a setting, changes in environmental parameters are generally interpreted as changes in terrestrial influence, allowing for a tentative assessment of changes in coastal proximity (Sluijs *et al.* 2005). In turn,

changes in coastal proximity can be interpreted as variations in relative sea level (Schiøler *et al.* 1997; Sluijs *et al.* 2005).

The poor preservation of carbonate in these types of deposit can be problematic for oxygen isotope and trace element palaeothermometry, hampering quantitative assessment of climate changes across this time interval. However, organic biomarker-based proxies present a promising alternative. The TEX_{86} palaeothermometer (Schouten *et al.* 2002) is based on archaeal membrane lipids, and is ideal for reconstructing changes in sea surface temperature (SST) across the studied interval (e.g. Vellekoop *et al.* 2016). The BIT-index, based on bacterial and archaeal membrane lipids (Hopmans *et al.* 2004) allows for the assessment of relative changes in the input of riverine and soil-derived organic matter (Huguet *et al.* 2007; Walsh *et al.* 2008; Zell *et al.* 2013).

Here, we combine marine palynological and organic geochemical analyses at the K–Pg boundary interval within the Lefipán Formation at the San Ramón section, north-western Patagonia, Argentina (Barreda *et al.* 2012; Scasso *et al.* 2012). Correlation of our palynological and organic geochemical data from this very shallow, nearshore site with similar recently published data from the mid-shelf deposits of the Bajada del Jagüel section in the Neuquén Basin, Argentina (~500 km north-north-east of the San Ramón section; Woelders *et al.* 2017) may help to distinguish local from regional signals, and will allow an evaluation of the stratigraphical completeness of our record. Combining these records provides a way of assessing possibly synchronous climatic and sea level changes across the K–Pg boundary in Argentina.

GEOLOGICAL SETTING

The stratigraphic section studied here is that of the San Ramón section in the Lefipán Formation, which crops out in north-western Patagonia, Argentina, in the Paso del Sapo Embayment (Fig. 1). During the Maastrichtian and Paleocene, this embayment was situated at approximately 45–50°S (van Hinsbergen *et al.* 2015) in the humid, warm-temperate climatic belt (Scasso *et al.* 2012). Palynological and megafloral studies suggest that this region was characterized by coastal mangrove forests and swamp communities, and a hinterland with rainforests comprising megathermal angiosperms (Baldoni 1992; Barreda & Palazzesi 2007; Iglesias *et al.* 2007; Palazzesi & Barreda 2007; Barreda *et al.* 2012).

The San Ramón section is up to 400 m thick (Scasso *et al.* 2012), of which approximately 260 m are latest Cretaceous in age, and the remainder are early Paleocene. The underlying unit is the Campanian to early Maastrichtian Paso del Sapo Formation, while the overlying
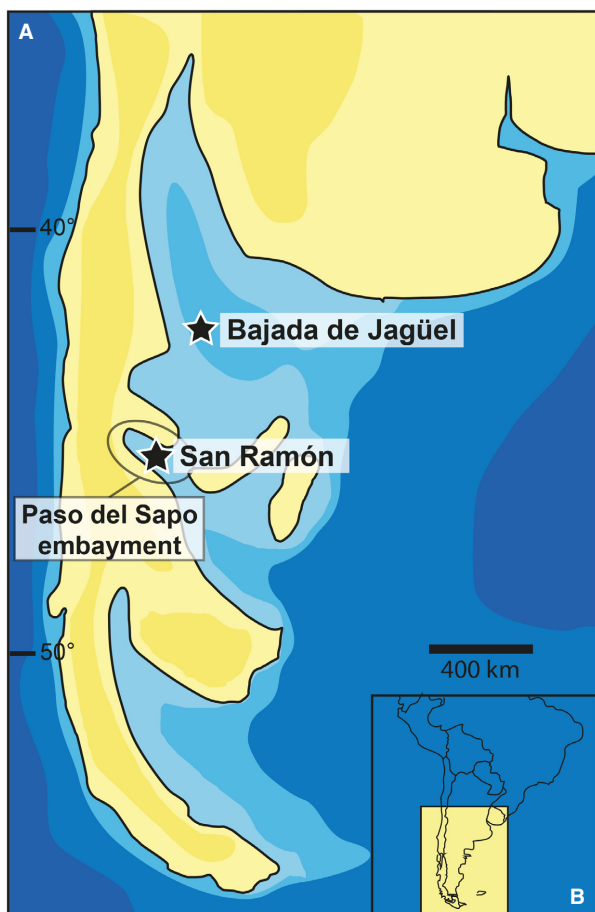
FIG. 1. A, palaeogeographical reconstruction of the marine basins in Patagonia (Argentina) during the Maastrichtian–Paleocene, with estimated palaeolatitudes, after Scasso *et al.* (2012). B, index map highlighting the area of South America represented in A. Colour online.

unit is the late Paleocene Bardas Coloradas Ignimbrite. Strata of the Lefipán Formation were deposited in a coarse-grained, tidally dominated delta environment with strong salinity variations, based on macrofossil communities (Scasso *et al.* 2012). At the San Ramón section, the uppermost Cretaceous of the Lefipán Formation is characterized by tidal channel, tidal gully and tidal flat deposits, whereas the lower Paleocene is characterized by tidal bars in a distal delta front (Scasso *et al.* 2012). One of the most significant lithological changes in this formation is a marker bed with members of the gastropod genera *Turritella* and *Pseudamaura*, which indicates the K–Pg boundary (Scasso *et al.* 2012). This massive bed, characterized by a dense aggregation of gastropods, with ray and shark teeth, and reworked concretions, immediately overlies the K–Pg boundary (Fazio *et al.* 2013). It has an erosive base, generally shows coarsening upwards and comprises parallel and crossbedding. For a more detailed

description of the lithological succession of the San Ramón section, see Scasso *et al.* (2012).

MATERIAL AND METHOD

Sampling

The Lefipán Formation is exposed in recessive cliffs along the Middle Chubut River Valley, Chubut Province, Argentina. For the present study, 38 samples were acquired from the San Ramón section, the most complete log of the Lefipán Formation in the area (Ruiz *et al.* 2005; Scasso *et al.* 2012). The base of the section is situated at 42.6699°S 69.8556°W; the top of the section is located at 42.6851°S 69.8268°W. Since the focus of the present study is on organic microfossils (organic-walled dinoflagellate cysts) and organic geochemistry (TEX_{86} and BIT-index) the samples were predominantly taken from fine-grained lithologies, as these are generally characterized by a better preservation of organic matter. Samples are currently stored at the sample storage of the Earth Science department of Utrecht University (The Netherlands) under sample codes PLW and LPF.

Palynology

The samples from the San Ramón section were processed following standard palynological processing techniques. Approximately 10 g of each sample was crushed, oven dried (60°C) and weighed. The samples were then treated with 10% HCl and 40% HF so as to dissolve carbonate and silicate minerals, respectively. The residue was sieved over nylon mesh sieves of 250 and 15 μm and treated with ultrasound for 5 min to break up agglutinated particles of the residue. Microscope slides were prepared by mounting well-mixed, representative fractions of the residue of the 15–250 μm fraction on standard microscope slides. All slides are stored in the collection of the Laboratory of Palaeobotany and Palynology, Utrecht University. Where possible, the palynomorphs were counted up to a minimum of 200 dinocysts. The taxonomy of dinocysts follows that cited in Fensome & Williams (2004) and Fensome *et al.* (2008). A species list can be found in the Dryad Digital Repository (Vellekoop *et al.* 2017).

Organic geochemistry

The organic geochemical samples from the San Ramón section were analysed for TEX_{86} and the BIT-index following standard procedures (see Schouten *et al.* 2002, 2007; Vellekoop *et al.* 2014). Organic compounds were

extracted from powdered and freeze-dried rock samples of approximately 10 g with dichloromethane (DCM)/ methanol (MeOH) (9:1, v/v) using a DIONEX accelerated solvent extractor (ASE). The total extracts were separated into three fractions over an activated Al_2O_3 column successively using hexane:dichloromethane (DCM) (9:1, v/v), DCM:MeOH (95:5, v/v) and MeOH (100%). The DCM: MeOH (95:5, v/v) fraction was subsequently analysed using high-performance liquid chromatography/atmospheric pressure positive ion chemical ionization mass spectrometry (HPLC/APCI-MS) according to Schouten *et al.* (2007). The TEX_{86} values were calculated following Schouten *et al.* (2002); BIT-index values were calculated following Hopmans *et al.* (2004). Different calibrations exist between relative abundances of GDGT and SST (for example, TEX_{86}, TEX_{86H}, TEX_{86L} and BAYSPAR) (Schouten *et al.* 2002; Kim *et al.* 2010; Tierney & Tingley 2014). The TEX_{86H} calibration proposed by Kim *et al.* (2010) has been frequently used to calibrate past greenhouse climates. Since we apply the TEX_{86} palaeothermometer on samples from a mid-latitude site from the Cretaceous–Palaeogene greenhouse world, unambiguously characterized by high sea surface temperatures (SSTs) (>15°C), we applied TEX_{86H} to translate TEX_{86} index values to mean annual sea surface temperature (SST). This calibration has an error of 2.5°C, whereas the analytical error of TEX_{86H}-based SSTs is 0.3°C (Schouten *et al.* 2013). However, for completeness, we also provide SSTs using the more recently developed BAYSPAR method (Tierney & Tingley 2014) in Vellekoop *et al.* (2017).

RESULTS

Palynology

The preservation of organic microfossils of the San Ramón varies between samples, ranging from very poor to well-preserved. Four samples are entirely barren of palynomorphs (see Vellekoop *et al.* (2017) for the palynological data) which is probably due to post-depositional oxidation. The productive samples display a strong predominance of terrestrial palynomorphs, mostly comprising fern spores, angiosperm pollen and gymnosperm pollen, with high abundances of podocarps and *Classopollis* sp. The marine component consists mostly of organic-walled dinoflagellate cysts and acritarchs. Throughout the section, the ratio of terrestrial palynomorphs to the sum of terrestrial and marine palynomorphs (t/m ratio) is very high (0.72–1.0; see Fig. 2). The t/m ratio reaches its highest values across the Maastrichtian interval: in the lower Danian (16 m above the K–Pg boundary) and in the upper part of the section (the interval between 35 and 70 m above the K–Pg boundary), where the t/m ratio is

generally >0.9. The highest relative abundance of marine palynomorphs (~28%) is reached at ~26 m above the K–Pg boundary. In the present study we focus on the marine component of the palynological assemblage. For a detailed study of the terrestrial palynomorphs of the San Ramón section, see Barreda *et al.* (2012). The dinocyst record is characterized by a very impoverished organic-walled dinoflagellate community. In total, 32 different dinocyst taxa have been identified, several of which were useful for providing stratigraphic age constraints.

To assess palaeoenvironmental signals in the palynological dataset, the dinocyst taxa were assigned to eight different morphological groups, following e.g. Schiøler *et al.* (1997): (1) *Senegalinium* spp., combining all species within the genus *Senegalinium*; (2) the *Andalusiella*–*Palaeocystodinium* complex, lumping all species belonging to *Andalusiella* and *Palaeocystodinium*; (3) other peridinioids, combining all other peridinioid dinocysts; (4) *Hystrichosphaeridium* spp., combining all species within the genus *Hystrichosphaeridium*; (5) the *Areoligera* group, lumping all dorsoventrally compressed gonyaulacoid cysts with an apical archeopyle, such as *Glaphyrocysta* and *Areoligera*; (6) fibrous cribroperidinioids, combining all Cribroperidinioidea with a fibrous wall, such as *Cordosphaeridium*, *Disphaerogena*, *Damassadinium* and *Fibrocysta*; (7) the *Spiniferites* group, combining all species of *Spiniferites* and the morphologically related genus *Achomosphaera*; and (8) other dinocysts, combining all dinocysts not assigned to any of the other groups.

The dinocyst community (see Fig. 2) is generally dominated by the presumed heterotrophic taxon *Senegalinium* (~10–100% of the assemblage). The highest abundances of this group are reached in the upper Maastrichtian (~13 m below the K–Pg boundary): in the lower Danian (16 m above the K–Pg boundary) and in the top part of the section (the interval between 40 and 70 m above the K–Pg boundary). The morphological group composed of the peridinioid dinocysts *Andalusiella* and *Palaeocystodinium* (referred to as the 'A–P complex'; Brinkhuis *et al.* 1998; Vellekoop *et al.* 2015) shows a peak occurrence with very high abundances approximately 20 m below the K–Pg boundary, where it reaches up to 77% of the dinocyst assemblage. Other peridinioid dinocysts, such as representatives of the genera *Cerodinium*, *Deflandrea*, *Laciniadinium* and *Alterbidinium*, are also abundant throughout the record (1–40% of the assemblage). Fibrous cribroperidinioids are relatively rare in most of the record (0–10%), but are comparatively abundant at three stratigraphic levels: at the base of the section; directly above the K–Pg boundary and at the top of the section, where they represent 30–50% of the assemblage. *Hystrichosphaeridium* spp. and the *Areoligera* group generally represent a minor component of the dinoflagellate assemblage (0–5%), but show slightly higher abundances directly above the K–Pg boundary (10–15%).
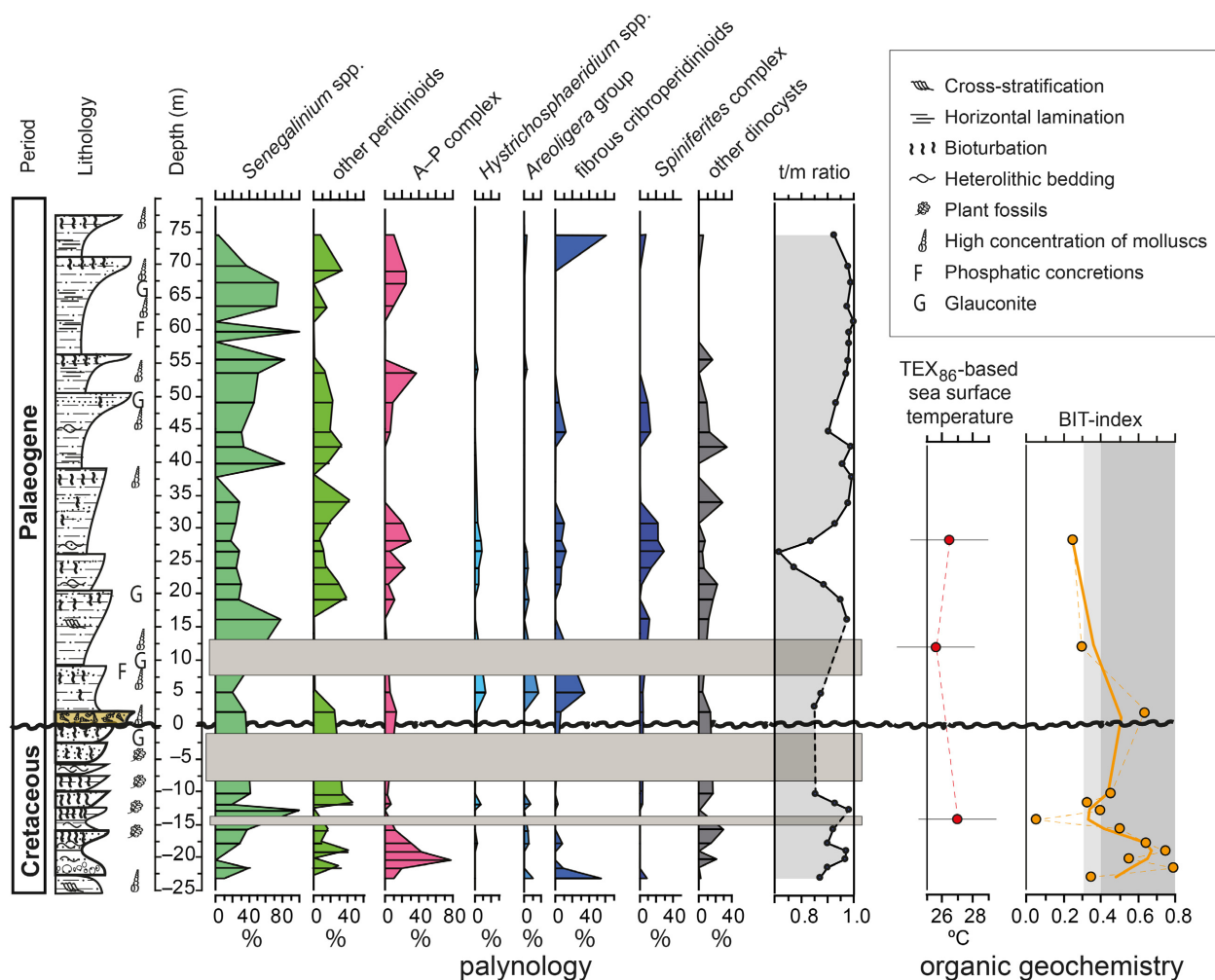
FIG. 2. Palynological and organic geochemical results for the San Ramón section. Lithological section after Scasso *et al.* (2012). The intervals barren of palynomorphs are indicated with grey bars. To identify the major trends in the BIT-index data, a LOESS fit ($\alpha = 0.45$; Npts = 6) was generated (solid line). A–P complex, *Adalusiella–Palaeocystodinium* complex. Colour online.

The *Spiniferites* complex is relatively rare in most of the record but becomes more abundant (10–28%) at 25–35 m above the boundary.

Organic geochemistry

Most of the 20 geochemical samples contained traces of glycerol dialkyl glycerol tetraether (GDGT) lipids. However, the overall concentrations were generally relatively low, in some samples only just above the detection limit, resulting in a poor signal-to-noise ratio. Only 13 samples had a good signal-to-noise ratio, allowing for the calculation of the BIT-index (Hopmans *et al.* 2004). There is a large bed-by-bed variability, with values ranging between 0.06 and 0.79 (see Fig. 2). In general, the BIT-index is relatively high, indicating high abundances of riverine and soil-derived organic matter (Hopmans *et al.* 2004). To

identify the major trends in the BIT-index data, a LOESS fit ($\alpha = 0.45$; Npts = 6) was generated (Fig. 2). The highest BIT-index values are reached at approximately 20 m below (0.79) and directly above (0.64) the K–Pg boundary *Turritella/Pseudamaura* bed.

High relative concentrations of soil organic matter in sediments can cause a substantial bias in TEX_{86}-reconstructed sea surface temperatures (Weijers *et al.* 2006). To exclude all TEX_{86}-reconstructed sea surface temperatures possibly biased by high concentrations of terrestrial-derived GDGTs, samples with a BIT-index exceeding 0.3 were discarded, following Weijers *et al.* (2006). As a result, TEX_{86}-based sea surface temperatures could be calculated for only three samples (see Fig. 2). The TEX_{86H}-reconstructed SSTs range from 25.6°C to 27.1°C; the average BAYSPAR-based SSTs range from 25.1°C to 27.3°C (see Vellekoop *et al.* (2017) for the organic geochemical data).

DISCUSSION

Stratigraphy

One of the most prominent lithological changes within the Lefipán Formation is a marker bed with a dense aggregation of the gastropod genera *Turritella* and *Pseudamaura*. Previous studies have identified this marker bed as the K–Pg boundary, based on a major change in invertebrate faunal composition (e.g. Medina & Malagnino 1990; Scasso *et al.* 2012) and on age-diagnostic palynomorphs (Barreda *et al.* 2012). The latter authors argued that a K–Pg boundary layer, characterized by global boundary markers such as an anomalous concentration in Ir, Ni-rich spinels and microkrystites (cf. Molina *et al.* 2006) is not preserved at San Ramón. This suggests a possible small stratigraphic hiatus at the boundary. Interestingly, at the relatively nearby Bajada del Jagüel K–Pg boundary section (Neuquén Basin, Argentina), ~500 km north-north-east of the San Ramón section (see Fig. 1) the K–Pg boundary is also represented by a stratigraphic hiatus (Scasso *et al.* 2005; Woelders *et al.* 2017). The concurrence of this hiatus directly at the boundary in both sections suggests that it might have been caused by a regional or even global process. In the mid-shelf setting of the Bajada de Jagüel (Scasso *et al.* 2005; Woelders *et al.* 2017) this stratigraphic hiatus roughly covers planktic foraminiferal Zones P0 to P1a, with sedimentation starting again in Zone P1b of Olsson *et al.* (1999; see Keller *et al.* 2007; Woelders *et al.* 2017). Although tentative, in view of the concurrence with the stratigraphic hiatus at the Bajada del Jagüel section, it is plausible that the stratigraphic hiatus at the K–Pg boundary in the San Ramón section roughly covers the same biostratigraphic interval.

The dinocyst record of the San Ramón section comprises several biostratigraphically important taxa (see Fig. 3) providing further stratigraphic constraints. Several taxa are indicative of a general Maastrichtian–Paleocene age. The taxon *Deflandrea galeata* (Fig 4K) occurs from the base of the section to up to ~54 m above the K–Pg boundary (Fig. 3). In the northern hemisphere, *D. galeata* has its first occurrence (FO) in the middle upper Maastrichtian (Schiøler & Wilson 1993; Nøhr-Hansen 1996; Herngreen *et al.* 1998; Slimani 2001; Slimani *et al.* 2016). In Argentina, this taxon has previously been recorded in the upper Maastrichtian of the Jagüel Formation in the Neuquén Basin, at the Cerro Butaló (Prámparo & Papú 2006), Opaso (Papú *et al.* 1999) and Bajada del Jagüel sections (Woelders *et al.* 2017). *Glaphyrocysta perforata* (Fig 4O), which is also considered to be typical for the Maastrichtian and Paleocene (Prámparo & Papú 2006), occurs from ~18 m below the K–Pg boundary to up to ~25 m above the boundary (Fig. 3.)
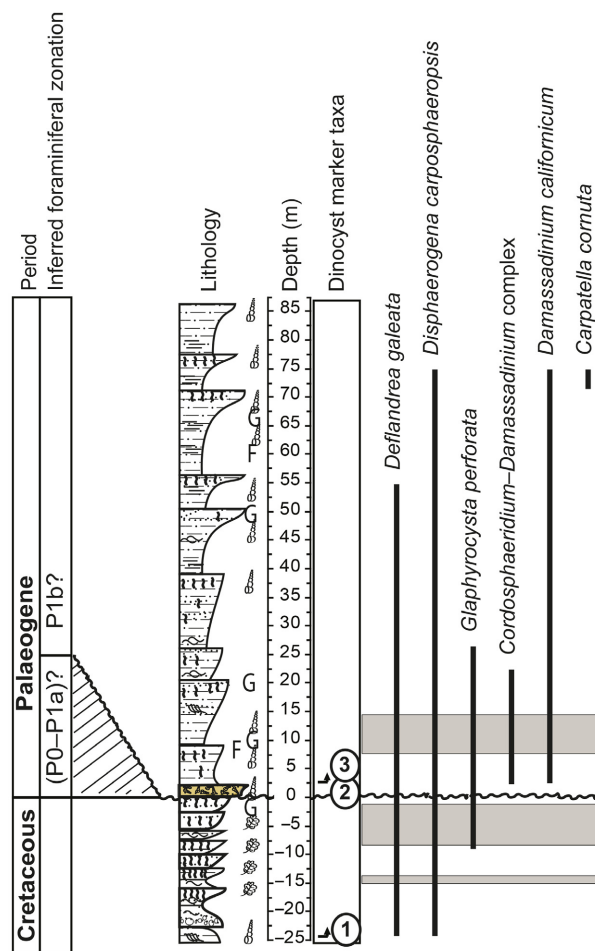

FIG. 3. Stratigraphic interpretation of the San Ramón section. The ranges of stratigraphic marker taxa are indicated. The most important 'dinocyst events' are numbered as follows: 1, the first occurrence (FO) of *Disphaerogena carposphaeropsis*; 2, the FO of the *Cordosphaeridium–Damassadinium* complex; 3, the FO of *Damassadinium californicum*. For lithological legend, see Fig. 2.

Disphaerogena carposphaeropsis, which has a global first appearance datum (FAD) at ~67 Ma (de Gracianski *et al.* 1998; Williams *et al.* 2004) appears throughout the studied interval (Fig. 3), indicating that the Maastrichtian part of this interval was deposited within the last million years prior to the K–Pg boundary. An interesting taxonomic feature of specimens of *D. carposphaeropsis* from the San Ramón section is the development of distinct apical and antapical horns (Fig. 4L, M). This is a typical feature that fibrous cribroperidinioids, such as *Disphaerogena*, *Cordosphaeridium*, *Damassadinium*, *Thalassiphora*, *Carpatella* and *Fibrocysta*, display in the latest Cretaceous and early Paleocene (Brinkhuis & Schiøler 1996; Herngreen *et al.* 1998; Prámparo & Papú 2006; Vellekoop *et al.* 2014; Açikalin *et al.* 2015; Slimani *et al.* 2016).

Senoniasphaera cf. *inornata* and *Senoniasphaera inornata s.s.* (Brinkhuis & Schiøler 1996; Vellekoop *et al.*

2014, 2016; Açikalin *et al.* 2015) were not encountered at San Ramón. Instead, the lowermost Paleocene of the section is characterized by the rare occurrences of inter-grades between the taxa *Cordosphaeridium fibrospinosum* and *Damassadinium californicum* (Fig. 4I). Several previous studies referred to such transitional morphotypes as *Damassadinium* cf. *californicum* (Vellekoop *et al.* 2014, 2015; Açikalin *et al.* 2015). These morphotypes are distinguished from *Damassadinium californicum s.s.* by having a narrower process base. These forms appear to have evolved during the early Danian (planktic foraminiferal Zones P0–P1a, see Vellekoop *et al.* 2014, 2015; Açikalin *et al.* 2015) and range throughout the Paleocene (Sluijs & Brinkhuis 2009). The oldest possible date for *D.* cf. *californicum* appears to be early, albeit not earliest, Danian (Vellekoop *et al.* 2014, 2015; Açikalin *et al.* 2015). At the San Ramón section, these intergrades already occur in the lowermost Paleocene sample, from directly above the *Turritella/Pseudamaura* bed (Fig. 3). The absence of typical early Danian markers, such as *Senoniasphaera* cf. *inornata* (Vellekoop *et al.* 2014; Açikalin *et al.* 2015; cf. Açikalin *et al.* 2015) and the presence of markers for the early, but not earliest, Danian directly above the *Turritella/Pseudamaura* bed is consistent with the presence of a small stratigraphic hiatus at the K–Pg boundary, as inferred by Barreda *et al.* (2012). The absence of the *S. inornata*, a taxon characterized by a stratigraphic range restricted to the early–middle Danian interval (66.00–62.6 Ma; (de Gracianski *et al.* 1998; Williams *et al.* 2004) could suggest that this hiatus at the K–Pg boundary comprises a larger time interval. However, as all members of the *Areoligera* group, the morphogroup to which *S. inornata* belongs, are generally very rare in the San Ramón section, the absence of this marker taxon is more likely to be caused by unfavourable conditions for this taxon, rather than a stratigraphic hiatus. The global biostratigraphic markers *D. californicum* and *Carpatella cornuta*, which have respective FADs at approximately ~65.75 and 65.7 Ma (Brinkhuis *et al.* 1998; Williams *et al.* 2004) are also very rare in the Paleocene of the San Ramón section. The lowest occurrence of *D. californicum* (Fig. 4J) is at ~2 m above the K–Pg boundary, ~50 cm above the top of the *Turritella/Pseudamaura* bed; the lowest occurrence of *C. cornuta* (Fig. 4F) is at ~75 m above the K–Pg boundary (Fig 3). In view of the rarity of this taxon, it is questionable whether this lowest occurrence in the San Ramón section corresponds to its global first appearance. Nevertheless, the presence of these stratigraphic markers suggests that the interval from ~2 m above the K–Pg boundary up to the top of the section is equivalent to (a part of) planktic foraminiferal Zones P1a or P1b of Olsson *et al.* (1999; see Habib *et al.* 1996; Açikalin *et al.* 2015).

Palaeoenvironment

The lithological succession as well as both the palynological and organic geochemical records of the San Ramón K–Pg boundary section are typical of a highly dynamic, very shallow marine setting. The coarse-grained lithologies of the Lefipán Formation yield a highly variable preservation of organic matter, with some beds entirely barren of organic matter, whilst others are characterized by abundant, well-preserved palynomorphs and GDGTs. In some intervals, in particular in the Maastrichtian part of the section, there are even muddy beds with abundant coalified plant remains (Scasso *et al.* 2012). The high abundances of terrestrial palynomorphs, high BIT-index values and occasional presence of plant fossils in this section are indicative of a large input of terrestrial organic material, and are probably related to the proximity to the coastline. As the high values of the BIT-index generally correspond to stratigraphic levels with high abundances of terrestrial palynomorphs (Fig. 2) and/or plant remains, they probably reflect an original signal of high input of soil organic matter, instead of poor preservation due to oxic degradation (cf. Huguet *et al.* 2008).

In general, the dinocyst assemblage is dominated by *Senegalinium* and other peridinioid taxa. Based on correlations between palynological records and other palaeo-proxies, it has been suggested that members of the *Senegalinium* group (*sensu* Sluijs & Brinkhuis 2009) reflect an inferred heterotrophic group that flourished best under high-nutrient conditions and were tolerant of decreased salinities (Brinkhuis & Zachariasse 1988; Lucas-Clark 2006; Sluijs & Brinkhuis 2009). The high abundances of *Senegalinium* and other peridinioid dinocyst taxa in the San Ramón record are therefore indicative of high-nutrient conditions, possibly under decreased salinities. Given the inferred proximity of the coastline, the high abundance of terrestrial material, high-nutrient conditions and decreased salinities are most likely to be related to a large fluvial input. This interpretation is also supported by the presence of intervals with low-diversity marine invertebrate faunas characteristic of high-stress environments with low salinities (Scasso *et al.* 2012). According to Scasso *et al.* (2012), salinity was the principal component controlling the biofacies at San Ramón, with salinity varying from oligohaline and mesohaline in the deltaic, high-stress environments, as typified by monospecific bivalve assemblages, to more normal marine and stable conditions, indicated by diverse and trophically more complex associations.

Sea level

In deltaic, very shallow marine sites, identifying relative sea level changes can be challenging, because autocyclic

deltaic processes can have a strong influence on the formation of sequences. However, several features of the Lefipán sequence suggest that a general pattern can be recognized, overprinting the smaller, autocyclic processes.

The uppermost Cretaceous at San Ramón is characterized by tidal channel, tidal gully and tidal flat deposits that are occasionally densely bioturbated and mostly lack marine macro- and megafauna (Scasso et al. 2012); this is indicative of a very shallow marine palaeoenvironment. The high abundances of terrestrial palynomorphs, predominance of peridinioid dinocysts, high BIT-index values (Fig. 5) and occasional presence of beds with coalified plant remains are all in agreement with such an interpretation. The upper Maastrichtian of San Ramón also comprises an interval dominated by the Corbicula assemblage (Scasso et al. 2012) characteristic of a high-stress environment, with salinities that strongly deviate from those of the open sea. According to Scasso et al. (2012), of all the macrobenthic biofacies of the San Ramón section, the Corbicula assemblage was the one closest to the freshwater end of the salinity scale. At approximately 10–12 m below the K–Pg boundary, slightly lower t/m ratio and BIT-index values are recorded, suggesting that this stratigraphic level represents an interval with a slightly stronger marine influence. Interestingly, in all Lefipán K–Pg boundary sections, the bioturbation increases in the approximate uppermost 10 m of the Maastrichtian (Scasso et al. 2012). In general, this interval is characterized by yellow-reddish-brown bioturbated sandstones that are barren of fossils and palynomorphs because of intense oxidation. Compared to the heterolithic beds below this interval, which are rich in plant remains and palynomorphs and are presumably deposited in muddy tidal flats and tidal gullies (Scasso et al. 2012), these bioturbated sandstones might reflect a higher energetic and slightly more distal environment. Therefore, in Chubut, Argentina, such strongly bioturbated beds potentially herald transgressions.

The inferred hiatus at the K–Pg boundary probably represents non-deposition or erosion during a lowstand. This suggests the occurrence of a sea level regression across the K–Pg boundary. If so, the uppermost Maastrichtian most likely represents a highstand systems tract (HST), capped by a sequence boundary (SB), marked by the erosive base of the K–Pg boundary Turritella/Pseudamaura bed.

The lowermost Paleocene, directly above the Turritella/Pseudamaura bed, is characterized by a relatively high abundance of marine palynomorphs and a relatively diverse dinoflagellate assemblage, indicative of more normal marine conditions (sensu Sluijs et al. 2005). Hystrichosphaeridium spp., the Areoligera group and fibrous cribroperidinioids are all relatively abundant directly above the Turritella/Pseudamaura bed. Fibrous cribroperidinioids are generally considered to be indicative of coastal, normal marine conditions (e.g. Schiøler et al. 1997; Pross & Brinkhuis 2005), whereas the Areoligera group is considered indicative of nearshore, high-energy environments (Brinkhuis & Zachariasse 1988; Brinkhuis 1994; Pross & Brinkhuis 2005). Previous studies have argued that high abundances of the Areoligera group might be characteristic of marine transgressions (e.g. Sluijs & Brinkhuis 2009; Slimani et al. 2010). Sedimentologically, the flat, erosive base of the Turritella/Pseudamaura bed, with a high concentration of marine fossils from various ichnofacies and intraformational particles, suggests energetic scouring and reworking of earlier sediments having taken place in a high-energy, shallow marine environment (Scasso et al. 2012). This erosion and winnowing was subsequently followed by rapid accumulation. This recorded transition from a regression and lowstand, represented by erosion and winnowing at the K–Pg boundary, to subsequent rapid accumulation under coastal, normal marine conditions, suggests that the Turritella/Pseudamaura bed represents a transgressive lag deposit (cf. Cattaneo & Steel 2003), as was also suggested by Fazio et al. (2013).

The lower Paleocene of the San Ramón section comprises deposits of tidal bars in a distal delta front (Scasso et al. 2012), indicative of a slightly more offshore setting in comparison with the Maastrichtian interval. However, the interval 10–20 m above the K–Pg boundary is nevertheless characterized by high t/m ratios and a high abundance of Senegalinium, suggesting that the lower Paleocene was still

FIG. 4. Representative dinocyst taxa. A, Achomosphaera sp. (PLW 08; −13 m). B, Andalusiella gabonensis (PLW 38; +75 m). C, Andalusiella mauthei (PLW 20; +26 m). D, Andalusiella polymorpha (PLW 38; +75 m). E, Areoligera medusettiformis (PLW 08; −13 m). F, Carpatella cornuta (PLW 38; +75 m). G, Cerodinium diebelii (PLW 20; +26 m). H, Cordosphaeridium fibrospinosum (PLW 13; +2.5 m). I, Cordosphaeridium–Damassadinium complex (PLW 38; +75 m). J, Damassadinium californicum (LPF 6; +2.5 m). K, Deflandrea galeata (PLW 08; −13 m). L, Disphaerogena carposphaeropsis (PLW 38; +75 m). M, Disphaerogena carposphaeropsis (PLW 38; +75 m). N, Fibrocysta sp. (LPF 1; −23 m). O, Glaphyrocysta perforata (LPF 6; +0.5 m). P, Hystrichosphaeridium ?tubiferum (PLW 38; +75 m). Q, Laciniadinium arcticum (PLW 14; +5.5 m). R, Phelodinium magnificum (LPF 6; +2.5 m). S, Palaeocystodinium lidiae (PLW 43; +75 m). T, Peridinioid cyst indet. (PLW 14; +5.5 m). U, Senegalinium sp. (PLW 14; +5.5 m). V, Senegalinium bicavatum (PLW 08; −13 m). W, Spiniferites ramosus complex (PLW 20; +26 m). X, Trithyrodinium evittii (PLW 38; +75 m). Y, Micrhystridium fragile (PLW 20; +26 m). PLW and LPF refer to two sample sets from the San Ramón section. Distance in metres from the K–Pg boundary. Scale bar represents 50 μm.
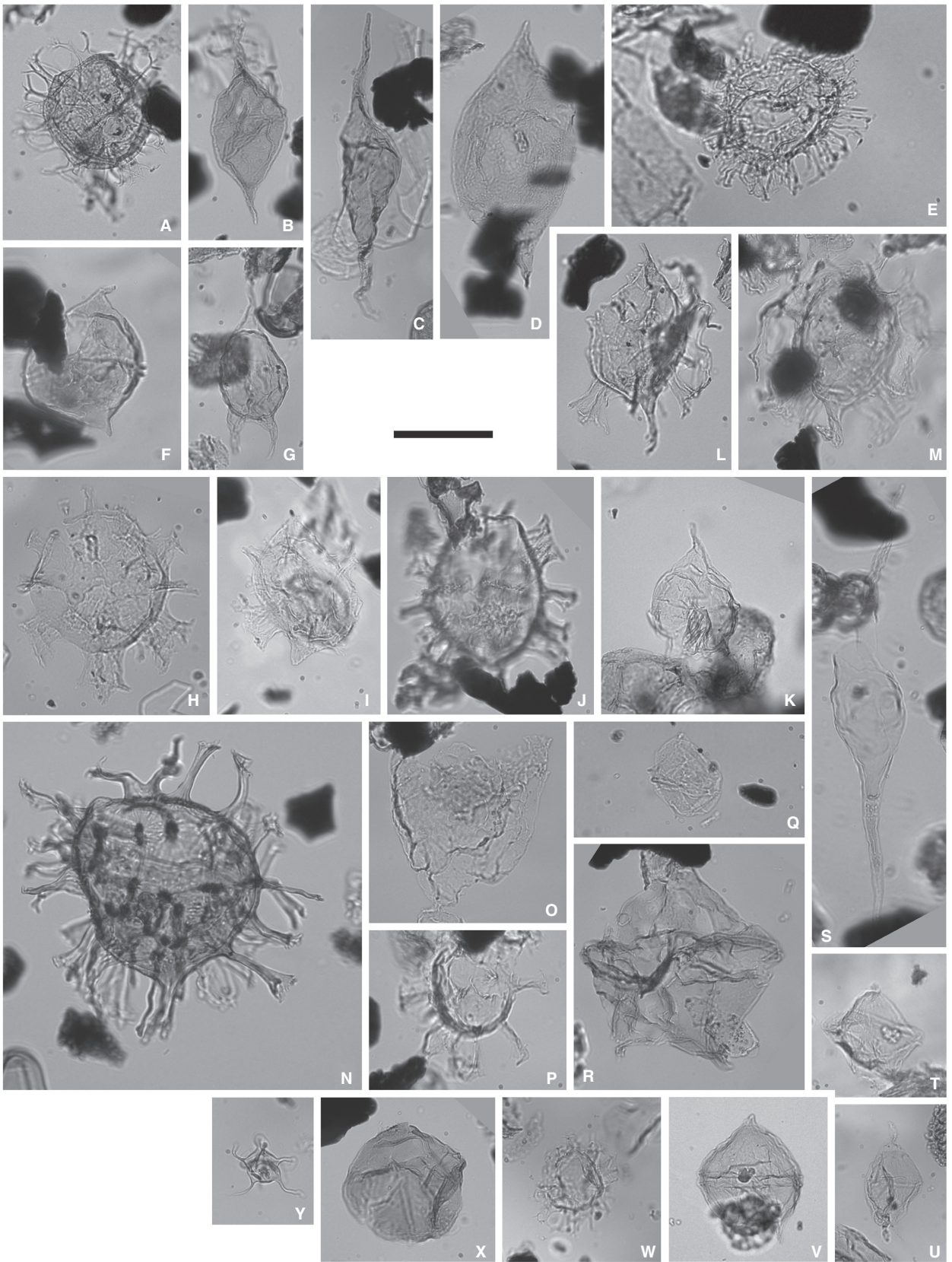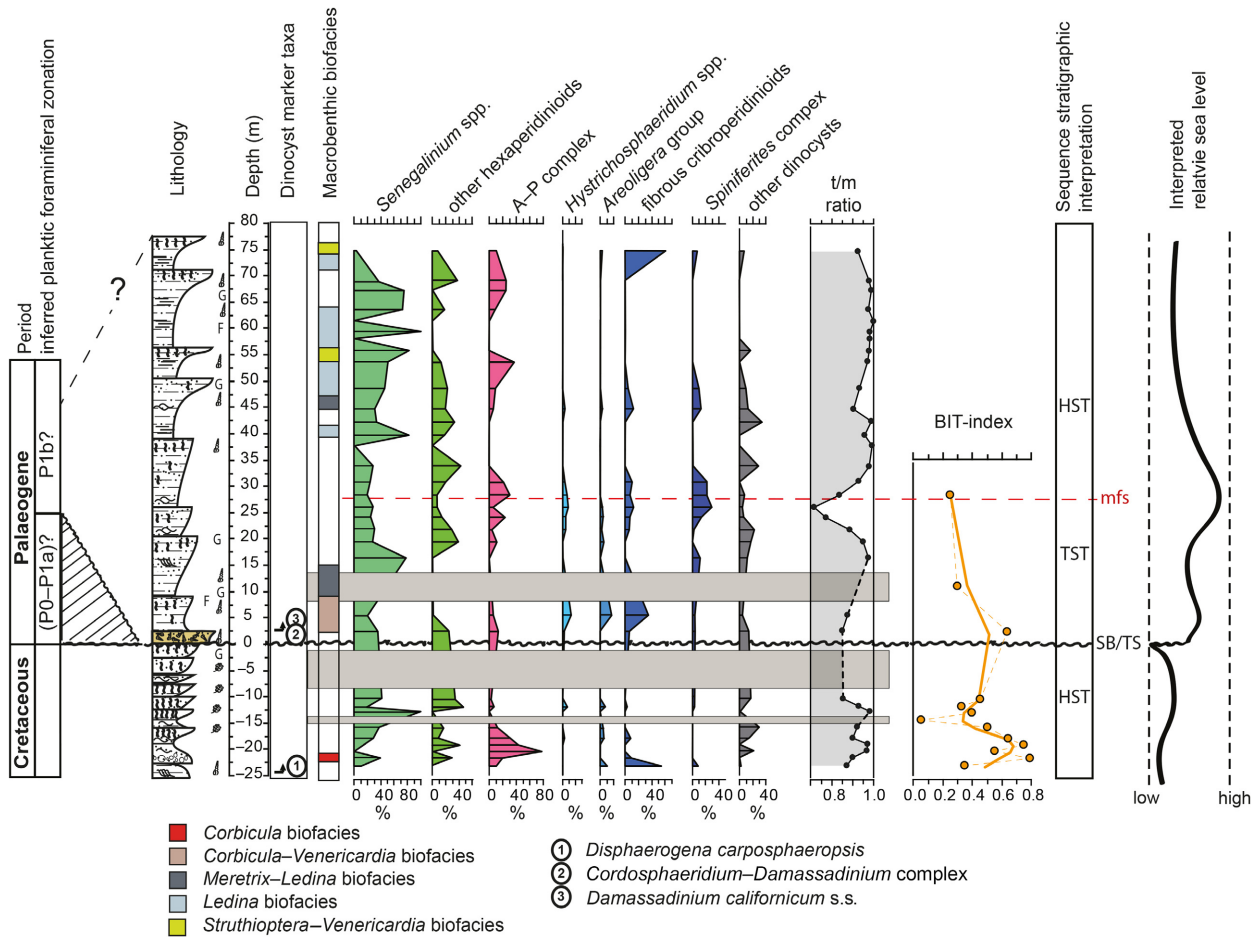
FIG. 5. A sea level interpretation of the San Ramón section. Dinocyst marker numbers indicate first occurrences. The macrobenthic biofacies data are from Scasso *et al.* (2012). The dinocyst morphogroups are ordered according to inferred habit, from very nearshore (left) to more open marine (right). A–P, *Andalusiella–Palaeocystodinium*; HST, highstand systems tract; mfs, maximum flooding surface; SB, sequence boundary; t/m, terrestrial/marine ratio; TS, transgressive surface; TST, transgressive systems tract. For lithological legend, see Fig. 2. Colour online.

dominated by high-nutrient and/or low salinity conditions, similar to the uppermost Maastrichtian interval. The presence of a *Corbicula–Venericardia* biofacies association at the base of the Paleocene (Fig. 5) is also indicative of an elevated degree of environmental stress, with salinity diverging from normal marine (Scasso *et al.* 2012).

From ~16 m above the K–Pg boundary to approximately 26 m above the boundary, the relative contribution of marine palynomorphs progressively increases. Within the same interval, peridinioid dinocysts, including *Senegalinium*, decrease in relative abundance, whilst fibrous cribroperidinioids and the *Spiniferites* complex both increase in abundance. The *Spiniferites* complex, the most 'offshore' component in the San Ramón dinoflagellate assemblage (cf. Schiøler *et al.* 1997; Sluijs *et al.* 2005), reaches its highest abundances at ~26 m above the K–Pg boundary. Since both fibrous cribroperidinioids and the *Spiniferites* complex are generally considered indicative of

coastal, normal marine conditions, their increased abundances suggest an elevated marine influence in the San Ramón record. This is recorded by the macrobenthic biofacies as well, which shows a transition to alternating intervals characterized by the *Ledina* and *Struthioptera–Venericardia* associations (Scasso *et al.* 2012), indicative of normal marine, low- and high-energy environments, respectively. The two BIT-index data points from this interval both show relatively low values (0.3 and 0.25), indicating a lower soil or riverine input, in accordance with the suggested increasing marine influence. This combined evidence suggests that the interval above the K–Pg boundary is characterized by a marine transgression, reaching a maximum flooding at approximately 26 m above the boundary (Fig. 5).

The interval from ~26 m above the boundary to the top of the succession studied is characterized by rapidly decreasing abundances of marine palynomorphs and a

marked predominance of *Senegalinium*, indicating another phase of high-nutrient input and/or lower salinity conditions, possibly related to increased fluvial input. The overall predominance of a *Ledina* macrobenthic biofacies association in this interval (Scasso *et al.* 2012) is indicative of a low-energy environment with a relatively high abundance of particulate organic matter within the sediment, leading to slightly reduced oxygen levels within the sediment. The high abundance of peridinioid taxa such as *Senegalinium* and the presence of the *Ledina* microbenthic biofacies association therefore suggest that this interval was characterized by high nutrient availability and high productivity. However, the occasional occurrences of a *Struthioptera–Venericardia* biofacies association indicate that parts of this interval were characterized by relatively stable, normal marine environments. In summary, the palynologial and palaeontological evidence shows that the upper part of the interval studied was typified by increased terrestrial input, possibly related to an increasing coastal proximity. This transition might be related to progradation and basin infill characteristic of a highstand systems tract (HST; Fig. 5).

Comparison with Bajada del Jagüel

The lithological, palynological and organic geochemical records of the Bajada del Jagüel section (~500 km north-north-east of the San Ramón section; Woelders *et al.* 2017) indicate that the depositional environment was fundamentally different from that at the San Ramón site. At Bajada del Jagüel, the succession consists of relatively monotonous, fine-grained sediments, characteristic of a mid-shelf setting (Scasso *et al.* 2005), whereas the much more variable, and generally more coarse-grained lithologies at San Ramón (Scasso *et al.* 2012) are characteristic of a highly dynamic, very shallow marine setting. In accordance with the inferred more open marine environment at Bajada del Jagüel, dinocyst taxa characteristic of normal marine conditions, such as the *Spiniferites* complex (*sensu* Sluijs *et al.* 2005) are much more predominant in that section, whereas the input of riverine or soil organic matter (BIT-index) is much lower (Fig. 6; Woelders *et al.* 2017).

However, both records exhibit overall high abundances of *Senegalinium* spp. and other peridinioid dinocysts, suggesting that both sites were influenced by high nutrient and/or freshwater input. Based on the palynological records of these sections, a tentative correlation can be made. Within the biostratigraphical framework provided by the FOs of the stratigraphic markers *D. carposphaeropsis*, the *Cordosphaeridium–Damassadinium* complex and *D. californicum*, five possibly correlatable events can be identified (see Fig. 6). The first is the FO of *D. carposphaeropsis* (Event A). In the Bajada de Jaguël section, this FO occurs at ~14 m below the K–Pg boundary, whereas at San Ramón, this taxon already occurs in the lowermost sample, at ~23 m below the boundary. This suggests that sedimentation rates were considerably higher at San Ramón, consistent with its more proximal, deltaic depositional setting. The second event is a peak abundance of *Senegalinium* spp. below the K–Pg boundary (Event B). Woelders *et al.* (2017) argued that this peak abundance might be related to enhanced runoff, resulting from more humid climatic conditions in central and northern Patagonia, caused by the latest Maastrichtian warming event. The third event (Event C) is the hiatus representing the K–Pg boundary. As discussed above, the occurrence of a hiatus directly at the K–Pg boundary at both Bajada del Jagüel and San Ramón suggests that a regional sea level regression occurred across the K–Pg boundary. The fourth event (Event D) is an ingression of more normal marine dinocyst taxa, above the K–Pg boundary hiatus, in the basal part of the interval equivalent to planktic foraminiferal Zone P1b. At both San Ramón and Bajada del Jagüel, this ingression occurs at ~5 m above the boundary. The last possibly correlatable stratigraphic event (Event E) is a peak in abundance of *Senegalinium* spp. at the top of the Bajada del Jagüel section, within the equivalent of planktic foraminiferal Zone P1b. According to our sequence-stratigraphic interpretation, this peak abundance occurs during the Danian transgression, in an increasingly distal setting. Therefore, it is likely that this peak of *Senegalinium* represents a runoff signal instead of a sea level signal, implying that these high abundances are related to enhanced runoff resulting from more humid climate conditions, similar to those of the late Maastrichtian.

Climate

Only three organic geochemical samples of the San Ramón section yielded reliable TEX_{86}-based sea surface temperatures (see Fig. 2). The reconstructed SSTs range from 25.6°C to 27.1°C, in accordance with the tropical climate inferred by palynological and megafloral studies, suggesting that this region was characterized by a hinterland with rainforests with megathermal angiosperms (Baldoni 1992; Barreda & Palazzesi 2007; Iglesias *et al.* 2007; Palazzesi & Barreda 2007; Barreda *et al.* 2012). Given the low number of TEX_{86} data points, climate trends across the studied interval could not be assessed.

Several studies have shown that dinocyst assemblages can also be used to assess relative changes in sea surface temperatures across the K–Pg boundary interval (Brinkhuis *et al.* 1998; Vellekoop *et al.* 2015). However, the records that are generally used for this approach
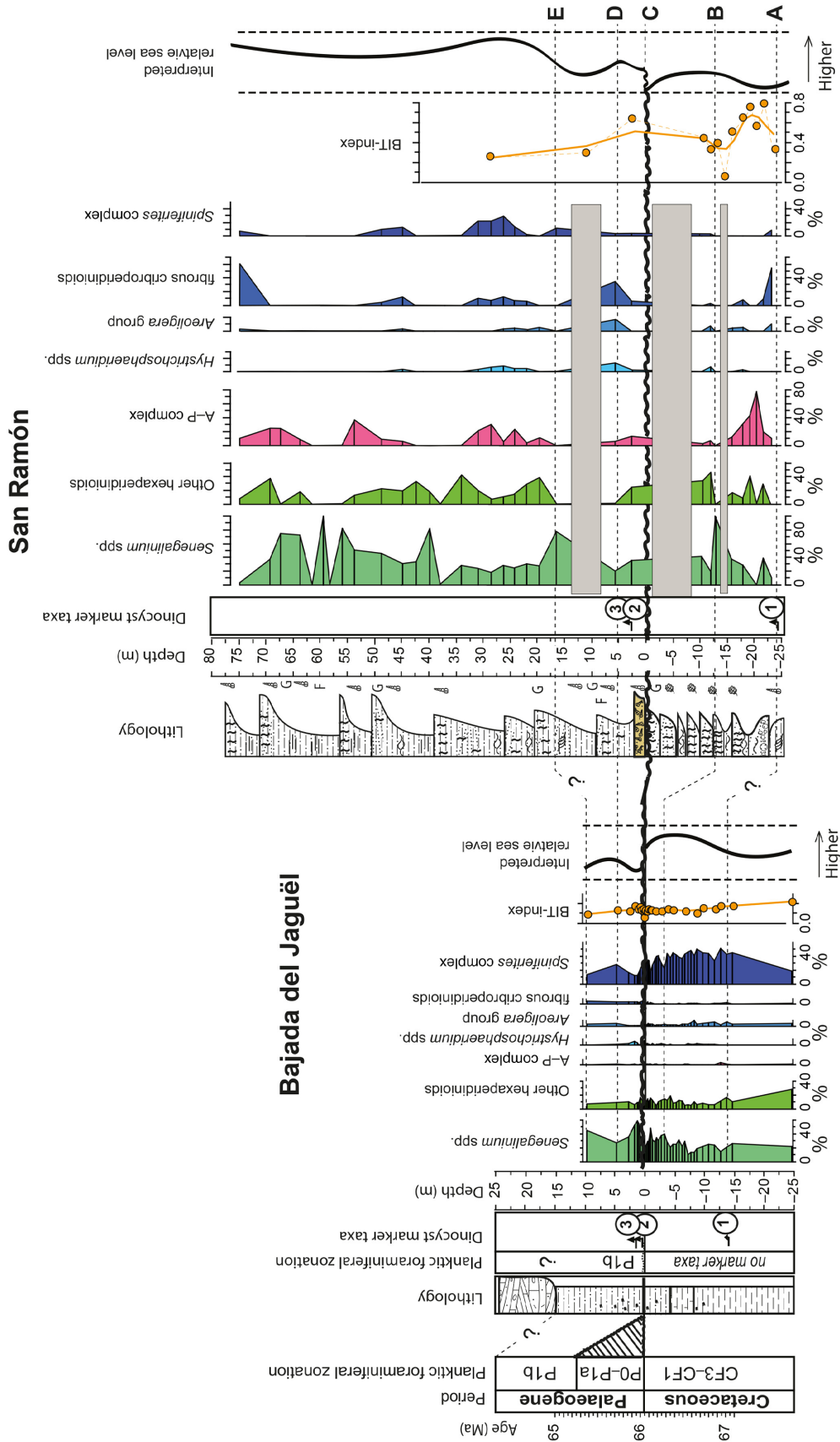
FIG. 6. A correlation of the palynological and organic geochemical records of the San Ramón and Bajada del Jagüel sections. The palynological and organic geochemical data of Bajada del Jagüel, as well as the inferred (relative) sea level interpretation for this site, are from Woelders *et al.* (2017). See text for details on the stratigraphically correlatable levels *A* to *E*. For lithological legend, see Fig. 2. Colour online.

commonly represent normal marine sites with high diversity dinoflagellate assemblages. The impoverished dinocyst community at San Ramón complicates this approach. An interesting feature of the palynological record of San Ramón is the peak of the *Andalusiella–Palaeocystodinium* complex, approximately 20 m below the K–Pg boundary, where it reaches up to 77% of the assemblage. (Brinkhuis *et al.* 1998) described this group as typical of high sea surface temperatures. This suggests that the upper Maastrichtian interval at the San Ramón section was characterized by relatively high temperatures, possibly related to the latest Maastrichtian warming event (Woelders *et al.* 2017). However, in view of the low number of reliable TEX$_{86}$ data points, this possible warming signal cannot be verified by our organic geochemical record.

CONCLUSIONS

Our new dinocyst biostratigraphy confirms the presence of uppermost Maastrichtian and lower Danian strata at the San Ramón site (Lefipán Formation), Argentina, and is consistent with a previously inferred small stratigraphic hiatus at the K–Pg boundary. The presence of *D. californicum* and *C. cornuta* above the K–Pg boundary suggests that this interval is equivalent to planktic foraminiferal zones P1a or P1b of Olsson *et al.* (1999).

The lithological succession and palynological and organic geochemical records from the San Ramón K–Pg boundary section are typical of a highly dynamic, very shallow marine setting. The high abundances of terrestrial palynomorphs, high BIT-index values and occasional presence of plant fossils are indicative of a large input of terrestrial organic material, related to the proximity of the coastline. The dinocyst assemblage is generally dominated by *Senegalinium* and other peridinioid dinocyst taxa, indicative of high-nutrient conditions and decreased salinities, presumably related to a large fluvial input.

The latest Maastrichtian of the San Ramón section was characterized by a very nearshore setting. The inferred hiatus at the K–Pg boundary suggests a sea level regression across the K–Pg boundary. The transition from a regression and lowstand at the K–Pg boundary to the winnowing and subsequent rapid accumulation under coastal, normal marine conditions, recorded by the *Turritella/Pseudamaura* K–Pg boundary bed, suggests that this bed represents a transgressive lag deposit. The lower Danian of San Ramón is characterized by a transgression, with a maximum flooding surface at approximately 26 m above the boundary. The palynological and palaeontological evidence shows that the upper part of the interval studied was characterized by increased terrestrial input, related to increased coastal proximity.

By comparing the palynological data from the very shallow marine, nearshore San Ramón site (Lefipán Formation) with that from the mid-shelf deposits of the Bajada del Jagüel section (Jagüel Formation), five possibly correlatable events can be identified. These suggest that sedimentation rates were considerably higher at San Ramón, consistent with its more proximal depositional setting. Both records are characterized by a peak abundance of *Senegalinium* spp. below the K–Pg boundary, possibly related to enhanced runoff, resulting from more humid climate conditions, potentially related to the warming in the latest Maastrichtian. The occurrence of a hiatus directly at the K–Pg boundary in both Bajada del Jagüel and San Ramón suggests at least a regional sea level regression across the K–Pg boundary in Argentina, followed by a transgression in the Danian. This new record will permit correlations to global sea level trends observed across the K–Pg boundary.

Author contributions. HB and JV designed the research; HB, RC and RS performed fieldwork; RC and RS performed systematic palynological sampling and provided the sedimentological sections and geological background for this study. FH and JV performed quantitative palynological analysis and wrote the paper. FH and JV are shared first authors and contributed to this work equally. JV and VW performed organic geochemical analysis; MP and SS assisted in the analyses. All authors contributed to the writing of the paper.

DATA ARCHIVING STATEMENT

Data for this study are available in the Dryad Digital Repository: https://doi.org/10.5061/dryad.r86pk

Editor. John Jagt

REFERENCES

AÇIKALIN, S., VELLEKOOP, J., OCAKOĞLU, F., ÖMER YILMAZ, I., SMIT, J., ALTINER, S. T., GODERIS, S., VONHOF, H., SPEIJER, R. P., WOELDERS, L., FORNACIARI, E. and BRINKHUIS, H. 2015. Geochemical and palaeontological characterization of a new K-Pg Boundary locality from the Northern branch of the

Neo-Tethys: Mudurnu – Göynük Basin, NW Turkey. *Cretaceous Research*, **52**, 251–267.

ADATTE, T., KELLER, G. and STINNESBECK, W. T. 2002. Late Cretaceous to early Paleocene climate and sea-level fluctuations: the Tunisian record. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **178**, 165–196.

ALEGRET, L., RODR, F. J. and UCHMAN, A. 2015. How bioturbation obscured the Cretaceous–Palaeogene boundary record. *Terra Nova*, **27**, 225–230.

BALDONI, A. M. 1992. Palynology of the lower Lefipán Formation (Upper Cretaceous) of Barranca de Los Perros, Chubut Province, Argentina. Part I, cryptogam spores and gymnosperm pollen. *Palynology*, **16**, 117–136.

BARREDA, V. D. and PALAZZESI, L. 2007. Patagonian vegetation turnovers during the Paleogene-Early Neogene: origin of arid-adapted floras. *Botanical Reviews*, **73**, 31–50.

—— CÚNEO, N. R., WILF, P., CURRANO, E. D., SCASSO, R. A. and BRINKHUIS, H. 2012. Cretaceous/Paleogene floral turnover in Patagonia: drop in diversity, low extinction, and a *Classopollis* spike. *PLoS One*, **7**, e52455.

BRINKHUIS, H. 1994. Late Eocene to Early Oligocene dinoflagellate cysts from the Priabonian type-area (Northeast Italy): biostratigraphy and paleoenvironmental interpretation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **107**, 121–163.

—— and SCHIØLER, P. 1996. Palynology of the Geulhemmerberg Cretaceous/Tertiary boundary section (Limburg, SE Netherlands). *Geologie en Mijnbouw*, **75**, 193–213.

—— and ZACHARIASSE, W. J. 1988. Dinoflagellate cysts, sea level changes and planktonic foraminifers across the Cretaceous-Tertiary boundary at El Haria, northwest Tunisia. *Marine Micropaleontology*, **13**, 153–191.

—— BUJAK, J. P., SMIT, J., VERSTEEGH, G. J. M. and VISSCHER, H. 1998. Dinoflagellate-based sea surface temperature reconstructions across the Cretaceous–Tertiary boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **141**, 67–83.

CATTANEO, A. and STEEL, R. J. 2003. Transgressive deposits: a review of their variability. *Earth-Science Reviews*, **62**, 187–228.

ELLIOT, D. H., ASKIN, R. A., KYTE, F. T. and ZINSMEISTER, W. J. 1994. Iridium and dinocysts at the Cretaceous-Tertiary boundary on Seymour Island, Antarctica: implications for the K-T event. *Geology*, **22**, 675–678.

FAZIO, A. M., CASTRO, L. N. and SCASSO, R. A. 2013. Geoquímica de tierras raras y fosfogénesis en un engolfamiento marino del Cretácico Tardío-Paleoceno de Patagonia, Provincia del Chubut, Argentina. *Revista Mexicana de Ciencias Geologicas*, **30**, 582–600.

FENSOME, R. A. and WILLIAMS, G. L. 2004. The Lentin and Williams Index of fossil dinoflagellates: 2004 Edition. *Contributions Series-American Association of Stratigraphic Palynologists*, **42**, 1–909.

—— MACRAE, R. A. and WILLIAMS, G. L. 2008. DINOFLAJ2, v. 1. American Association of Stratigraphic Palynologists, Data Series 1. http://dinoflaj.smu.ca/wiki/Main_Page

GALEOTTI, S., BRINKHUIS, H. and HUBER, M. 2004. Records of post-Cretaceous-Tertiary boundary millennial-scale cooling from the western Tethys: a smoking gun for the impact-winter hypothesis? *Geology*, **32**, 529–532.

GRACIANSKI, P.-C. DE, HARDENBOL, J., JACQUIN, T. and VAIL, P. R. 1998. *Mesozoic and Cenozoic sequence stratigraphy of European basins*. SEPM Special Publication, **60**.

HABIB, D. and SAEEDI, F. 2007. The *Manumiella seelandica* global spike: cooling during regression at the close of the Maastrichtian. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **255**, 87–97.

—— MOSHKOVITZ, S. and KRAMER, C. 1992. Dinoflagellate and calcareous nannofossil response to sea-level change in Cretaceous-Tertiary boundary sections. *Geology*, **20**, 165–168.

—— OLSSON, R. K., LIU, C. and MOSHKOVITZ, S. 1996. High-resolution biostratigraphy of sea-level low, biotic extinction, and chaotic sedimentation at the Cretaceous-Tertiary boundary in Alabama, north of the Chicxulub crater. *GSA Special Papers*, **307**, 243–252.

HART, M. B., YANCEY, T. E., LEIGHTON, A. D., MILLER, B., LIU, C., SMART, C. W. and TWITCHETT, R. J. 2012. The Cretaceous-Paleogene boundary on the Brazos River, Texas: new stratigraphic sections and revised interpretations. *GCAGS Journal*, **1**, 69–80.

HERNGREEN, G. F. W., SCHUURMAN, H. A. H. M., VERBEEK, J. W., BRINKHUIS, H., BURNETT, J. A., FELDER, W. M. and KEDVES, M. 1998. *Biostratigraphy of Cretaceous/Tertiary boundary strata in the Curfs quarry*. Mededelingen Nederlands Instituut voor Toegepaste Geowetenschppen TNO, **61**, 58 pp.

HINSBERGEN, D. J. J. VAN, GROOT, L. V. DE, SCHAIK, S. J. VAN, SPAKMAN, W., BIJL, P. K., SLUIJS, A., LANGEREIS, C. G. and BRINKHUIS, H. 2015. A Paleolatitude Calculator for Paleoclimate Studies. *PLoS One*, **10**, e0126946.

HOPMANS, E. C., WEIJERS, J. W. H., SCHEFUS, E., HERFORT, L., SINNINGHE DAMSTÉ, J. S. and SCHOUTEN, S. 2004. A novel proxy for terrestrial organic matter in sediments based on branched and isoprenoid tetraether lipids. *Earth & Planetary Science Letters*, **224**, 107–116.

HUGUET, C., SCHIMMELMANN, A., THUNELL, R., LOURENS, L. J., SINNINGHE DAMSTÉ, J. S. and SCHOUTEN, S. 2007. A study of the TEX$_{86}$ paleothermometer in the water column and sediments of the Santa Barbara Basin, California. *Paleoceanography*, **22**, PA3203.

—— LANGE, G. J. DE, GUSTAFSSON, Ö., MIDDELBURG, J. J., SINNINGHE DAMSTÉ, J. S. and SCHOUTEN, S. 2008. Selective preservation of soil organic matter in oxidized marine sediments (Madeira Abyssal Plain). *Geochimica et Cosmochimica Acta*, **72**, 6061–6068.

IGLESIAS, A., WILF, P., JOHNSON, K. R., ZAMUNER, A. B., CÚNEO, N. R., MATHEOS, S. D. and SINGER, B. S. 2007. A Paleocene lowland macroflora from Patagonia reveals significantly greater richness than North American analogs. *Geology*, **35**, 947–950.

KELLER, G., ADATTE, T., TANTAWY, A., BERNER, Z., STINNESBECK, W., STUEBEN, D. and LEANZA, H. 2007. High stress late Maastrichtian – early Danian

palaeoenvironment in the Neuquén Basin, Argentina. *Cretaceous Research*, **28**, 939–960.

KIESSLING, W. and CLAEYS, P. 2002. A geographic database approach to the KT boundary. 83–140. *In* BUFFE-TAUT, E. and KOEBERL, C. (eds). *Geological and biological effects of impact events*. Springer.

KIM, J. H., VAN DER MEER, J., SCHOUTEN, S., HELMKE, P., WILLMOTT, V., SANGIORGI, F., KOC, N., HOPMANS, E. C. and SINNINGHE DAMSTÉ, J. S. 2010. New indices and calibrations derived from the distribution of crenarchaeal isoprenoid tetraether lipids: implications for past sea surface temperature reconstructions. *Geochimica et Cosmochimica Acta*, **74**, 4639–4654.

KOMINZ, M. A., BROWNING, J. V., MILLER, K. G., SUGARMAN, P. J., MIZINTSEVA, S. and SCOTESE, C. R. 2008. Late Cretaceous to Miocene sea-level estimates from the New Jersey and Delaware coastal plain coreholes: an error analysis. *Basin Research*, **20**, 211–226.

KRING, D. A. 2007. The Chicxulub impact event and its environmental consequences at the Cretaceous–Tertiary boundary. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **255**, 4–21.

LUCAS-CLARK, J. 2006. Small peridinioid dinoflagellate cysts from the Paleocene of South Carolina, U.S.A. *Palynology*, **30**, 183–210.

MACLEOD, N. and KELLER, G. 1991. Hiatus distributions and mass extinctions at the Cretaceous/Tertiary boundary. *Geology*, **19**, 497–501.

MEDINA, F. A. and MALAGNINO, E. C. 1990. Bioestratigrafía del Cretácico superior-Paleoceno Marino de la Formación Lefipán, Barranca de los Perros, Río Chubut, Chubut. . V Congreso Argentino de Paleontología y Bioestratigrafía, San Miguel de Tucumán, Argentina, **7**, 137–142.

MILLER, K. G., WRIGHT, J. D. and BROWNING, J. V. 2005. Visions of ice sheets in a greenhouse world. *Marine Geology*, **217**, 215–231.

MOLINA, E., ALEGRET, L., ARENILLAS, I., ARZ, J. A., GALLALA, N., HARDENBOL, J., SALIS, K. VON, STEURBAUT, E., VANDENBERGHE, N. and ZAGH-BIB-TURKI, D. 2006. The Global Boundary Stratotype Section and Point for the base of the Danian Stage (Paleocene, Paleogene', Tertiary', Cenozoic) at El Kef, Tunisia-Original definition and revision. *Episodes*, **29**, 263–273.

NØHR-HANSEN, H. 1996. Upper Cretaceous dinoflagellate cyst stratigraphy, onshore West Greenland. *Gronlands Geologiske Undersiøgelse Bulletin*, **170**, 1–104.

OLSSON, R. K., HEMLEBEN, C., BERGGREN, W. A. and HUBER, B. T. 1999. Atlas of Paleocene planktonic foraminifera. *Smithsonian Contributions to Paleobiology*, **85**, 1–252.

—— MILLER, K. G., BROWNING, J. V., WRIGHT, J. D. and CRAMER, B. S. 2002. Sequence stratigraphy and sea-level change across the Cretaceous–Tertiary boundary on the New Jersey passive margin. *GSA Special Papers*, **356**, 97–108.

PALAZZESI, L. and BARREDA, V. D. 2007. Major vegetation trends in the Tertiary of Patagonia (Argentina): a qualitative paleoclimatic approach based on palynological evidence. *Flora – Morphology, Distribution, Functional Ecology of Plants*, **202**, 328–337.

PAPÚ, O. H., PRÁMPARO, M. B., NÁÑEZ, C. and CON-CHEYRO, A. 1999. Palinología y micropaleontología de la Formación Jagüel (Maastrichtiano-Daniano), perfil Opaso, Cuenca Neuquina, Argentina. *Simposio Paleogeno de América del Sur (Buenos Aires. 1996). Actas Subsecretaria de Mlneria de la Nación, Servicio Geológlco Minero Argentino*, **33**, 17–33.

PRÁMPARO, M. B. and PAPÚ, O. H. 2006. Late Maastrichtian dinoflagellate cysts from the Cerro Butaló section, southern Mendoza province, Argentina. *Journal of Micropalaeontology*, **25**, 23–33.

PROSS, J. and BRINKHUIS, H. 2005. Organic-walled dinoflagellate cysts as paleoenvironmental indicators in the Paleogene; a synopsis of concepts. *Paläontologische Zeitschrift*, **79**, 53–59.

RUIZ, L., SCASSO, R. A., ABERHAN, M., KIESSLING, W., BANDE, A., MEDINA, F. and WEIDEMEYER, S. 2005. La Formación Lefipán en el Valle Medio del Río Chubut: ambientes sedimentarios y su relación con la tectónica del Cretácico Tardío-Paleoceno. *XVI Congreso Geológico Argentino, La Plata, Argentina, Actas*, **3**, 231–238.

SCASSO, R. A., CONCHEYRO, A., ABERHAN, M., HECHT, L., MEDINA, F. A. and TAGLE, R. 2005. A tsunami deposit at the Cretaceous/Paleogene boundary in the Neuquén Basin of Argentina. *Cretaceous Research*, **26**, 283–297.

—— ABERHAN, M., RUIZ, L., WEIDEMEYER, S., MEDINA, F. A. and KIESSLING, W. 2012. Integrated bio- and lithofacies analysis of coarse-grained, tide-dominated deltaic environments across the Cretaceous/Paleogene boundary in Patagonia, Argentina. *Cretaceous Research*, **36**, 37–57.

SCHIØLER, P. and WILSON, G. J. 1993. Maastrichtian dinoflagellate zonation in the Dan Field, Danish North Sea. *Review of Palaeobotany & Palynology*, **78**, 312–351.

—— BRINKHUIS, H., RONCAGLIA, L. and WILSON, G. J. 1997. Dinoflagellate biostratigraphy and sequence stratigraphy of the type Maastrichtian (Upper Cretaceous), ENCI Quarry, The Netherlands. *Marine Micropaleontology*, **31**, 65–95.

SCHOUTEN, S., HOPMANS, E. C., SCHEFUS, E. and SINNINGHE DAMSTÉ, J. S. 2002. Distributional variations in marine crenarchaeotal membrane lipids: a new tool for reconstructing ancient sea water temperatures? *Earth & Planetary Science Letters*, **204**, 265–274.

—— HUGUET, C., HOPMANS, E. C., KIENHUIS, M. V. M. and SINNINGHE DAMSTÉ, J. S. 2007. Analytical methodology for TEX86 paleothermometry by high-performance liquid chromatography/atmospheric pressure chemical ionization-mass spectrometry. *Analytical Chemistry*, **79**, 2940–2944.

—— HOPMANS, E. C. and SINNINGHE DAMSTÉ, J. S. 2013. The organic geochemistry of glycerol dialkyl glycerol tetraether lipids: a review. *Organic Geochemistry*, **54**, 19–61.

SCHULTE, P., SPEIJER, R., MAI, H. and KONTNY, A. 2006. The Cretaceous–Paleogene (K–P) boundary at Brazos, Texas: sequence stratigraphy, depositional events and the Chicxulub impact. *Sedimentary Geology*, **184**, 77–109.

—— ALEGRET, L., ARENILLAS, I., ARZ, J. A., BARTON, P. J., BOWN, P. R., BRALOWER, T. J.,

CHRISTESON, G. L., CLAEYS, P., COCKELL, C. S., COLLINS, G. S., DEUTSCH, A., GOLDIN, T. J., GOTO, K., GRAJALES-NISHIMURA, J. M., GRIEVE, R. A. F., GULICK, S. P. S., JOHNSON, K. R., KIES-SLING, W., KOEBERL, C., KRING, D. A., MACLEOD, K. G., MATSUI, T., MELOSH, J., MONTANARI, A., MORGAN, J. V., NEAL, C. R., NICHOLS, D. J., NOR-RIS, R. D., PIERAZZO, E., RAVIZZA, G., REBOL-LEDO-VIEYRA, M., REIMOLD, W. U., ROBIN, E., SALGE, T., SPEIJER, R. P., SWEET, A. R., URRUTIA-FUCUGAUCHI, J., VAJDA, V., WHALEN, M. T. and WILLUMSEN, P. S. 2010. The Chicxulub asteroid impact and mass extinction at the Cretaceous-Paleogene boundary. *Science*, **327**, 1214–1218.

SLIMANI, H. 2001. New species of dinoflagellate cysts from the Campanian-Danian chalks at Hallembaye and Turnhout (Belgium) and at Beutenaken (the Netherlands). *Journal of Micropalaeontology*, **20**, 1–11.

—— LOUWYE, S. and TOUFIQ, A. 2010. Dinoflagellate cysts from the Cretaceous–Paleogene boundary at Ouled Had-dou, southeastern Rif, Morocco: biostratigraphy, paleoenvi-ronments and paleobiogeography. *Palynology*, **34**, 90–124.

—— GUÉDÉ, K. É., WILLIAMS, G. L., ASEBRIY, L. and AHMAMOU, M. 2016. Campanian to Eocene dinoflagellate cyst biostratigraphy from the Tahar and Sekada sections at Arba Ayacha, western External Rif, Morocco. *Review of Palaeobotany & Palynology*, **228**, 26–46.

SLUIJS, A. and BRINKHUIS, H. 2009. A dynamic climate and ecosystem state during the Paleocene-Eocene Thermal Maximum – inferences from dinoflagellate cyst assemblages at the New Jersey Shelf. *Biogeosciences*, **6**, 5163–5215.

—— PROSS, J. and BRINKHUIS, H. 2005. From green-house to icehouse; organic-walled dinoflagellate cysts as pale-oenvironmental indicators in the Paleogene. *Earth-Science Reviews*, **68**, 281–315.

SPALLETTI, L. A. 1996. Estuarine and shallow-marine sedi-mentation in the upper Cretaceous-Lower Tertiary west-cen-tral Patagonian Basin (Argentina). *Geological Society, London, Special Publications*, **117**, 81–93.

TIERNEY, J. E. and TINGLEY, M. P. 2014. A Bayesian, spa-tially-varying calibration model for the TEX_{86} proxy. *Geochim-ica et Cosmochimica Acta*, **127**, 83–106.

VELLEKOOP, J., SLUIJS, A., SMIT, J., SCHOUTEN, S., WEIJERS, J. W. H., SINNINGHE DAMSTÉ, J. S. and BRINKHUIS, H. 2014. Rapid short-term cooling following the Chicxulub impact at the Cretaceous–Paleogene boundary. *Proceedings of the National Academy of Sciences*, **111**, 7537–7541.

—— SMIT, J., SCHOOTBRUGGE, B. VAN DE, WEI-JERS, J. W. H., GALEOTTI, S., SINNINGHE

DAMSTÉ, J. S. and BRINKHUIS, H. 2015. Palynological evidence for prolonged cooling along the Tunisian continental shelf following the K–Pg boundary impact. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **426**, 216–228.

—— ESMERAY-SENLET, S., MILLER, K. G., BROWN-ING, J. V., SLUIJS, A., SCHOOTBRUGGE, B. VAN DE, SINNINGHE DAMSTÉ, J. S. and BRINKHUIS, H. 2016. Evidence for Cretaceous-Paleogene boundary bolide "impact winter" conditions from New Jersey, USA. *Geology*, **44**, 619–622.

—— HOLWERDA, F., PRÁMPARO, M. B., WILL-MOTT, V., SCHOUTEN, S., CÚNEO, N. R., SCASSO, R. A. and BRINKHUIS, H. 2017. Data from: Climate and sea level changes across a shallow marine Cretaceous-Paleo-gene boundary succession in Patagonia, Argentina. *Dryad Dig-ital Repository*. doi: 10.5061/dryad.r86pk

WALSH, E. M., INGALLS, A. E. and KEIL, R. G. 2008. Sources and transport of terrestrial organic matter in Vancou-ver Island fjords and the Vancouver-Washington Margin: a multiproxy approach using d13Corg, lignin phenols, and the ether lipid BIT index. *Limnology & Oceanography*, **53**, 1054–1063.

WEIJERS, J. W. H., SCHOUTEN, S., SPAARGAREN, O. C. and SINNINGHE DAMSTÉ, J. S. 2006. Occurrence and distribution of tetraether membrane lipids in soils: impli-cations for the use of the TEX_{86} proxy and the BIT index. *Organic Geochemistry*, **37**, 1680–1693.

WILLIAMS, G. L., BRINKHUIS, H., PEARCE, M. A., FENSOME, R. A. and WEEGINK, J. W. 2004. Southern Ocean and global dinoflagellate cyst events compared: index events for the Late Cretaceous–Neogene. 1–98. *In* EXON, N. F., KENNETT, J. P. and MALONE, M. J. (eds). *Proceed-ings of the Ocean Drilling Program, Scientific Results*, **189**.

WOELDERS, L. and SPEIJER, R. P. 2015. Stable seafloor conditions, sea level and food supply during the latest Maas-trichtian at Brazos River, Texas. *Marine Micropaleontology*, **121**, 41–51.

—— VELLEKOOP, J., KROON, D., SMIT, J., CASADIÓ, S., PRÁMPARO, M. B., DINARÈS-TURELL, J., PETERSE, F., SLUIJS, A., LENAERTS, J. T. M. and SPEIJER, R. P. 2017. Latest Cretaceous climatic and environ-mental change in the South Atlantic region. *Paleoceanography*, published online 4 May. doi: 10.1002/2016PA003007

ZELL, C., KIM, J.-H., MOREIRA-TURCQ, P., ABRIL, G., HOPMANS, E. C., BONNET, M.-P., LIMA SOBRINHO, R. and SINNINGHE DAMSTÉ, J. S. 2013. Disentangling the origins of branched tetraether lipids and cre-narchaeol in the lower Amazon River: implications for GDGT-based proxies. *Limnology & Oceanography*, **58**, 343–353.