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Biochronocorrelation of K/Pg-Danian sections near Chicxulub: application of new planktic foraminiferal scales

Ignacio Arenillas [a,*], Vicente Gilabert [a,b], Iván Aparicio [a], Hermann D. Bermúdez [c], Liliana Bolívar [c], Thierry Calmus [d], Daniel Ferrer [a], José M. Grajales-Nishimura [e], Carlos L. Liesa [a], Kenya E. Núñez-Cambra [f], Ligia Pérez-Cruz [g,h], Reinaldo Rojas-Consuegra [i], María del Carmen Rosales-Domínguez [j], Ana R. Soria [a], Jaime Urrutia-Fucugauchi [g,h], José A. Arz [a]

[a] *Departamento de Ciencias de la Tierra, and Instituto Universitario de Investigación en Ciencias Ambientales de Aragón (IUCA), Universidad de Zaragoza, C/Pedro Cerbuna, 12, E-50009, Zaragoza, Spain*
[b] *Geologia Saila, Zientzia eta Teknologia Fakultatea, Euskal Herriko Unibertsitatea (EHU), Barrio Sarriena s/n, 48940, Leioa, Bizkaia, Spain*
[c] *Grupo de Investigación Paleoexplorer, Bogotá, D.C., 111621, Colombia*
[d] *Estación Regional del Noroeste, Instituto de Geología, UNAM, Hermosillo, Sonora, 83000, Mexico*
[e] *Seminario Universitario sobre Investigación en Hidrocarburos and Posgrado en Ciencias de la Tierra, Universidad Nacional Autónoma de México, Ciudad Universitaria, Coyoacán, Ciudad de México, C. P. 04510, Mexico*
[f] *Instituto de Geología y Paleontología, Vía Blanca No. 1002, Virgen del Camino, San Miguel del Padrón, La Habana, 11000, Cuba*
[g] *Programa Universitario de Perforaciones en Océanos y Continentes, Instituto de Geofísica, Universidad Nacional Autónoma de México, Coyoacán, 04510, Mexico*
[h] *Instituto de Investigación Científica y Estudios Avanzados Chicxulub, Parque Científico y Tecnológico de Yucatán, Sierra Papacal, Mérida, Yucatán, 97302, Mexico*
[i] *Centro de Investigación del Petróleo, Ministerio de Energía y Minas, Churruca No. 481 e/ Washington y Vía Blanca, Municipio Cerro, La Habana, 12000, Cuba*
[j] *Consultora independiente. C/ California 172-C3, Delegación Coyoacán, Ciudad de México, C.P. 04040, Mexico*

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ABSTRACT

Using qualitative and quantitative planktic foraminiferal stratigraphy, we correlated the Danian sediments directly overlying the Chicxulub impact-related Cretaceous/Paleogene boundary deposits (K/Pg deposits) at localities across the Gulf of Mexico, the Caribbean, and the Colombian Pacific. The aim of this study was to apply recently developed planktic foraminiferal biochronological scales to determine whether these American K/Pg sections record continuous stratigraphic succession or show evidence of a hiatus between the K/Pg deposits and the first Danian sediments deposited under normal conditions (K/Pg-Danian hiatus). To accomplish this, we reviewed, completed, and updated biostratigraphic information generated over the last three decades, incorporating new data from thirty K/Pg sections. This effort resulted in a highly comprehensive biostratigraphic database for the lower to upper Danian across the studied regions. Leveraging this database, we developed two biochronological scales with a higher resolution than the more standardized scale by extending the Dan-achrozonation and the DanAZ-acmezonation of Arenillas et al. (2021)into the middle-upper Danian. These new planktic foraminiferal scales enable the estimation of stratigraphic continuity in the K/Pg sections or, where applicable, the temporal duration of the K/Pg-Danian hiatuses. We conclude that, among the sections studied, only Bochil and Guayal (Mexico), Moncada (Cuba), Beloc HA, Nan Pak and Roche à Pierre (Haiti), and probably Isla Gorgonilla (Colombia) exhibit stratigraphic continuity between the K/Pg deposits and the first normal Danian sediments.

1. Introduction

Planktic foraminifera provide precise biostratigraphic and biochronological scales, particularly for the lowermost/earliest Danian, an interval characterized by a major evolutionary radiation following the catastrophic mass extinction at the Cretaceous/Paleogene (K/Pg)

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* Corresponding author.
E-mail address: ias@unizar.es (I. Arenillas).

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boundary (Luterbacher and Premoli-Silva, 1964; Smit, 1982; Arenillas and Arz, 2000, 2017; Arenillas et al., 2000a, 2000b, 2022). This event is generally attributed by the scientific community to the Chicxulub impact on the Yucatán Peninsula, Mexico (Alvarez et al., 1980; Smit and Hertogen, 1980; Hildebrand et al., 1991; Schulte et al., 2010; Arz et al., 2022). Two 'explosive' evolutionary radiations of planktic foraminifera occurred in the earliest Danian (see Arenillas and Arz, 2017, and references cited therein): 1) The first evolutionary radiation occurred approximately 3–20 kyr after the K/Pg boundary and includes the first appearances of parvularugoglobigerinids (*Pseudocaucasina*, *Parvularuglobigerina* and *Palaeoglobigerina*), chiloguembelinids (*Woodringina* and *Chiloguembelina*), and new incoming guembelitriids (*Chiloguembelitria*); 2) The second evolutionary radiation occurred approximately 40–80 kyr after the K/Pg boundary and includes the first appearances of eoglobigerinids (*Eoglobigerina* and *Parasubbotina*), globanomalinids (*Globanomalina*), truncorotaliids (*Praemurica*), and globoconusids (*Trochoguembelitria*). The globoconusid *Globoconusa* and the eoglobigerinid *Subbotina* appeared later, at ~140 and ~210 kyr after the K/Pg boundary, respectively (Arenillas et al., 2021; Gilabert et al., 2022). From the second evolutionary radiation onward, the evolution of new planktic foraminiferal species (or speciation rate) slowed considerably. Consequently, relatively few new species are reported for the remainder of the early Danian and the middle-upper Danian. This difference in evolutionary tempo accounts for the varying precision of biochronological scales: they are highly pinpointed in the earliest Danian, with some biozones/biochrons having an estimated duration of only ~5 kyr (e.g., Biozone P0 of Smit, 1982), but become less precise thereafter, with some biozones/biochrons spanning as long as ~2100 kyr in estimated duration (e.g., Biozone P1c of Wade et al., 2011).

Planktic foraminiferal specialists must strive to establish increasingly detailed scales. With this objective, Arenillas et al. (2021) proposed two scales with planktic foraminifera for the lower Danian: one, the Dan-scale, based on qualitative data and range and interval zones/-chrons (achrozones/achrochrons); and another, the DanAZ-scale, based on quantitative data and abundance zones/chrons (acmezones/acmechrons). To establish both scales, very detailed sampling was carried out in the most continuous lower Danian sections worldwide, particularly from the western Tethys and North-East Atlantic, but also from the Gulf of Mexico. The proposed scales were calibrated using magnetochronological (Arenillas et al., 2004, 2021; Metsana-Oussaid et al., 2019) and astrochronological dating (Gilabert et al., 2022). These calibrations allowed for the establishment of planktic foraminiferal scales with higher resolution than the most standardized P-scale of Wade et al. (2011). However, the Dan- and DanAZ-scales of Arenillas et al. (2021) only spanned the first 1000 kyr of the Danian.

We aim to extend both scales to the first 3300 kyr of the Danian, thereby spanning almost the entire Danian, except for its uppermost/latest part. To achieve this, we conducted detailed and/or high resolution planktic foraminiferal stratigraphic studies, employing both qualitative and quantitative methods on the ≥63 μm size fraction, across thirty sections located in the Gulf of Mexico, the Caribbean, and the Colombian Pacific. Most of these sections are well known for their K/Pg deposits (specifically, ejecta-rich clastic units and impactites), which are linked to the Chicxulub impact, and are the focus of studies on the planktic foraminiferal mass extinction at the K/Pg boundary (see Arz et al., 2022). Known collectively as K/Pg sections, all of these localities are situated relatively near the Chicxulub impact site, including several boreholes drilled directly into the Chicxulub structure. Their sedimentology, mineralogy, petrography, and geochemistry have been the subject of decades of analysis by both the co-authors of this manuscript and numerous other specialists (see references in Table 1 and supplementary material –Appendix A).

The K/Pg deposits in the American sections in or near the Chicxulub structure can be grouped in three types: 1) Chicxulub Impactite Sequence (CIS), characterized mainly by the melt-rock and suevite (impact breccia); 2) Complex Clastic Unit (CCU), characterized by ejecta-rich clastic deposits, such as carbonate or polymictic breccia, siliciclastic sandstones-siltstones, etc.; and 3) Impact Spherule-rich Bed (ISB), characterized almost exclusively by impact spherules. In continuous pelagic sections distant from the Chicxulub impact site, the K/Pg deposits consist of a thin Eject-rich Airfall Layer (EAL). This later was generated by the settling of ballistically transported impact spherules and iridium-rich impact dust (Alvarez et al., 1980; Smit and Hertogen, 1980; Molina et al., 2006, 2009; Schulte et al., 2010; Bermúdez et al., 2025). The EAL is placed at the base of the well-known post-K/Pg Dark Clay Bed (DCB). Although previously questioned, the chronocorrelation between the Chicxulub impact-linked deposits in the Gulf of Mexico and the Caribbean and the EAL of the Global Boundary Stratotype Section and Point (GSSP) for the base of the Danian (or the K/Pg boundary) at El Kef (Tunisia) and other continuous pelagic sections worldwide has been established beyond doubt (see Arz et al., 2022, and supplementary material –Appendix A– for a comprehensive compilation).

Table 1
Basic types of K/Pg deposits in the American K/Pg sections analyzed, with a comprehensive list of references.

Type of K/Pg deposit	References
1) Chicxulub Impactite Sequence (CIS)	Urrutia-Fucugauchi et al. (2004, 2025), Arz et al. (2004), Morgan et al. (2017), Lowery et al. (2018, 2021), Whalen et al. (2020)
2) Complex Clastic Unit (CCU)	Bourgeois et al. (1988), Keller (1989), Hildebrand and Boynton (1990), Alvarez et al. (1992a,b), Smit et al. (1992, 1996), Stinnesbeck et al. (1993, 1997, 1999, 2001), Iturralde-Vinent (1994, 1998), Grajales-Nishimura et al. (1996, 2000, 2003, 2009), Yancey (1996), Bohor (1996), López-Oliva (1996), López-Oliva and Keller (1996), Keller et al. (1997, 2007), López-Oliva et al. (1998), Bralower et al. (1998), Smit (1999), González-Lara (2001), Takayama et al. (2000), Arz et al. (2001a,b), Soria et al. (2001), Arenillas et al. (2002, 2006), Alegret et al. (2002a,b, 2005), Tada et al. (2002, 2003), Matsui et al. (2002), Schulte et al. (2003, 2006, 2012), Dressler et al. (2004), Schulte and Kontny (2005), Rojas-Consuegra and Núñez-Cambra (2007, 2017), Campbell et al. (2008), Goto et al. (2008), Denne et al. (2013), Paull et al. (2014), Sanford et al. (2016), Poag (2017), Gulick et al. (2019)
3) Impact Spherule-rich Bed (ISB)	Maurrasse and Sen (1991), Izett et al. (1991), Leroux et al. (1995), Keller et al. (2001), Maurrasse et al. (2005), Bermúdez et al. (2016, 2019), Renne et al. (2018)

This manuscript aims to apply biochronological scales with planktic foraminifera recently developed by Arenillas et al. (2021) to determine whether American K/Pg sections record continuous sedimentation or a hiatus between the K/Pg deposits and the first normal Danian sediments (i.e., K/Pg-Danian hiatus). To accomplish this, we reviewed, completed, and updated biostratigraphic information generated over the last three decades and incorporated new data from lesser-known sections. This effort resulted in a highly comprehensive biostratigraphic database for the Danian across the American regions studied, as well as an extension of the qualitative and quantitative scales (the Dan- and DanAZ-scales, respectively) of Arenillas et al. (2021) to the first 3300 kyr of the Danian. To check the validity of these scales, we correlated the Danian sediments overlying the K/Pg deposits using planktic foraminifera. This allowed us to evaluate stratigraphic continuity and estimate the temporal duration of K/Pg-Danian hiatuses, if present.

2. Material and methods

2.1. Localities studied

New qualitative and quantitative studies using planktic foraminifera, along with the review and update of previous studies, have been conducted on thirty Danian sections located in or near the Chicxulub impact structure (Fig. 1; Table 2). A total of 550 Danian samples were analyzed for the planktic foraminiferal stratigraphic study. We reviewed and/or updated all samples, taxonomic identifications, and stratigraphic distributions from previous studies. Although extensive research exits on the sedimentology, mineralogy, petrography, and geochemistry of all these sections, fully covering this background information is beyond the scope of this manuscript. Therefore, we provide additional information and a comprehensive list of references to the geological and micropaleontological work carried out in each section within the supplementary material (Appendix A; see also Schulte et al., 2010; Arz et al., 2022, for more information).

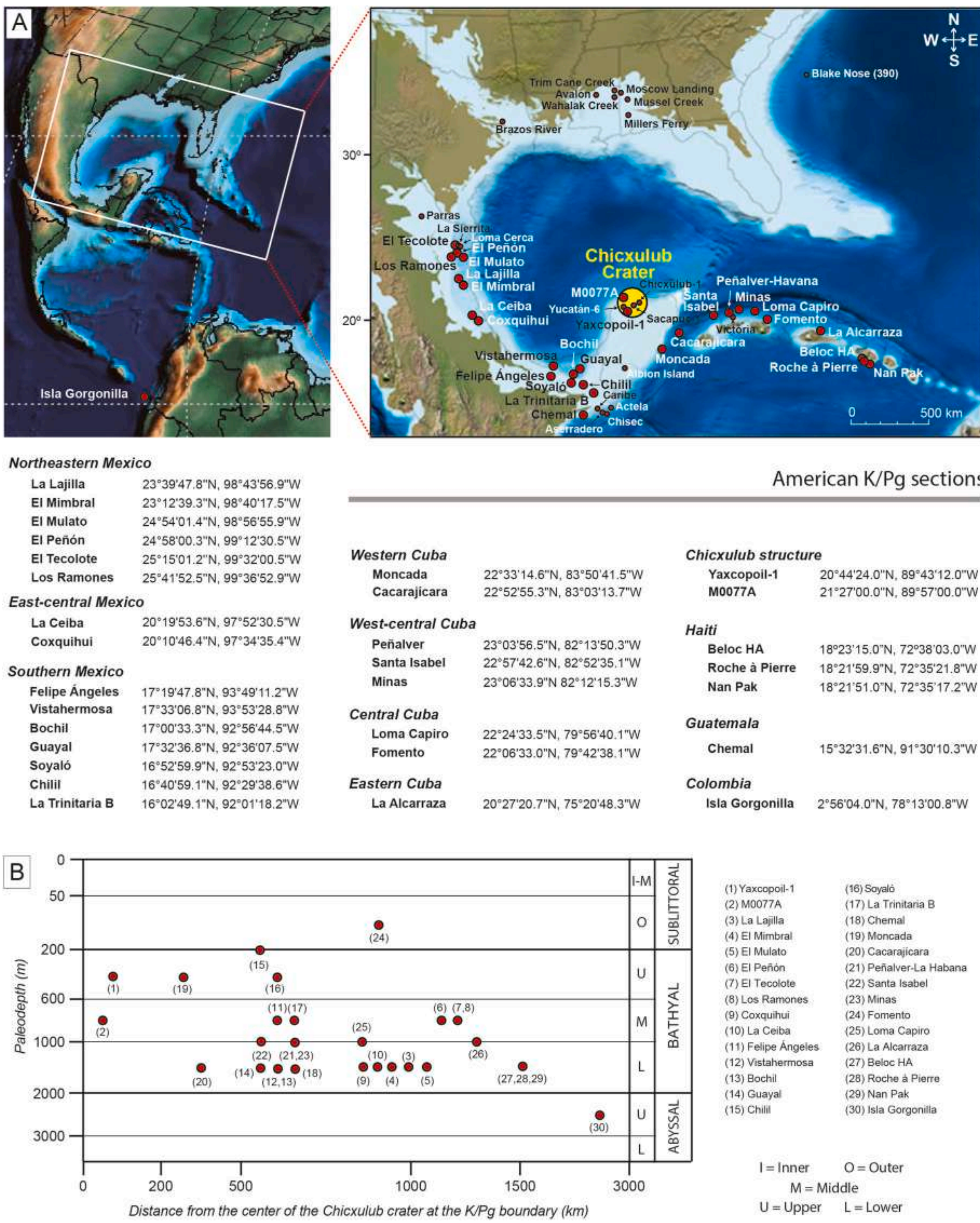

Fig. 1. (A) Paleogeographic location and geographic coordinates of the 30 K/Pg sections (large red circles) subjected to detailed micropaleontological analysis for this study, spanning the Gulf of Mexico, the Caribbean, and the Colombian Pacific. Other relevant K/Pg sections in these regions are also included (small red circles), many of which have been analyzed by the co-authors, although not to the same micropaleontological detail. Paleogeographic base maps are modified from Blakey (2011) and Scotese (2021). (B) Approximate distance (in km) from the center of the Chicxulub crater at the K/Pg boundary, and approximate paleodepth (in m) of each studied locality. Paleobathymetric environments according to the division established by Van Morkhoven et al. (1986).

Table 2
American localities (K/Pg sections) studied grouped by regions. Approximate distance in km from the center of the Chicxulub crater at the K/Pg boundary. Paleobathymetry according to the division established by Van Morkhoven et al. (1986). Duration in Kyr of the K/Pg-Danian hiatus according to what is established in this work (valor 0 = continuous sedimentation). Figures (Supp Figs. 1–30) and tables (Supp Tables 1–5, 9–19, and 24–30) of each locality included in the supplementary material (Appendix A).

Region/Locality	Distance (km)	Paleobathymetry	K/Pg-Danian hiatus (duration in kyr)
Chicxulub structure			
Yaxcopoil-1	60–70	Upper Bathyal	~800
M0077A	40–50	Middle bathyal	~8
Northeastern Mexico			
La Lajilla	1000	Lower bathyal	~10
El Mimbral	950	Lower bathyal	~10
El Mulato	1050	Lower bathyal	~12
El Peñón	1100	Middle bathyal	Not provided
El Tecolote	1150	Middle bathyal	Not provided
Los Ramones	1150	Middle bathyal	Not provided
East-central Mexico			
Coxquihui	850	Lower bathyal	~10
La Ceiba	900	Lower bathyal	~600
Southern Mexico			
Felipe Ángeles	600	Middle bathyal	~10
Vistahermosa	600	Lower bathyal	~10
Bochil	600	Lower bathyal	0
Guayal	550	Lower bathyal	0
Chilil	550	Middle-outer sublittoral	~10
Soyaló	600	Upper bathyal	~15
La Trinitaria B	650	Middle bathyal	>2500
Guatemala			
Chemal	650	Lower bathyal	~15
Western Cuba			
Moncada	300	Upper bathyal	0
Cacarajícara	350	Lower bathyal	Not provided
West-central Cuba			
Peñalver-La Habana	650	Middle-lower bathyal	Not provided
Santa Isabel	550	Middle-lower bathyal	Not provided
Minas	650	Middle-lower bathyal	Not provided
Central Cuba			
Fomento	900	Outer sublittoral	~650
Loma Capiro	850	Middle-lower bathyal	~10
Eastern Cuba			
La Alcarraza	1300	Middle-lower Bathyal	~15
Haiti			
Beloc HA	1500	Lower bathyal	0
Roche à Pierre	1500	Lower bathyal	0
Nan Pak	1500	Lower bathyal	0
Colombian Pacific			
Isla Gorgonilla	2700	Upper abyssal	0 ? (~5)

2.2. Methods

The lowermost Danian stratigraphic intervals of the studied sections were sampled at high resolution (biostratigraphic and biochronological centimeter intervals). The overlying Danian strata were sampled at lower resolution (decimeter-to meter-intervals), a resolution sufficient to correctly recognize the biozones and their stratigraphic continuity or discontinuity. Clay and marly samples were processed using the standard disaggregating technique with diluted H_2O_2. More lithified samples were disaggregated using an 80 % acetic acid solution. All samples were then washed and sieved into ≥63 μm size fractions, and dried at ≤50 °C. When possible, a statistically representative aliquot of between 200 and 400 planktic foraminiferal specimens was extracted from each sample using a microsplitter, and the residue of each sample was intensively scanned to find low-abundance species. All picked foraminiferal specimens were identified, sorted, and fixed on standard 60–square micropaleontological slides. Select specimens were examined under a scanning electron microscope (Zeiss MERLIN FE–SEM) at the Servicio de Microscopía Electrónica de Materiales of the Universidad de Zaragoza, Spain (Figs. 2–10).

3. Limitations of the biostratigraphic study and how to minimize them

Biochronology using planktic foraminifera (and other micropaleontological groups) provides timescales that allow for fairly precise dating of stratigraphic series (e.g., Toumarkine and Luterbacher, 1985; Wade et al., 2011). Furthermore, planktic foraminifera are abundant in the marine stratigraphic record, which is one of the key characteristics that a good key taxon must possess. However, biostratigraphic and biochronological scales have inherent limitations or biases that must be considered. A review of these biases can be found in Signor and Lipps (1982), Molina (1994, 1995), Walsh (1998), Arenillas (2003) and Arenillas et al. (2022). These limitations can be divided into two main types: diachronism of biostratigraphic boundaries (see section 3.1), and limitations in the interpretation of biostratigraphic data (Arenillas, 2003). The latter can be further subdivided into the following factors: taxonomic problems (3.2), paleoenvironmental factors (3.3), taphonomic factors (3.4), sampling quality (3.5), and stratigraphic hiatuses (3.6).

To fully understand the implications of these limitations, it is necessary clarify the meaning of biostratigraphic and biochronological terms. The former (biostratigraphic) includes operational stratigraphic terms, such as 'occurrence datum' (='biohorizon') and 'biozones'. According to the International Stratigraphic Guide (Hedberg, 1976; Salvador, 1994), there are two basic types of occurrence datum: Lowest Occurrence Datum (LOD) and Highest Occurrence Datum (HOD). The LOD refers to the first record in a stratigraphic series, and the HOD to the last stratigraphic record. The second (biochronological) includes inferred or theoretical chronological terms, such as 'paleobiological event' (='bioevent') and 'biochron'. There are also two basic types of bioevent: First Appearance (FA) and Last Appearance (LA), which are inferred from the LOD and HOD respectively. Common past expressions such as First Appearance Datum (FAD) and Last Appearance Datum (LAD) should be considered incorrect (Walsh, 1998). This is because they improperly mix operational stratigraphic terms (biostratigraphic 'data': lowest or highest occurrence datum) with inferred chronological terms (biochronological 'events': first or last appearance event).

The diachronism of biostratigraphic boundaries (see discussion in Walsh, 1998) requires distinguishing two sets of biochronostratigraphic terms: teilchronozones (stratigraphical intervals limited by local biochronohorizons) and holochronozones (stratigraphical intervals limited by historical or 'global' biochronohorizons), and their equivalent biochronological terms: teilchrons (time intervals limited by local bioevents) and holochrons (time intervals limited by historical or 'global' bioevents). Teilchronozones and holochronozones are biochronozones, more commonly known as 'standard biozones'. They need to be defined by the best key taxa available, ensuring these taxa provide the most robust biochronohorizons (or key biohorizons) for establishing their bases and tops. It means that the LODs and HODs of the chosen key taxa must be as synchronous (isochrones) as possible, whether on a local or global scale. Teilchrons and holochrons are biochrons, which require temporal calibration, primarily using magneto- and astrochronological methods. These calibrations rely on the existing biostratigraphic data and the establishment of reliable age models. On the other hand, at least from a theoretical point of view (Walsh, 1998), the limitations in the interpretation of biostratigraphic data require distinguishing between two types of terms: epizones (stratigraphic intervals limited by 'known'

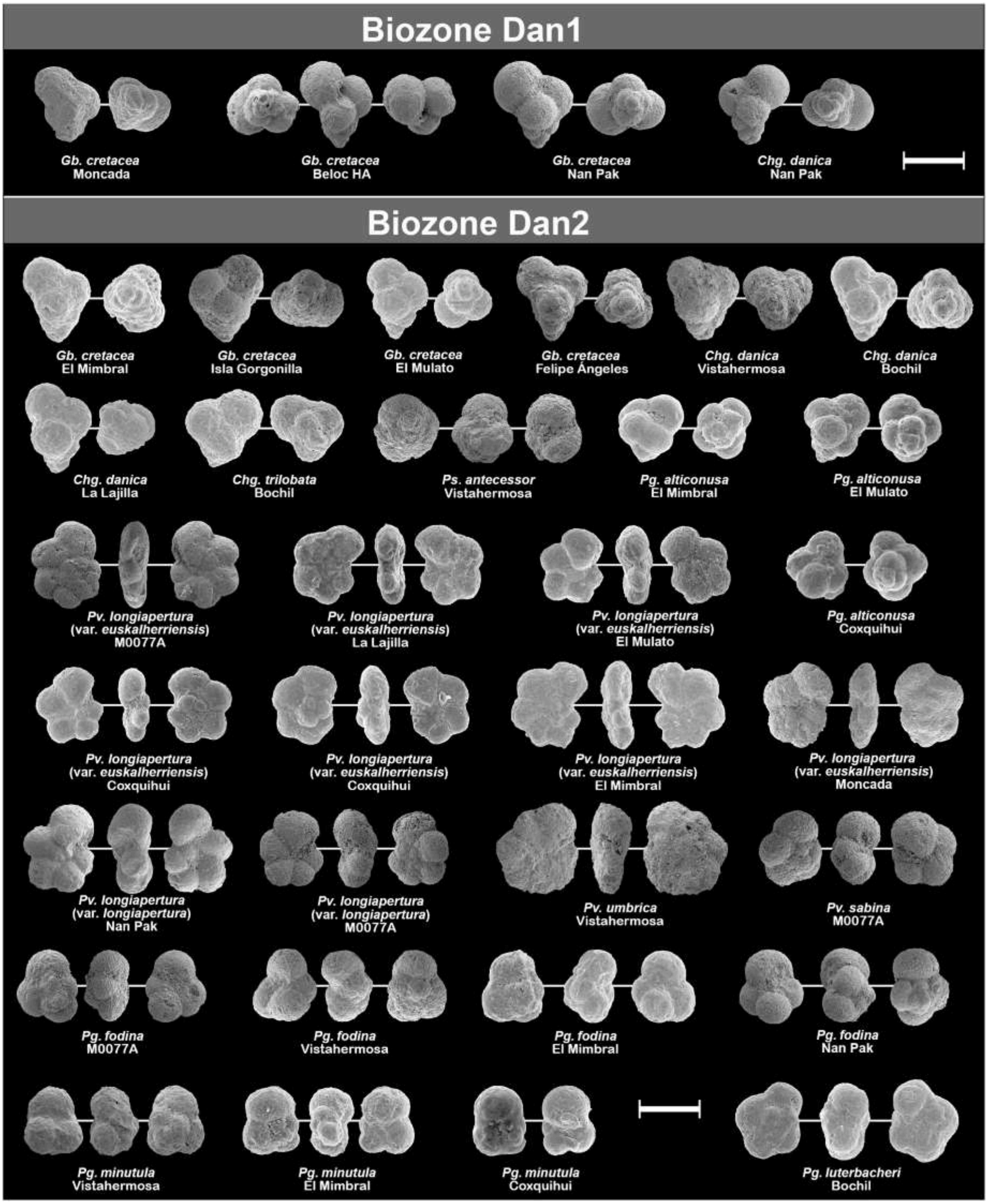

Fig. 2. SEM micrographs of selected planktic foraminiferal specimens recovered from the Biozones Dan1 and Dan2. Species name and locality of origin for each specimen are included on the plate. Scale bars = 100 µm. *Gb.* = *Guembelitria*; *Chg.* = *Chiloguembelitria*; *Ps.* = *Pseudocaucasina*; *Pv.* = *Parvularuglobigerina*; *Pg.* = *Palaeoglobigerina*.

biohorizons = operational data) and entozones (stratigraphic intervals limited by 'actual' biohorizons = inferred biohorizons). Inferring the base and top of the entozones in each locality requires performing biostratigraphic correlations among several sections while simultaneously minimizing the influence of taxonomic, taphonomic, and methodological problems.

3.1. Diachronism of biostratigraphic boundaries

The appearance and disappearance of a taxon in each region or site are usually local and diachronic bioevents, especially in macropaleontological and/or non-marine groups (see discussion in Walsh, 1998). Consequently, the LOD and HOD of most species cannot be used to establish biochronohorizons (or key biohorizons) for precise biochronocorrelations between distant sections. However, this limitation generally does not apply to planktic foraminifera and other planktic

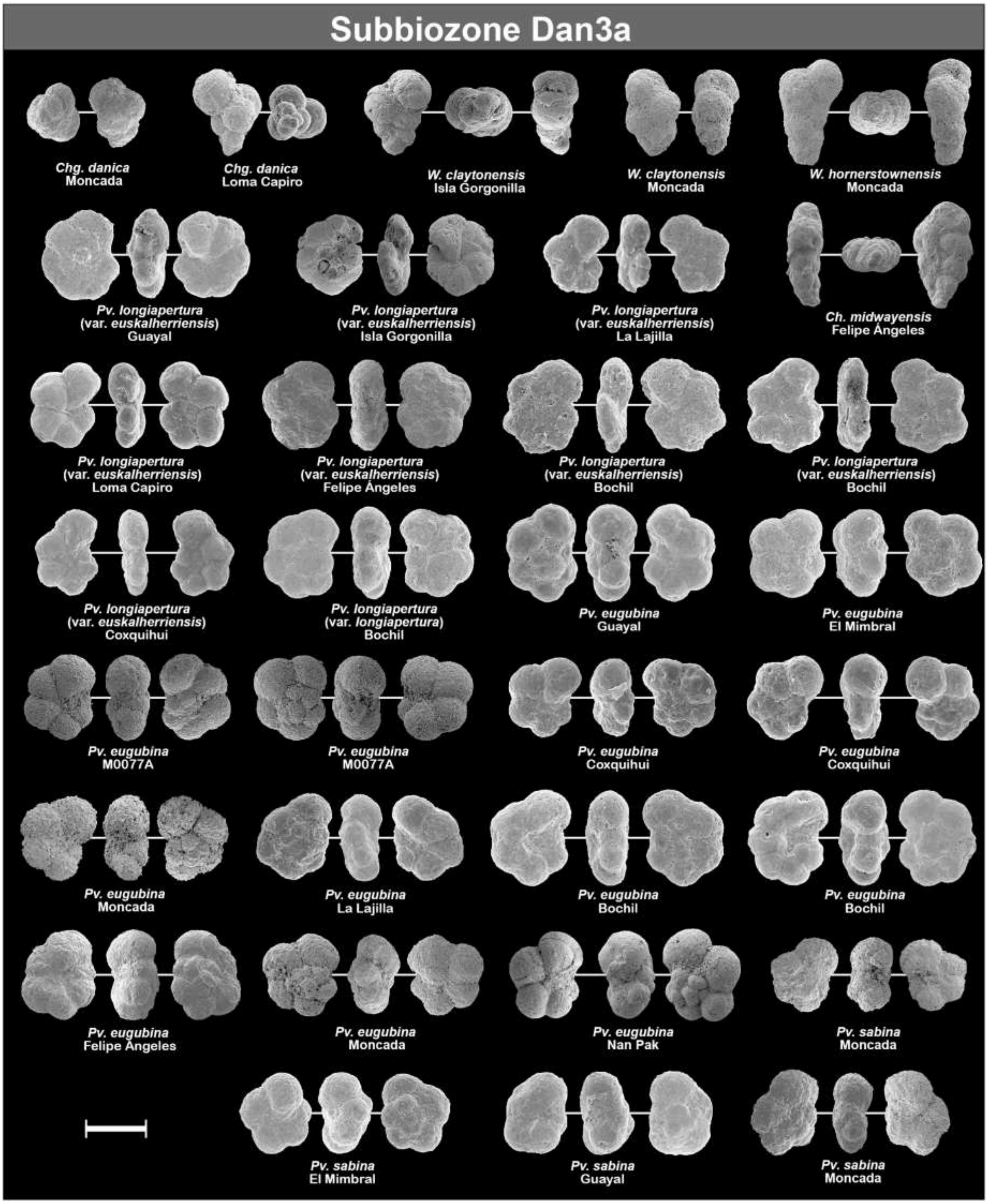

Fig. 3. SEM micrographs of selected planktic foraminiferal specimens recovered from the Subbiozone Dan3a. Species name and locality of origin for each specimen are included on the plate. Scale bar = 100 μm. *Chg.* = *Chiloguembelitria*; *W.* = *Woodringina*; *Ch.* = *Chiloguembelina*; *Pv.* = *Parvularuglobigerina*.

pelagic groups. Their species exhibit the fastest and widest initial dispersal, primarily in oceanic and outer neritic environments. It is possible to assume that the appearance and disappearance of many of their species are synchronous worldwide. Consequently, if taxonomic, taphonomic and methodological problems are minimized, their 'known' LOD and HOD will be stratigraphically very close to their 'actual' LOD and HOD. In other words, it can be assumed that the lower and upper boundaries of the epizones defined on operational stratigraphic studies with planktic foraminifera (and other pelagic groups) will be stratigraphically very close to those of the equivalent entozones, and potentially even to those of the equivalent holochronozones. This is one of the primary reasons why planktic pelagic groups provide the best key taxa. The only significant limitation for some taxa involves climatic or oceanographic biogeographic barriers, which occasionally require defining scales or biozones/biochrons that are only valid for a single hemisphere or for certain latitudes, especially for high latitudes.

3.2. Taxonomic problems

Paleontological taxonomy and systematics are theoretical and

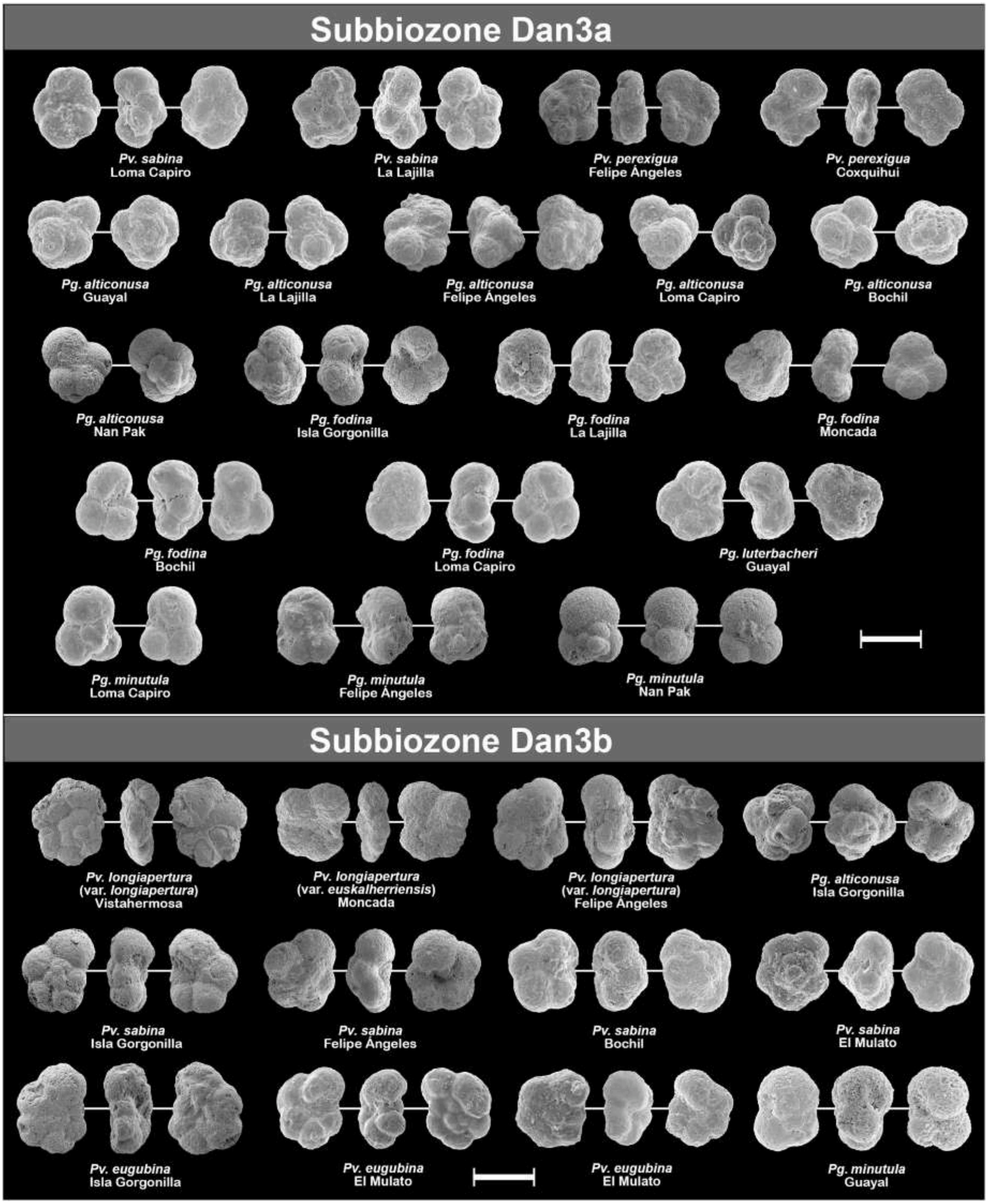

Fig. 4. SEM micrographs of selected planktic foraminiferal specimens recovered from the Subbiozones Dan3a and Dan3b. Species name and locality of origin for each specimen are included on the plate. Scale bars = 100 μm. *Pv.* = *Parvularuglobigerina*; *Pg.* = *Palaeoglobigerina*.

interpretive sciences in their own right, and thus often carry a high degree of uncertainty. Mainly for this reason, no two proposals in planktic foraminiferal systematics are exactly alike (e.g., for the earliest Danian, Luterbacher and Premoli-Silva, 1964, vs. Blow, 1979, vs. Smit, 1982, vs. Toumarkine and Luterbacher, 1985, vs. Keller, 1988, 1989, vs. Olsson et al., 1999, vs. Arenillas et al., 2021). This inherent variation means that species identification is often highly subjective. The paleontological taxonomy and systematics may represent a problem in the biostratigraphic study for several reasons, including different taxonomic assignments, gradual evolution of key species, intraspecific variability, homeomorphy, test preservation, and sieve size fraction used.

3.2.1. Different taxonomic assignments

To help resolve the dispute between specialists supporting a catastrophic mass extinction model for planktic foraminifera (Smit, 1982) and those supporting a gradual mass extinction model (Keller, 1988), a blind test was proposed (Lipps, 1997; Ginsburg, 1997a). In this test, four specialists (Canudo, 1997; Masters, 1997; Olsson, 1997; Orue-Etxebarria, 1997) blindly examined unlabeled samples from the classic El Kef section (Tunisia). Despite the test execution, both Smit (Smit and

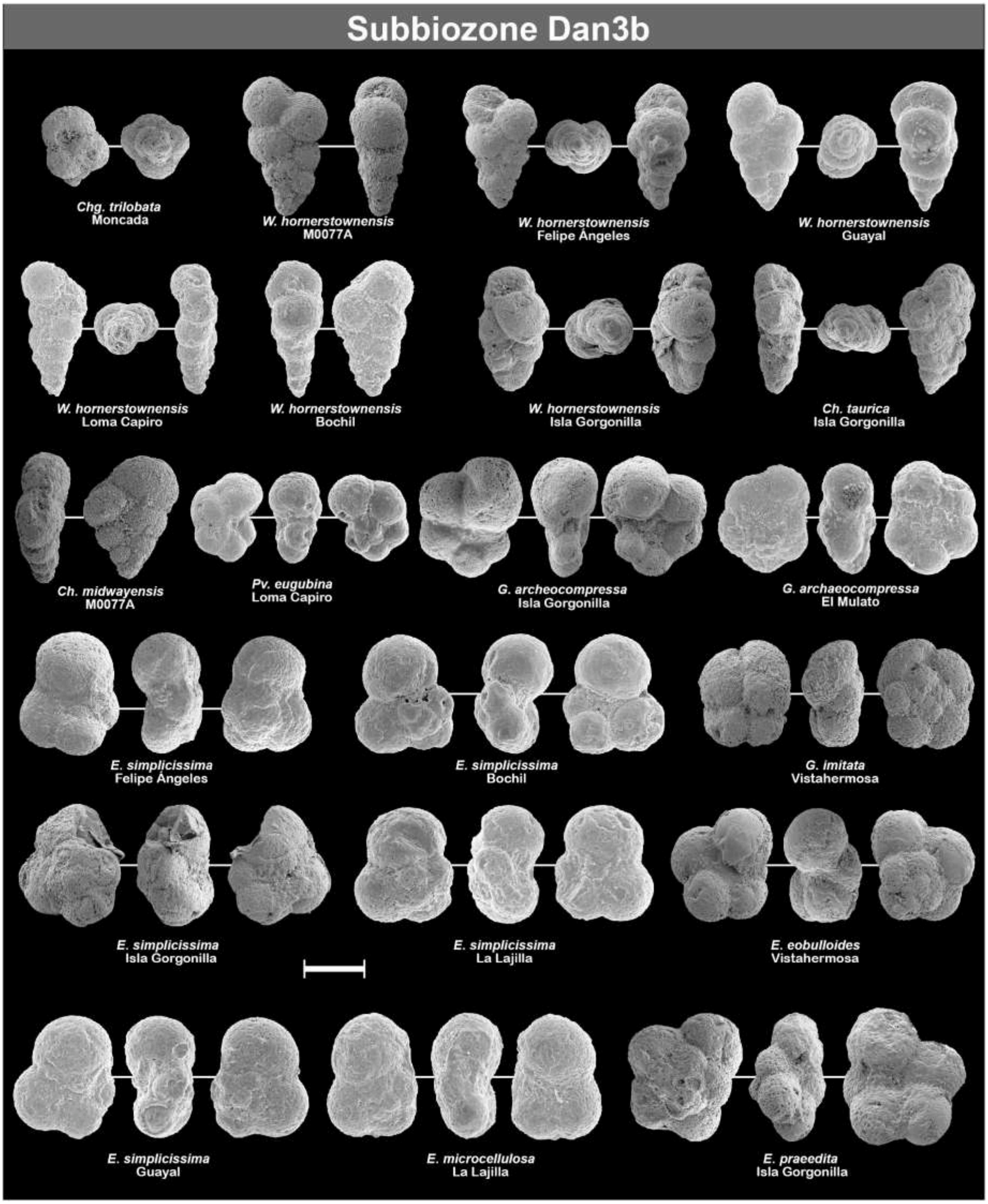

Fig. 5. SEM micrographs of selected planktic foraminiferal specimens recovered from the Subbiozone Dan3b. Species name and locality of origin for each specimen are included on the plate. Scale bar = 100 μm. *Chg.* = *Chiloguembelitria*; *W.* = *Woodringina*; *Ch.* = *Chiloguembelina*; *Pv.* = *Parvularuglobigerina*; *E.* = *Eoglobigerina*; *G.* = *Globanomalina*.

Nederbragt, 1997) and Keller (1997) claimed that the outcome supported their own views. Ginsburg (1997b) concluded that the blind test had ultimately failed, citing, among other reasons, the persistent differences in the taxonomic naming of the species among the specialists. Each of the four specialists proposed different taxonomic assignments, with each following some of the systematic proposals mentioned above.

This difficult arises partly because some holotypes of the key species are either badly illustrated or poorly preserved. Furthermore, holotypes that are deformed, aberrant, or juvenile also impede objective species identification. A third challenge stems from the fact that the definition of paratypes often involves the inclusion of very subjective interpretations when establishing the morphological variability of defined species. In the case of planktic foraminifera, this issue is partially resolved by conveniently illustrating the species, particularly the key species. Voucher images are an accessible and time-effective way to mitigate (though not abolish) poor taxonomy by exposing preventable misidentifications, as they allow scientists to judge specimen identification based on available visual data (Bianchi and Gonçalves, 2021). This is

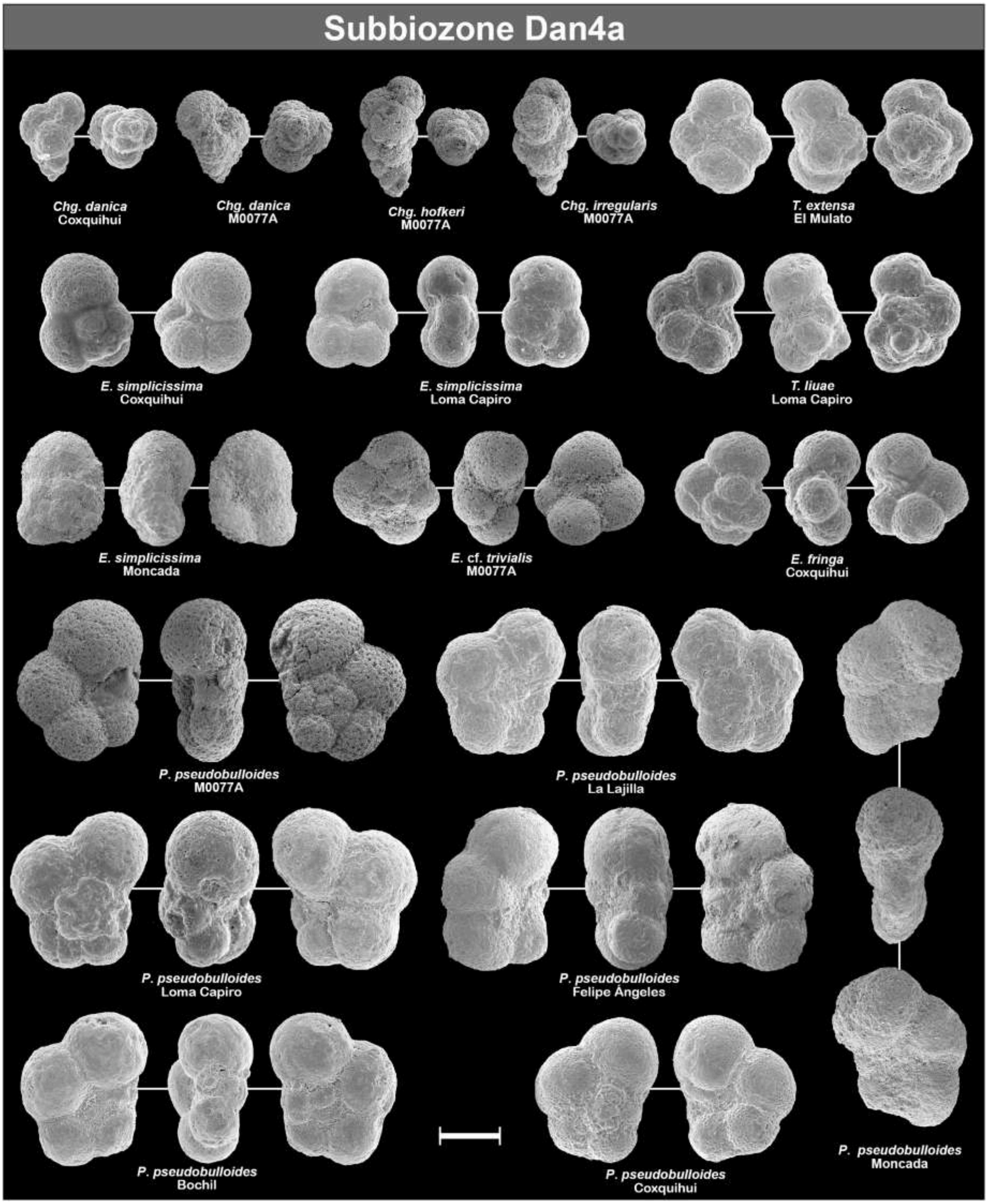

Fig. 6. SEM micrographs of selected planktic foraminiferal specimens recovered from the Subbiozone Dan4a. Species name and locality of origin for each specimen are included on the plate. Scale bar = 100 μm. *Chg.* = *Chiloguembelitria*; *T.* = *Trochoguembelitria*; *E.* = *Eoglobigerina*; *P.* = *Parasubbotina*.

how biostratigraphers show their taxonomic identification criteria. To properly illustrate planktic foraminiferal specimens, it is essential to photograph the three main sides of each with a Scanning Electron Microscope (SEM), at least those with trochospiral coiling (i.e., umbilical, axial and spiral views). In most cases, showing only one side of a trochospiral specimen is useless, as some of the species diagnostic features are visible only in the other views of its test. For the serial and planispiral species (or even high trochospiral), illustrating their two main sides may be sufficient, but greater rigor often requires illustrating additional sides of their test. The essential views in these cases are: frontal and lateral views in biserial, axial (frontal) and spiral (apical) views in triserial, axial view and one of the umbilical views in planispiral, and axial and spiral views in high trochospiral.

3.2.2. Gradual evolution of key species

Establishing biozone boundaries requires clearly defined key species that are easy and reliable to determine would, a need often very complicated because by issues such as the ambiguity of the concept of species in paleontology (paleospecies). Its conception differs between the various branches of paleontology (e.g., morphospecies,

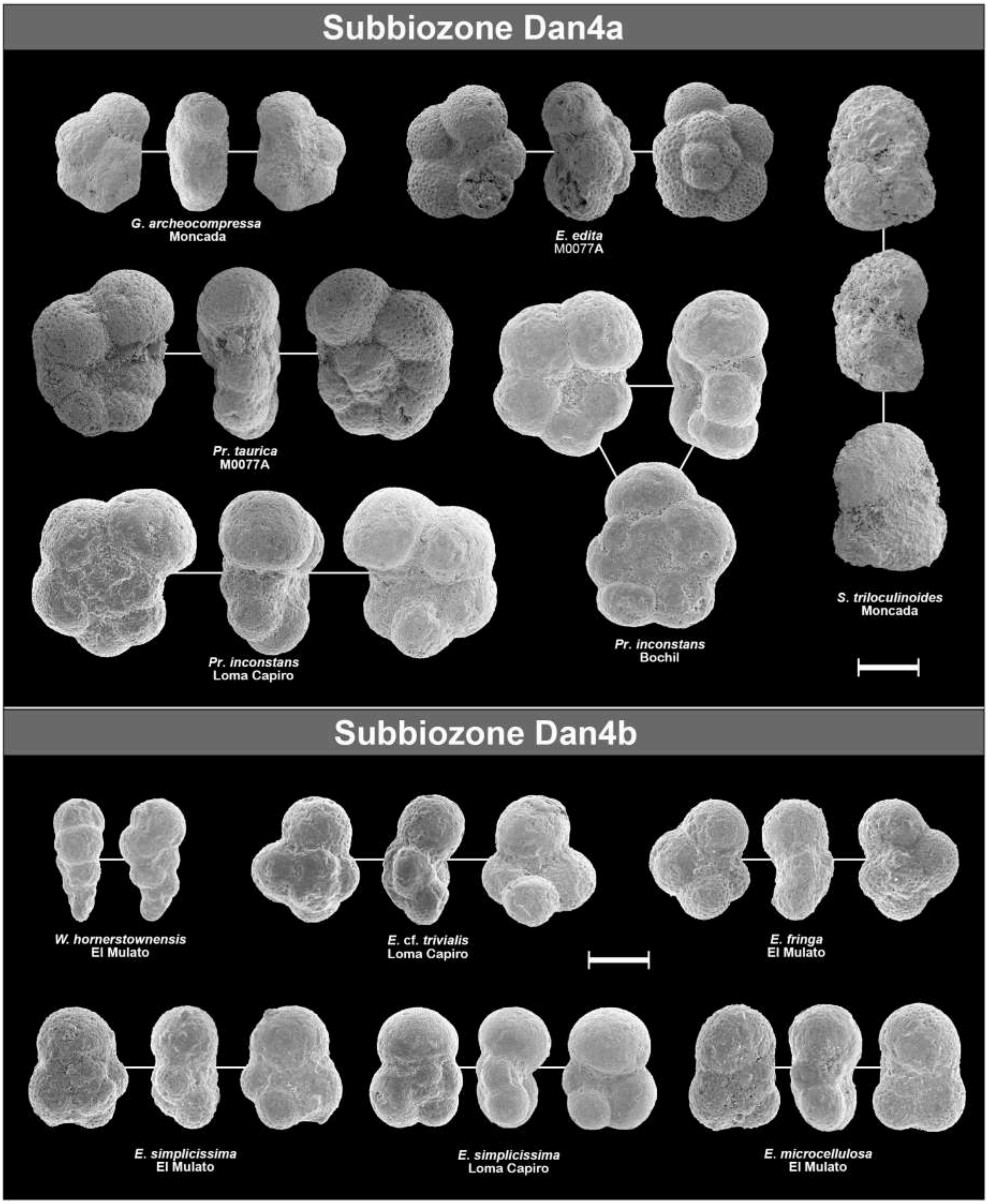

Fig. 7. SEM micrographs of selected planktic foraminiferal specimens recovered from the Subbiozones Dan4a and Dan4b. Species name and locality of origin for each specimen are included on the plate. Scale bars = 100 μm. *W.* = *Woodringina*; *E.* = *Eoglobigerina*; *G.* = *Globanomalina*; *Pr.* = *Praemurica*; *S.* = *Subbotina*.

chronospecies, phylospecies, cladospecies). The appearance (and disappearance) of morphospecies belonging to a phylogenetic lineage (chronospecies) is often a gradual anagenetic process (see examples with Danian planktic foraminifera in Arenillas and Arz, 2017, Arenillas et al., 2021; Metsana-Oussaid et al., 2019). Consequently, when chronospecies are used as key species, some biostratigraphers may argue that transition zones exist between biozones instead of sharply defined boundaries. To minimize this problem, biostratigraphers look for species that exhibit rapid evolution, which is another key characteristic of a good key taxon. Planktic foraminifera provide strong examples of such rapid evolution. However, even with these species, a degree of uncertainty always remains when attempting to determine the precise stratigraphic position of the LOD of an key species in a high resolution biostratigraphic study.

3.2.3. Intraspecific variability: lumper vs. splitter

The great morphological variability exhibited by micropaleontological groups such as planktic foraminifera provokes the debate between splitter taxonomists, who tend to recognize many species with little intraspecific morphological variability, and lumper taxonomists, who tend to recognize few species with significant intraspecific

Fig. 8. SEM micrographs of selected planktic foraminiferal specimens recovered from the Subbiozone Dan4b. Species name and locality of origin for each specimen are included on the plate. Scale bar = 100 μm. *P.* = *Parasubbotina*; *Pr.* = *Praemurica*; *S.* = *Subbotina*.

morphological variability (see historical discussion in Endersby, 2009). This represents an obvious biostratigraphic problem: the same morphotypes can be assigned to one or several species depending on the biostratigrapher, thereby obscuring the synchronicity and similarity of the key species used (see discussion in Arenillas et al., 2021). Furthermore, the morphological differences between successive species (chronospecies) within a phylogenetic lineage are sometimes smaller than the range of morphological variability of a species at a stratigraphic level or 'instant' of geological time. Consequently, establishing the boundaries between chronospecies is often highly subjective, representing a biostratigraphic challenge when slow-evolving species are used as key species. To minimize these problems, biostratigraphers must, as previously noted, search for species that exhibit rapid evolution to reduce the degree of biostratigraphic uncertainty. Additionally, they must illustrate these species appropriately to clearly document and communicate their taxonomic identification criteria.

3.2.4. Homeomorphy (Elvis effect)

Biostratigraphic errors frequently result when a biostratigrapher confuses or synonymizes two homeomorphic species. Homeomorphism

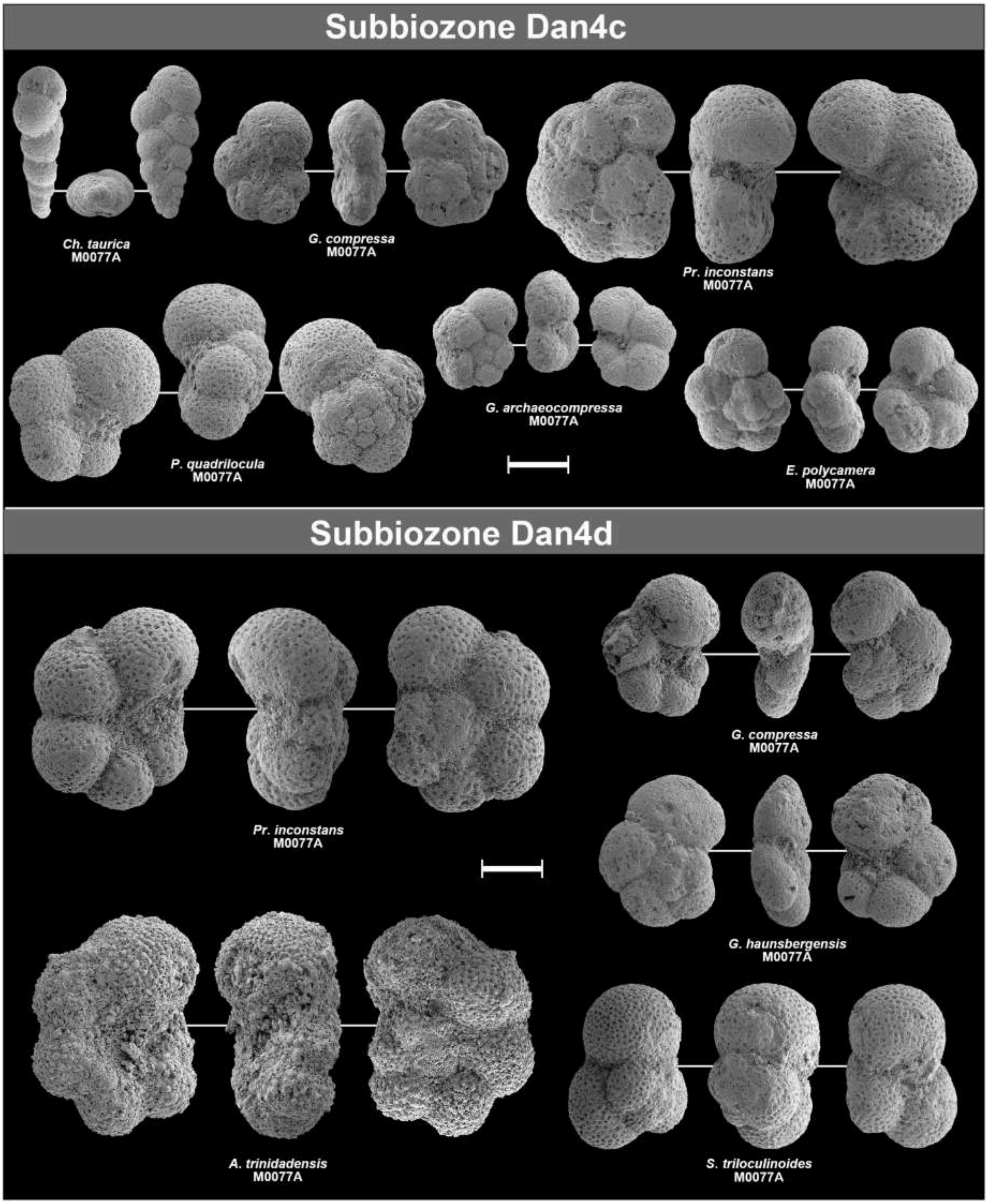

Fig. 9. SEM micrographs of selected planktic foraminiferal specimens recovered from the Subbiozones Dan4c and Dan4d. Species name and locality of origin for each specimen are included on the plate. Scale bars = 100 μm. *Ch.* = *Chiloguembelina*; *E.* = *Eoglobigerina*; *P.* = *Parasubbotina*; *G.* = *Globanomalina*; *Pr.* = *Praemurica*; *S.* = *Subbotina; A.* = *Acarinina*.

arises through processes of convergent and iterative evolution. The problem of homeomorphism in chronologically consecutive species (iterative evolution) has attracted the most attention in biostratigraphy. This has been termed the Elvis effect, a term introduced by Erwin and Droser (1993) in honor of Elvis Presley, whom different people claimed to have seen after his official death. Taxonomic confusion between two homeomorphic species is particularly common when evolutionary convergence is pronounced and occurs within a short geological time interval. This problem has occurred relatively frequently in the past (e.g., between Cretaceous *Planoheterohelix globulosa* and Danian *Woodringina hornerstownensis* in Keller et al., 1993). In planktic foraminifera, this problem is generally resolved when the wall-texture of the tests is carefully examined, if possible, and when sampling is sufficiently detailed to accurately observe the 'actual' evolution of the species and assemblages.

3.2.5. *Test preservation*

The preservation of planktic foraminiferal specimens is a significant

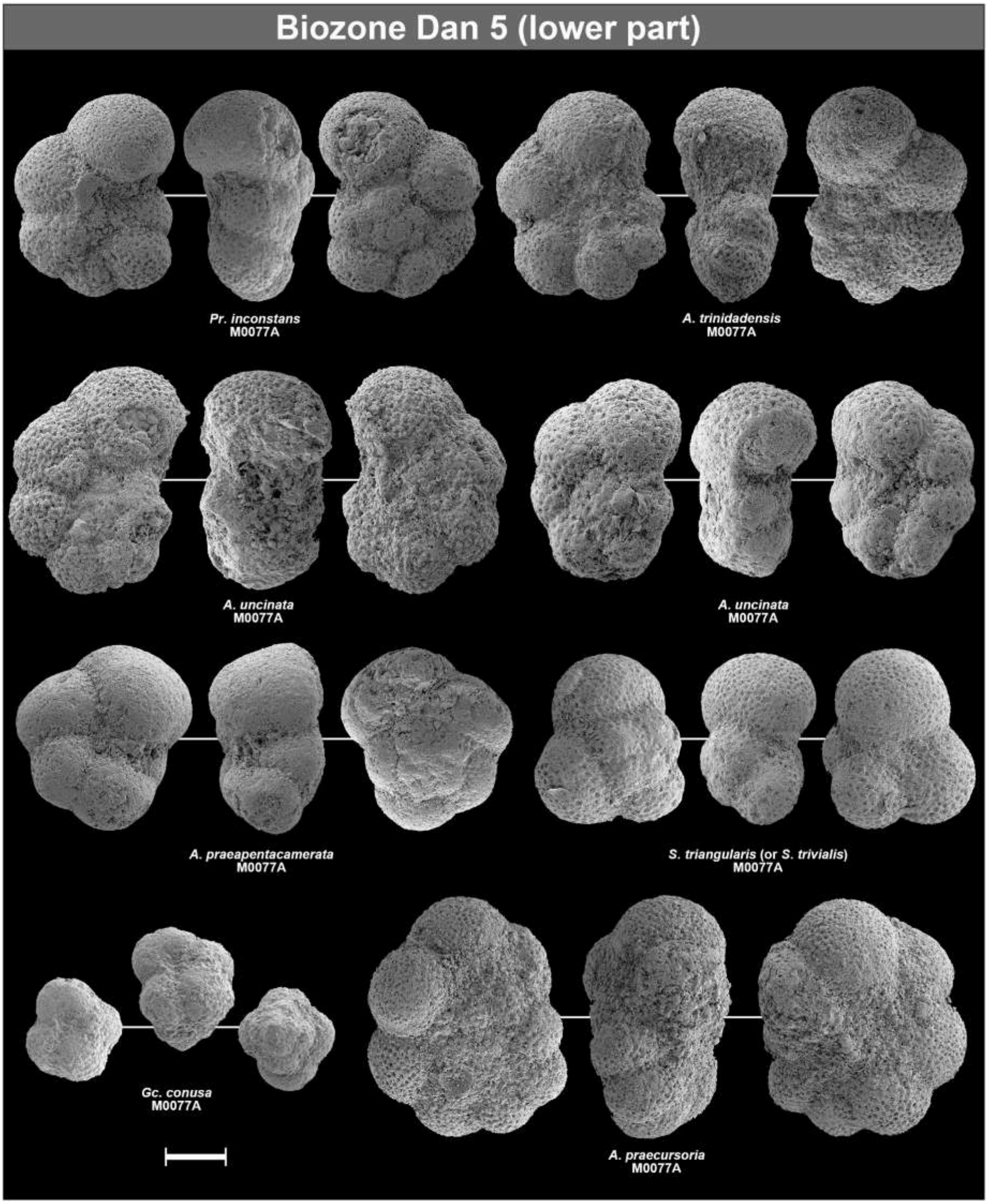

Fig. 10. SEM micrographs of selected planktic foraminiferal specimens recovered from the Biozone Dan5. Species name and locality of origin for each specimen are included on the plate. Scale bar = 100 μm. *Gc.* = *Globoconusa*; *Pr.* = *Praemurica*; *S.* = *Subbotina; A.* = *Acarinina.*

issue in biostratigraphic studies (Molina, 1994, 1995; Arenillas, 2003). Current taxonomists, when defining a species and selecting its type-specimens, seek sites where the tests are well or excellently preserved to properly characterize its morphology and wall-texture. However, test preservation is poor or bad in most of the localities analyzed biostratigraphically, such as almost all of the American sections studied here (see discussions in supplementary material–Appendix A). This significantly impedes the accurate recognition of key species that mark biozone boundaries. To mitigate this problem, it is advisable to study statistically representative aliquots of each sample, as this increases the probability of finding some sufficiently well-preserved specimens. Nevertheless, achieving this objective is often challenging in practice.

3.2.6. *Sieve size fraction used*

Taxonomic identification of species should ideally be performed only on adult specimens. Determining the species to which a juvenile specimen belongs is often an impossible mission in routine biostratigraphic studies. The sieve size fraction used during sample preparation directly controls the proportion of juvenile specimens. In our experience, studying planktic foraminifera in a <63 μm size fraction is counterproductive when analyzing the lowermost Danian, as this fraction is replete with indistinguishable juvenile specimens. It is even a problem when studying planktic foraminifera from more modern stratigraphic intervals (e.g., in the rest of the Paleocene) in a <100 μm size fraction. For example, in some samples from La Trinitaria B (analyzed in the ≥63 μm size fraction), more than half of the extracted specimens were juveniles, which made determinations at the species level impossible, and sometimes even at the genus level. The difficulty in identifying juvenile specimens is partly because juvenile specimens of a species may exhibit morphologies very similar to the adult specimens of its phylogenetic descendants or, conversely, juvenile specimens of a species may exhibit morphologies very similar to the adult specimens of its phylogenetic ancestors (see taxonomic discussions in Arenillas and Arz, 2017, Arenillas et al., 2021; Metsana-Oussaid et al., 2019, and references cited therein). The first case is caused by palingenesis, an evolutionary process that leads to peramorphosis or recapitulation during the ontogenetic development. Examples: adult specimens of *Chiloguembelitria* resemble juvenile specimens of their descendants *Woodringina* and *Trochoguembelitria*; adult specimens of *Pseudocaucasina antecessor*, *Praemurica taurica*, *Praemurica pseudoinconstans*, *Acarinina praeangulata, Globanomalina compressa* and *Globanomalina haunsbergensis* resemble juvenile specimens of their descendants *Palaeoglobigerina alticonusa, Praemurica pseudoinconstans, Praemurica inconstans, Morozovella angulata, Globanomalina haunsbergensis* and *Luterbacheria ehrenbergi* respectively. The second case is caused by proterogenesis, an evolutionary process that leads to paedomorphosis or juvenilization (e.g., neoteny) in the ontogenetic development. Examples: juvenile specimens of *Pseudocaucasina antecessor, Acarinina trinidadensis* and *Acarinina uncinata* resemble adult specimens of their descendants *Parvularugoglobigerina longiapertura, Acarinina uncinata* and *Acarinina praepentacamerata* respectively.

3.3. Paleoenvironmental factors (Lazarus effect)

The stratigraphic distribution of many species is frequently disrupted at the local level due to paleoenvironmental variations (such as eustatic, paleoclimatic, or paleoceanographic changes). These shifts temporarily prevent a species' preferred habitat from being permanently present in a specific geographic area. This results in the temporary disappearance of a species in this area and its later reappearance, causing discontinuous biostratigraphic distributions at the local or regional level (Molina, 1994, 1995; Arenillas, 2003). This is the so-called Lazarus effect, a term coined by Jablonski (1986) in honor of Lazarus (a biblical figure who was supposedly resurrected). In taphonomic terms (Fernández-López, 2000), this results in a species record/registratic hiatus (specifically a productive hiatus) caused by a lack of production of their taphonomic entities. To minimize the problem caused by the Lazarus effect, it is advisable to use key species that have the widest possible geographical and environmental distribution. However, these species should not be overly generalist, as such species tend to have significantly extended biostratigraphic ranges, nor morphologically very simple, as this compromises the reliability of taxonomic identification.

3.4. Taphonomic factors

Taphonomic processes, including both biostratinomic and fossil-diagenetic processes, can significantly distort biostratigraphic studies and compromise biochronostratigraphic and biochronological inferences (Smit, 1982, 1990; Molina, 1994, 1995; Smit and Nederbragt, 1997; Olsson, 1997; Ginsburg, 1997b; Arenillas, 2003). Dissolution, fragmentation, recrystallization, or deformation significantly impair microfossil-based biostratigraphic studies, as they either obscure diagnostic features or cause the complete absence of fossils in the stratigraphic record. In taphonomic terms (Fernández-López, 2000), this results in a species record/registratic hiatus (specifically an alterative hiatus) caused by the alteration of their taphonomic entities. In addition to the aforementioned taphonomic processes, reworking and infiltration due to erosion, resuspension, and bioturbation processes introduce further major problems in microfossil-based biostratigraphic studies (Molina, 1994, 1995; Olsson, 1997; Smit and Nederbragt, 1997; Arenillas et al., 2000a). Another pervasive problem is the contamination and mixing of specimens during core drilling, whose effects are similar to those caused by reworking and/or infiltration.

Theoretically, biostratigraphic studies as well as reliable biochronostratigraphic and biochronological inferences should be based exclusively on *in situ* specimens. Specifically, the fossils used must not be reworked (older specimens deposited in younger strata) nor infiltrated (younger specimens mixed down into older strata). To reduce this problem, prior taphonomic analyses are necessary before making biochronological interpretations. For example, it is not possible to carry out biostratigraphic studies with microfossils in clastic units because all the microfossils they contain are reworked. In biostratigraphic studies, clastic units should be included in barren interzones if they are placed between two biozones (as occurs with the Chicxulub-linked K/Pg deposits), or in barren intrazones, if they are placed within a biozone. An extensive discussion on the problem of reworking in interpreting the Cretaceous species survival pattern after the K/Pg boundary extinction can be found in Arenillas et al. (2022), where it was concluded that all end-Maastrichtian species became extinct at the K/Pg boundary, except for some of *Guembelitria*.

3.5. Sampling quality (Signor-Lipps effect)

Insufficiently detailed sampling or an insufficient amount of sample studied leads to errors in the interpretation of biostratigraphic data (Koch, 1987; Hubard and Gilinsky, 1992; Molina, 1994, 1995; Arenillas et al., 2000a). This is the well-known Signor-Lipps effect (Signor and Lipps, 1982), which primarily affects the biostratigraphic study of macropaleontological groups because, in general, macrofossils tend to be scarce (or absent) in most of the stratigraphic record. This scarcity leads directly to samplings that are often statistically unrepresentative and/or incomplete, and a sample size studied (i.e., number of specimens found) that is usually small.

The micropaleontological record is usually much more complete due to the abundance and small size of microfossils. Consequently, the sampling effects are quite minimized in micropaleontology, mainly when detailed sampling is carried out. However, the Signor-Lipps effect in micropaleontology is also manifested by inadequate or insufficient intensity in the search for low-abundance species in a sample (Molina, 1995, 2015; Arenillas, 2003). These species may appear to be absent from various samples (or horizons) if they are not searched for intensively. In a graphic representation of the stratigraphic distribution of these species, they would appear absent from the horizons equivalent to poorly studied samples (record/registratic hiatuses by methodological biases). The result is discontinuous and seemingly truncated stratigraphic distributions, even when the paleoenvironmental and taphonomic conditions remain constant. To minimize the Signor-Lipps effect in biostratigraphic studies, the researcher must be intensively search in the washing residue for low-abundance species, particularly those absent in the statistically representative aliquot.

3.6. Stratigraphic hiatuses

Hiatuses are a universal problem affecting all stratigraphic scales. They lead to highly incomplete biostratigraphic information in a section, causing the apparent truncation of species stratigraphic ranges or the complete absence of species whose ranges fall within the missing stratigraphic interval. This problem is especially critical when studying extinction patterns, as even small, difficult-to-detect hiatuses can give the appearance of an abrupt mass extinction of numerous taxa in a single horizon (Newell, 1982; Dingus, 1984). Conversely, a catastrophic mass extinction pattern can be misinterpreted as being due to a hiatus, as has frequently occurred when studying the planktic foraminiferal extinction pattern at the K/Pg boundary (see discussion in Molina, 1994, 1995; Molina et al., 1996).

The same problem arises when studying evolutionary patterns, as a hiatus can create the appearance of abrupt evolution of a significant number of taxa at a single horizon, leading to a mistaken interpretation of an instantaneous evolutionary radiation (Arenillas, 2003). The K/Pg-Danian hiatuses often create a false impression in biostratigraphic studies that many planktic foraminiferal species evolved abruptly right at the K/Pg boundary, or that species that evolved much later (tens or hundreds of thousands of years) seem to appear shortly after it (Arenillas et al., 2021). As mentioned above, the main objective of this manuscript is precisely to evaluate the duration of the K/Pg-Danian hiatuses by applying planktic foraminiferal zonations with higher resolution than the standard one. This approach will allow for the drawing of the most robust inferences in the field of planktic foraminiferal phylogeny and for the establishment of accurate age models essential for analyzing paleoenvironmental, paleoceanographic, and paleoclimatic changes throughout the Danian.

4. Extended planktic foraminiferal Dan- and DanAZ-scales of Arenillas et al. (2021)

The qualitative and quantitative stratigraphic study of planktic foraminifera from the 30 analyzed American K/Pg sections, combined with the biostratigraphic correlations between them, and the biohorizon ranking and the temporal calibrations based on previous studies (Table 3), resulted in the extension of the two biostratigraphic (and biochronological) scales of Arenillas et al. (2021) applicable to low and mid-latitudes (Fig. 11): one qualitative or achrostratigraphic (Dan-scale) and the other quantitative or acmestratigraphic (DanAZ-scale). To ensure the maximum robustness, these results were compared with those obtained from the most expanded and complete sections of the western Tethyan and North-East Atlantic regions (see Arenillas et al., 2004, 2021; Arenillas and Arz, 2009; Metsana-Oussaid et al., 2019; Gilabert et al., 2021, 2022). The definitions for the biostratigraphic units of the extended Dan- and DanAZ-scales are detailed in Tables 4 and 5.

4.1. Achrostratigraphic Dan-scale: calibration and problematic

An achrostratigraphic scale refers to a scale that utilizes range and interval zones (achrozones) and is based on qualitative biostratigraphic data: LOD and HOD of key species. We have used and extended the Dan-achrozonation of Arenillas et al. (2021), who originally defined four biozones (Fig. 11): *Guembelitria cretacea* Zone (Dan1), *Parvularugoglobigerina longiapertura* Zone (Dan2), the *Parvularugoglobigerina eugubina* Zone (Dan3), and *Parasubbotina pseudobulloides* Zone (Dan4). The latter two were further divided into several subbiozones: *Parvularugoglobigerina sabina* Subzone (Dan3a), *Eoglobigerina simplicissima* Subzone (Dan3b), *Praemurica taurica* Subzone (Dan4a), *Subbotina triloculinoides* Subzone (Dan4b), and *Globanomalina compressa* Subzone (Dan4c). In this work (Fig. 11; Table 4), we propose a fourth subbiozone for Dan4, the *Acarinina trinidadensis* Subzone (Dan4d), and a fifth biozone, the *Acarinina uncinata* Zone (Dan5).

This new biozonation has been calibrated and converted into a biochronological scale using two main approaches (Table 3): (1) Magnetochronological dating by Arenillas et al. (2004, 2021) and Metsana-Oussaid et al. (2019), primarily based on bio-magnetostratigraphic correlations from Gubbio (Italy), and Caravaca and Agost (Spain); and (2) Astrochronological dating by Gilabert et al. (2022), primarily based on bio-cyclostratigraphic correlations from Zumaia (Spain).

The Dan-scale has been compared with the more standardized P-scale of Wade et al. (2011), as well as with the earlier scales by Toumarkine and Luterbacher (1985), Smit (1982) and Smit and Romein (1985), Keller (1988, 1993) and Keller et al. (1995), and Arenillas and Molina (1997) and Arenillas et al. (2004) (Fig. 11). Biostratigraphers who proposed these scales used different taxonomic criteria to distinguish planktic foraminiferal species, which sometimes making it difficult establish precise comparisons between them (see discussions in Metsana-Oussaid et al., 2019; Arenillas et al., 2021). To avoid any ambiguity regarding our taxonomic identification criteria, we have illustrated an extensive collection of specimens of the Dan-scale key species, as well as other species, sourced from almost all sections studied (Figs. 2–10).

Table 3
Estimation of ages (in kyr) from the K/Pg boundary for the bases of Dan-achrozones and DanAZ-acmezones (see definitions in Tables 4 and 5) according to previous magneto- and astrochronological calibrations of Arenillas et al. (2004, 2021), Metsana-Oussaid et al. (2019), and Gilabert et al. (2022). Comparison with the estimated ages of the bases of magnetozones (chronozones), as well as with the most relevant stratigraphic units of the lowermost Danian. Magnetohorizon ages based on the GTS2020 (Gradstein et al., 2020). Duration of the post-K/Pg DCB deposition is based on cosmic ^{3}He sedimentation rates (Mukhopadhyay et al., 2001) and astrochronological calibrations (Gilabert et al., 2022). Approximate estimated duration of global sedimentation of all recognized K/Pg deposits (CIS, CCU, ISB, EAL) in 1–3 years (in any case, <20 years according to Arenillas et al., 2002).

Dan-achrozones	DanAZ-acmezones	Estimated Age (kyr)	Magnetozones -Stratigraphic units	Estimated Age (kyr)
			Base - C27n	3471.000
	Base - DanAZ5b	3320.000		
Base - Dan5		3100.000		
			Base - C27r	2464.000
	Base - DanAZ5a	2390.000		
Base - Dan4d		2115.000		
			Base - C28n	1356.000
	Base - DanAZ4b	1315.000		
			Base - C28r	1139.000
	Base - DanAZ4a	600.000		
Base - Dan4c		516.000		
	Base - DanAZ3b	241.000		
			Base - C29n	301.000
Base - Dan4b		204.000		
Base - Dan4a		68.000		
	Base - DanAZ3a	40.000		
Base - Dan3b		28.000		
Base - Dan3a		19.000		
			Top - DCB	10.000
	Base - DanAZ2	8.000		
Base - Dan2		6.000		
Base - Dan1	Base - DanAZ1	0.002	Top - K/Pg deposits	0.002
Base - Barren Interzone		0.000	K/Pg boundary	0.000

4.2. Acmestratigraphic DanAZ-scale: calibration and problematic

An acmestratigraphic scale refers to a scale that utilizes abundance zones (acmezones) and is based on quantitative biostratigraphic data: LOD and HOD of abundance peaks (acmes) of species, genera, or taxon groups. The use of quantitative data, especially when referring to the relative abundances of a species group (e.g., a genus or a genus group), minimizes the subjectivity and confusion inherent in the taxonomic identification of a particular species. Biostratigraphers or taxonomists

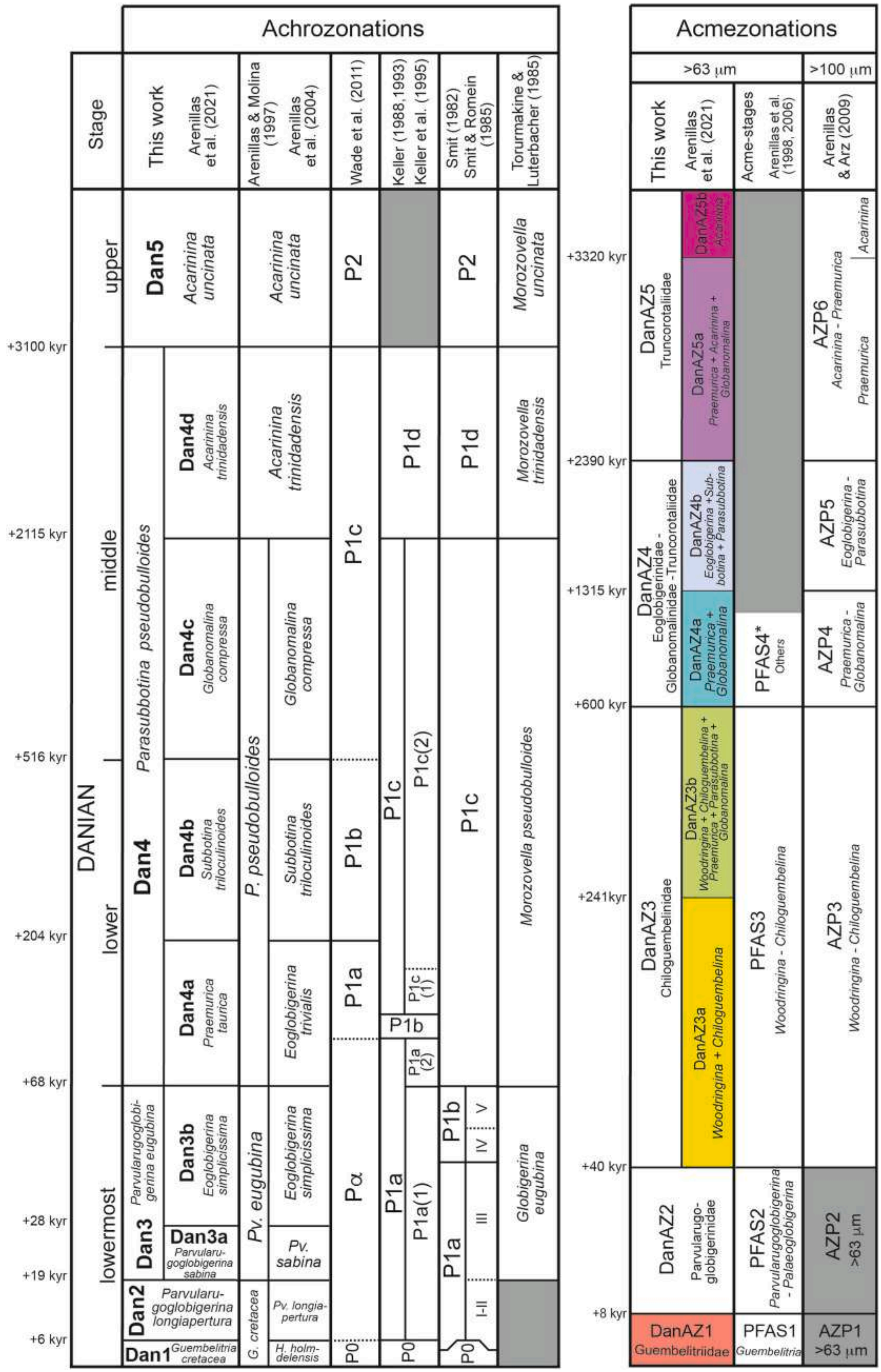

Fig. 11. Extended Dan-achrozonation of Arenillas et al. (2021), compared with the more standardized P-scale of Wade et al. (2011), as well as with the previous ones of Toumarkine and Luterbacher (1985), Smit (1982) and Smit and Romein (1985), Keller (1988, 1993) and Keller et al. (1995), and Arenillas and Molina (1997) and Arenillas et al. (2004). Extended DanAZ-acmezonation of Arenillas et al. (2021) for the ≥63 μm size fraction, compared with the acmestages PFAS of Arenillas et al. (1998, 2006), and the AZP-acmezonation of Arenillas and Arz (2009) for the ≥100 μm size fraction.

Table 4
Definition of the extended achrostratigraphic Dan-scale of Arenillas et al. (2021). Estimated ages of the biozone bases expressed in kyr after the K/Pg boundary (see Table 3). HOD = Highest Occurrence Datum. LOD = Lowest Occurrence Datum. (1) It is necessary a more precise calibration. (2) It is necessary to calibrate its top.

Achrozone/Subachrozone name, and full name	Base and top definition	Author	Estimated age of the base
***Guembelitria cretacea* Zone (Dan1):** *Abathomphalus mayaroensis–Parvularugoglo-bigerina longiapertura* Partial-Range Interval Zone.	**Base:** HOD of *Abathomphalus mayaroensis* (or K/Pg boundary mass extinction horizon) **Top:** LOD of *Parvularugoglobigerina longiapertura*	Smit (1982), emended by Arenillas et al. (2004, 2021).	~0.002 kyr
***Parvularugoglobigerina longiapertura* Zone (Dan2):** *Parvularugoglobigerina longiapertura–Parvularu-goglobigerina eugubina* Lowest-occurrence Interval Zone	B **Base:** LOD of *Parvularugoglobigerina longiapertura* **Top:** LOD of *Parvularugoglobigerina eugubina*	Blow (1979), emended by Arenillas et al. (2021).	~6 kyr
***Parvularugoglobigerina eugubina* Zone (Dan3):** *Parvularugoglobigerina eugubina–Parasubbotina pseudobulloides* Lowest-occurrence Interval Zone	**Base:** LOD of *Parvularugoglobigerina eugubina* **Top:** LOD of *Parasubbotina pseudo-bulloides*	Luterbacher and Premoli Silva (1964), emended by Bolli (1966) and Premoli Silva and Bolli (1973)	~19 kyr
***Parvularugoglobigerina sabina* Subzone (Dan3a):** *Parvularugoglobigerina eugubina–Eoglobigerina simplicissima* Lowest-occurrence Interval Subzone	**Base:** LOD of *Parvularugoglobigerina longiapertura* **Top:** LOD of *Eoglobigerina simplicis-sima*	Arenillas et al. (2004)	~19 kyr
***Eoglobigerina simplicissima* Subzone (Dan3b):** *Eoglobigerina simplicissima–Parasubbotina pseudobulloides* Lowest-occurrence Interval Subzone	**Base:** LOD of Eoglobigerina simplicis-sima **Top:** LOD of *Parasubbotina pseudo-bulloides*	Arenillas et al. (2004)	~28 kyr
***Parasubbotina pseudobulloides* Zone (Dan4):** Parasubbotina pseudobulloides–Acarinina trinida-densis Lowest-occurrence Interval Zone	**Base:** LOD of *Parasubbotina pseudo-bulloides* **Top:** LOD of *Subbotina triloculinoides*	Leonov and Alimarina (1961), emended by Molina et al. (1996)	~68 kyr
***Praemurica taurica* Subzone (Dan4a):** *Parasubbotina pseudobulloides–Subbotina triloculinoides* Lowest-occurrence Interval Subzone	**Base:** LOD of *Parasubbotina pseudo-bulloides* **Top:** LOD of *Subbotina triloculinoides*	Arenillas et al. (2004), renamed by Arenillas et al. (2021)	~68 kyr
***Subbotina triloculinoides* Subzone (Dan4b):** *Subbotina triloculinoides–Globanomalina com-pressa* Lowest-occurrence Interval Subzone	**Base:** LOD of *Subbotina triloculinoides* **Top:** LOD of *Globanomalina compressa*	Berggren (1969), emended by Arenillas et al. (2004)	~204 kyr
***Globanomalina compressa* Subzone (Dan4c):** *Globanomalina compressa–Acarinina trinida-densis* Lowest-occurrence Interval Subzone	**Base:** LOD of *Globanomalina compres-sa* **Top:** LOD of *Acarinina trinidadensis*	Berggren (1969), emended by Arenillas et al. (2004)	~516 kyr
***Acarinina trinidadensis* Subzone (Dan4d):** *Acarinina trinidadensis–Acarinina uncinata* Lo-west-occurrence Interval Subzone	**Base:** LOD of *Acarinina trinidadensis* **Top:** LOD of *Acarinina uncinata*	Bolli (1957)	~2110 kyr(1)
***Acarinina uncinata* Zone (Dan5):** *Acarinina uncinata–Morozovella angulata* Lowest-occurrence Interval Zone	**Base:** LOD of *Acarinina uncinata* **Top:** LOD of *Morozovella angulata*	Bolli (1957), emended by Bolli (1966)	~3100 kyr(1,2)

may disagree on species identification due to divergent preferences for splitter or lumper taxonomies, or simply because they assign different names to the same species. However, they are more likely to agree when identifying the acme of a taxon group characterized by easily distinguishable morphologies (see discussion in Arenillas et al., 2021).

A disadvantage of using acmestratigraphic scales is their susceptibility to significant alteration by local or even global environmental changes. For example, the early Danian blooms of opportunistic guembelitriids, which were triggered by episodes of environmental stress (sudden changes in temperature, nutrient availability, chemical contamination, or sea level), can complicate the identification of acmezones (Gilabert et al., 2021). To minimize this problem and accurately recognize acmezones, it can be helpful to recalculate relative abundances by subtracting the abundance of the opportunistic taxa (e.g., guembelitriids and globoconusids) within the stratigraphic interval affected by these environmental stress episodes.

We have used and extended the Dan-acmezonation of Arenillas et al. (2021), who originally defined three abundance zones (Fig. 11): *Guembelitria* Acmezone (DanAZ1), *Parvularugoglobigerina* and *Palaeoglobigerina* Acmezone (DanAZ2), and *Woodringina* and *Chiloguembelina* Acmezone (DanAZ3). They also suggested a fourth, the 'Others' Acmezone (DanAZ4), where 'Others' refers to macroperforate trochospiral species of genera *Eoglobigerina*, *Parasubbotina*, *Subbotina*, *Globanomalina*, and *Praemurica*. We extend the DanAZ-scale by formally defining the subacmezone DanAZ4 and adding a new acmezone, DanAZ5 (Fig. 11; Table 5).

In addition, we have renamed the previous acmezones of Arenillas et al. (2021) as Guembelitriidae Acmezone (DanAZ1), Parvularugoglobigerinidae Acmezone (DanAZ2), and Chiloguembelinidae Acmezone (DanAZ3). We also define the new acmezones as Eoglobigerinidae, Globanomalinidae and Truncorotaliidae Acmezone (DanAZ4), and Truncorotaliidae Acmezone (DanAZ5). Moreover, the last three acmezones (DanAZ3, DanAZ4 and DanAZ5) have been divided into two subacmezones each: *Woodringina* and *Chiloguembelina* Subacmezone (DanAZ3a), *Woodringina, Chiloguembelina, Praemurica, Parasubbotina* and *Globanomalina* Subacmezone (DanAZ3b), *Praemurica* and *Globanomalina* Subacmezone (DanAZ4a), *Eoglobigerina*, *Parasubbotina* and *Subbotina* Subacmezone (DanAZ4b), *Praemurica, Acarinina* and *Globanomalina* Subacmezone (DanAZ5a), and *Acarinina* Subacmezone (DanAZ5b).

The new DanAZ-acmezonation has been calibrated (and converted into a biochronological scale) using the already calibrated Dan-scale (Table 3). This was accomplished through qualitative and quantitative biostratigraphic studies, which are summarized in Arenillas et al. (2004, 2021), Metsana-Oussaid et al. (2019), and Gilabert et al. (2021, 2022). The DanAZ-scale has been compared with the AZP-acmezonation of Arenillas and Arz (2009), which covers the entire Paleocene. The AZP-acmezonation was established after conducting quantitative studies in the ≥100 size fraction μm, making it not strictly comparable with the one proposed here (which is based on the ≥63 μm size fraction). However, a significant equivalence appears to exist between the two, allowing us to corroborate the DanAZ-acmezonation for the middle-upper Danian. No acmestratigraphic scale utilizing planktic foraminifera has been established in the Danian by other biostratigraphers.

The described acmezones were based on previously Planktic Foraminiferal Acme-Stages (PFAS) recognized in sections of the Tethys, the Gulf of Mexico and the Caribbean (Arenillas et al., 1998, 2000a, 2006; see also Arenillas et al., 2021, and references cited therein). The acme-stages are informal biostratigraphic units defined by the peak abundance of a taxon or taxon group. Their usage is analogous to that of the Marine Isotope Stages (MIS) during the Quaternary. If an acmestage

Table 5
Definition of the extended acmestratigraphic DanAZ-scale of Arenillas et al. (2021). Estimated ages of the biozone bases expressed in Kyr after the K/Pg boundary (see Table 3). LOD = Lowest Occurrence Datum. (1) It is necessary a more precise calibration. (2) It is necessary to calibrate its top.

Acmezone/Subacmezone name	Base and top definition	Author	Estimated age of the base (kyr)
Guembelitriidae Abundance Zone (DanAZ1)	**Base:** LOD of Guembelitriidae dominance **Top:** LOD of Parvularugoglobigerinidae domi-nance	Arenillas et al. (2021), emended and renamed in this work	~0.002
Parvularugoglobigerinidae Abundance Zone (DanAZ2)	**Base:** LOD of Parvularugoglobigerinidae dominance **Top:** LOD of Chiloguembelinidae dominance	Arenillas et al. (2021), emended and renamed in this work	~8
Chiloguembelinidae Abundance Zone (DanAZ3)	**Base:** LOD of Chiloguembelinidae dominance **Top:** LOD of Eoglobigerinidae, Globano-malinidae and Truncorotalidae dominance	Arenillas et al. (2021), emended and renamed in this work	~40
***Woodringina* and *Chiloguembelina* Abundance Subzone (DanAZ3a)**	**Base:** LOD of *Woodringina* and *Chiloguem-belina* dominance **Top:** LOD of *Woodringina, Chiloguembelina, Praemurica, Parasubbotina, Globanomalina* dominance	This work	~40
***Woodringina, Chiloguembelina, Praemurica, Parasubbotina,* and *Globanomalina* Abundance Subzone (DanAZ3b)**	**Base:** LOD of *Woodringina, Chiloguembelina, Praemurica, Parasubbotina, Globanomalina* dominance **Top:** LOD of *Praemurica and Globanomalina* dominance	This work	~241
Eoglobigerinidae, Globanomalinidae and Truncorotaliidae Abundance Zone (DanAZ4)	**Base:** LOD of Eoglobigerinidae, Globanoma-linidae and Truncorotalidae dominance Top: LOD of Truncorotalidae dominance	Arenillas et al. (2021), emended and renamed in this work	~600 (1)
***Praemurica* and *Globanomalina* Abundance Subzone (DanAZ4a)**	**Base:** LOD of *Praemurica* and *Globanoma-lina* dominance Top: LOD of *Eoglobigerina, Subbotina* and *Parasubbotina* dominance	This work	~600 (1)
***Eoglobigerina, Subbotina* and *Parasubbotina* Abundance Subzone (DanAZ4b)**	**Base:** LOD of *Eoglobigerina, Subbotina* and *Parasubbotina* dominance **Top:** LOD of *Praemurica, Acarinina* and *Globanomalina* dominance	This work	~1315 1)
Truncorotaliidae Abundance Zone (DanAZ5)	**Base:** LOD of Truncorotalidae dominance (referred to Praemurica and Acarinina) **Top:** LOD of Morozovella dominance	This work	~2390 (1)
***Praemurica, Acarinina* and *Globanomalina* Abundance Subzone (DanAZ5a)**	**Base:** LOD of *Praemurica, Acarinina* and *Globanomalina* dominance **Top:** LOD of *Acarinina* dominance	This work	~2390 (1)
***Acarinina* Abundance Subzone (DanAZ5b)**	**Base:** LOD of *Acarinina* dominance **Top:** LOD of *Morozovella* dominance	This work	~3320 (1,2)

does not recur over time because it is the result of evolutionary change, it is susceptible to being formally reconverted into an abundance zone or acmezone. If it repeats over time due to iterative or cyclical paleoenvironmental changes, it is then susceptible to reconversion into an ecostratigraphic unit or ecozone.

Arenillas et al. (2021) reconverted acmestages PFAS into acmezones after confirming their evolutionary origin and their significant utility for global chronocorrelation. At Caravaca (southern Spain), Gilabert et al. (2021) recognized seven subacmestages within PFAS-3 (=DanAZ3), which they named α, T1, O1, T2, O2, T3, and O3. Of these, the substages T represent *Chiloguembelitria* blooms. These acmestages appear to be the result of cyclic paleoenvironmental or paleoclimatic changes, likely caused by orbital cycles. Therefore, they could be defined as ecozones, irrespective of their usefulness for global chronocorrelation. Currently, these ecozones have only been reported in the nearby Agost section (southern Spain; Arenillas et al., 2024), but the Ecozone T1 appears to be recorded at M0077A, La Lajilla, Guayal, Bochil, and Loma Capiro; the Ecozone T2 at M0077A and Loma Capiro; and the Ecozone T3 at M0077A (Figs. 12–14 and 17). These ecozones are recognized in the sections as *Chiloguembelitria* blooms within the Biozones Dan4a and Dan4b. Other *Chiloguembelitria* blooms (usually minor) can also be recognized within the Biozones Dan4c and Dan4d at M0077A, Yaxcopoil-1, and Fomento (Fig. 17).

5. Planktic foraminiferal chronocorrelation of American K/Pg sections

5.1. Methodological steps followed to minimize the limitations of the biostratigraphic study

The biochronostratigraphic correlations of the Danian across the American K/Pg sections (Figs. 12–17) relied primarily on the DanAZ-acmezonation, that is, on quantitative- and acmestratigraphy with planktic foraminifera. Nevertheless, the Dan-achrozonation was used to refine these biochronocorrelations, particularly in the lowermost Danian. To minimize the inherent limitations in the aforementioned biostratigraphic study, several methodological steps were taken.

(1) The Danian of all American K/Pg sections was sampled in detail (or at high resolution for the lowermost Danian) to minimize the Signor-Lipps effect. Moreover, when possible, we attempted to extract statistically representative aliquots from all samples (supplementary tables–Appendix A) and intensively searched for low-abundance species in the washing residue.
(2) The Danian sediments of all sections studied were deposited at low (0–25°N) latitude and at outer sublittoral and bathyal depths, except for Isla Gorgonilla, which was deposited at abyssal depths (see supplementary material–Appendix A). For this reason, there were no significant problems in the biostratigraphic study related to the Lazarus effect in most sections, with the exception of Isla Gorgonilla. This section was located at upper abyssal depths (2500–3000 m), generally below the Calcite Compensation Depth (CCD), which caused the absence of planktic foraminifera in most of the section (Bermúdez et al., 2019).
(3) The use of the DanAZ-acmezonation for correlation has allowed us to significantly minimize the taxonomic problems in the biostratigraphic study. Irrespective of the planktic foraminiferal taxonomy employed by other taxonomists or biostratigraphers, they will be able to recognize the acme intervals of the key taxon groups used in the DanAZ-scale, as these groups are morphologically easy to identify. Additionally, a large number of planktic foraminiferal specimens, especially of the key species used in the

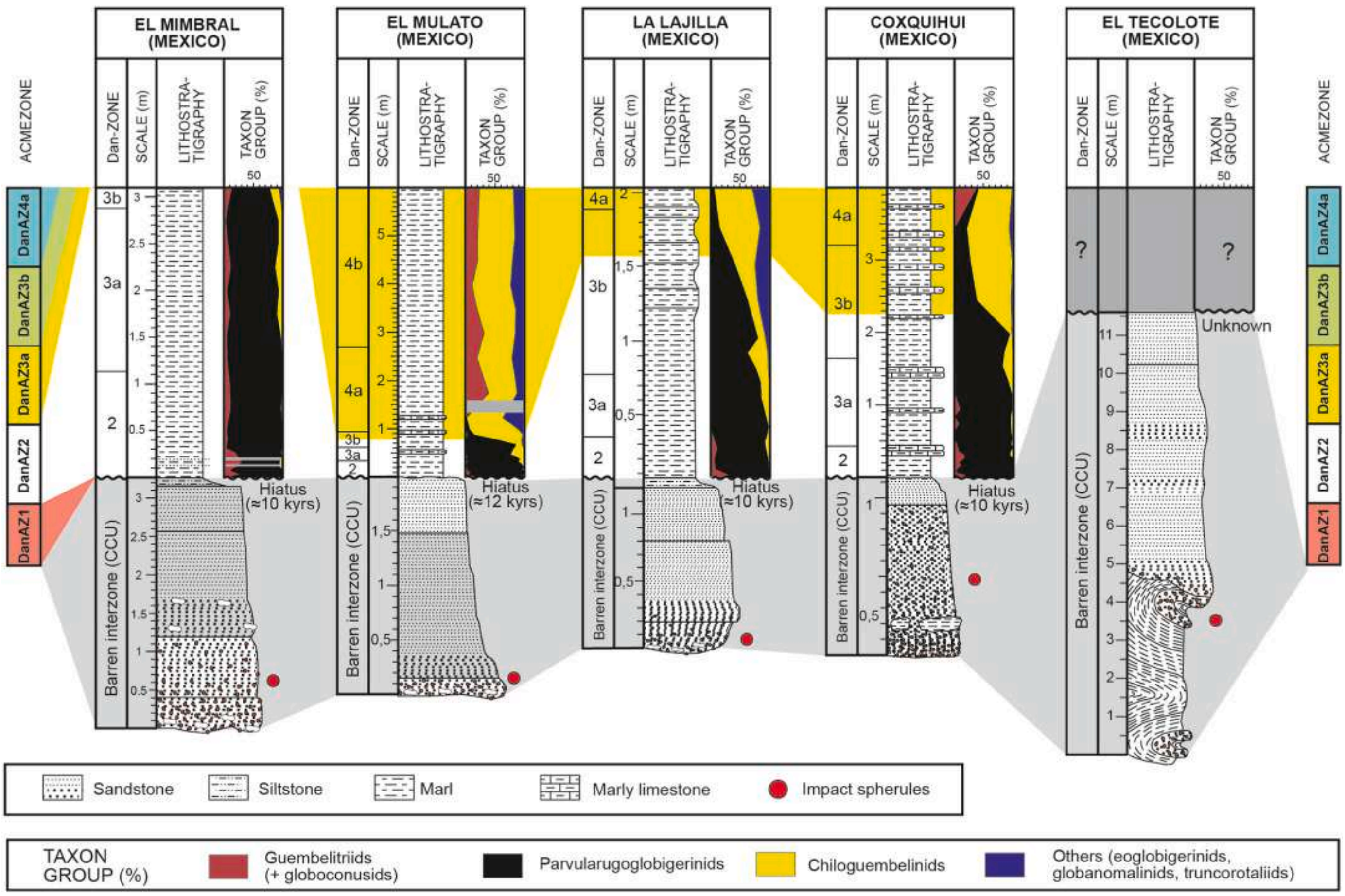

Fig. 12. Biochronocorrelation with planktic foraminifera of the K/Pg deposits and Danian pelagic sediments of El Mimbral, El Mulato, La Lajilla, Coxquihui and El Tecolote (Mexico), applying the DanAZ-acmezonation. Estimation of the duration in kyr of K/Pg-Danian hiatuses, where present. Taxon Group (%) = cumulative relative abundance of taxa or taxon groups: guembelitriids + globoconusids, parvularugoglobigerinids, chiloguembelenids, and "others" (eoglobigerinids, globanomalinids, truncorotaliids).

Dan-scale, were photographed with a SEM and adequately illustrated in plates (Figs. 2–10) to display our taxonomic identification criteria.

(4) To minimize the taphonomic problem associated with the reworking of Cretaceous planktic foraminiferal specimens in the Danian biostratigraphic study, we relied on criteria established by Arenillas et al. (2022). These authors demonstrated that all specimens of Cretaceous species in the Danian sediments are reworked, with the exception of some of the *Guembelitria* species. The poor preservation of the planktic foraminiferal tests represents the major problem in the biostratigraphic study across most of the American K/Pg sections examined. To minimize this problem as much as possible, an attempt was made to extract the largest possible number of specimens from all samples to at least ensure the recognition of the DanAZ-acmezones.

5.2. Biochronocorrelation of the American K/Pg sections and hiatus control

The results obtained from all studied localities are consistent with the quantitative distribution of taxonomic groups recognized in other localities from diverse paleogeographic contexts, particularly those from the Tethys (see Arenillas et al., 2021, and references cited therein). Consequently, we consider the biochronocorrelations established among the sections with the DanAZ-scale to be robust. Section-specific challenges in interpreting the biostratigraphic data are detailed in the supplementary material (Appendix A).

The biochronocorrelations based on the DanAZ-scale (Figs. 12–17) enabled us to evaluate the stratigraphic continuity of each section and the duration of the K/Pg-Danian hiatus where present (Appendix A). The results, analyzed by their geographical distribution, are summarized below.

(1) *Northeastern Mexico*: El Mimbral, El Mulato, La Lajilla, and Coxquihui. Their Danian acmecorrelation is illustrated in Fig. 12, which suggests that all these sections contain K/Pg-Danian hiatuses of about 10 kyr, evidenced by the absence of the Acmezone DanAZ1. The El Tecolote section has also been included in this figure, although no Danian pelagic sediments crop out at that locality.

(2) *Southeastern Mexico and within the Chicxulub structure*: Guayal, Bochil, Chilil, and Soyaló (Southeastern Mexico), and M0077A (Chicxulub structure). Their Danian acmecorrelation is illustrated in Fig. 13, which suggests stratigraphic continuity only at Guayal and Bochil, where the Acmezone DanAZ1, the Achrozone Dan1 (≈P0), and the DCB have been identified. The remaining sections exhibit a small K/Pg-Danian hiatus, with durations approximately ranging from 8 kyr in M0077A to 15 kyr in Soyaló. We suggest a K/Pg-Danian hiatus of approximately 8 kyr for M0077A, as the upper part of both the Acmezone DanAZ1 and the DCB could still be present at that locality. For Chilil, we suggest a K/Pg-Danian hiatus of approximately 15 kyr, as the common occurrence of chiloguembelinids is typical of the middle and upper part of the Acmezone DanAZ2.

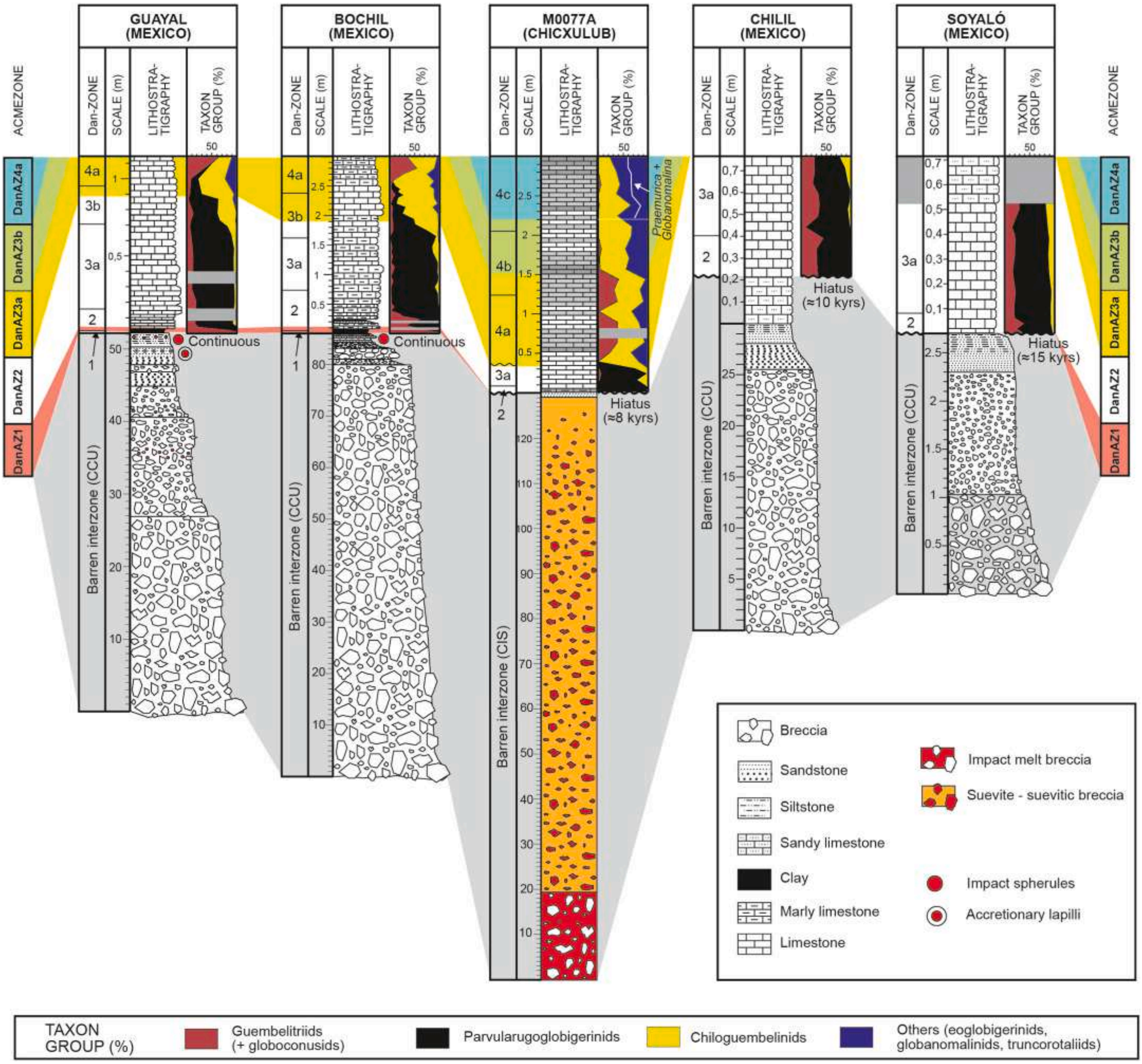

Fig. 13. Biochronocorrelation with planktic foraminifera of the K/Pg deposits and Danian pelagic sediments of Guayal, Bochil, Chilil and Soyaló (Mexico), and Site M0077A (within the Chicxulub structure), applying the DanAZ-acmezonation. Estimation of the duration in kyr of K/Pg-Danian hiatuses, where present. Taxon Group (%) = cumulative relative abundance of taxa or taxon groups: guembelitriids + globoconusids, parvularugoglobigerinids, chiloguembelenids, and "others" (eoglobigerinids, globanomalinids, truncorotaliids). Relative abundance curves (white) of index taxa (*Praemurica* + *Globanomalina*) of the Subacmezone DanAZ4a (at M0077A).

(3) *West/Central Cuba, Southern Mexico and Guatemala*: Moncada and Loma Capiro (West and Central Cuba), Felipe Ángeles and Vistahermosa (Southern Mexico), and Chemal (Guatemala). Their Danian acmecorrelation is illustrated in Fig. 14, which suggests stratigraphic continuity only at Moncada, where the Acmezone DanAZ1, the Achrozone Dan1 (≈ Biozone P0 of Smit, 1982) and the DCB have been identified. The remaining sections exhibit small K/Pg-Danian hiatuses, with durations approximately ranging from 10 kyr (in Loma Capiro, Felipe Ángeles, and Vistahermosa) to 15 kyr (in Chemal).

(4) *Eastern Caribbean and Colombian Pacific*: Isla Gorgonilla (Colombia), La Alcarraza (Eastern Cuba), Roche à Pierre, Nan Pak, and Beloc HA (Haiti). Their Danian acmecorrelation is illustrated in Fig. 15., which suggests stratigraphic continuity only at Roche à Pierre, Nan Pak, and Beloc HA. This is evidence by the identification of the Acmezone DanAZ1, the Achrozone Dan1 (≈P0), and the DCB. In these localities, the middle and upper part of the DCB appears to be partially masked by the high carbonate and silica content of the sediments. The Isla Gorgonilla section could also be continuous, as the Acmezone DanAZ1 has been clearly identified. This is despite the absence of the Achrozone Dan1, which has not been recorded due to carbonate dissolution affecting the planktic foraminifera in the first few centimeters of the Danian. Otherwise, the K/Pg-Danian hiatus at Isla Gorgonilla would not exceed 5 kyr. Conversely, the La Alcarraza section appears to contain a small K/Pg-Danian hiatus

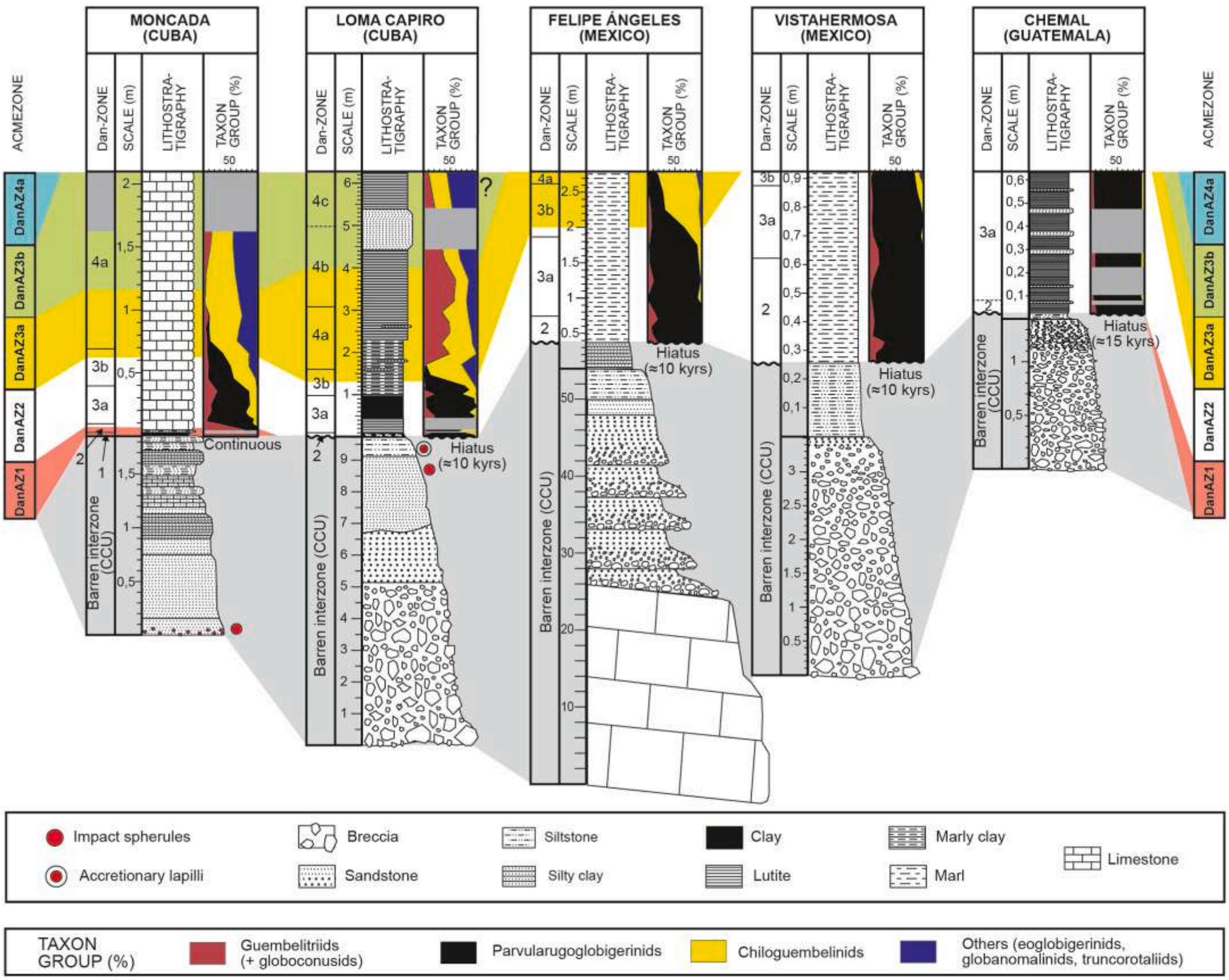

Fig. 14. Biochronocorrelation with planktic foraminifera of the K/Pg deposits and Danian pelagic sediments of Moncada and Loma Capiro (Cuba), Felipe Ángeles and Vistahermosa (Mexico), and Chemal (Guatemala), applying the DanAZ-acmezonation. Estimation of the duration in kyr of K/Pg-Danian hiatuses, where present. Taxon Group (%) = cumulative relative abundance of taxon groups: guembelitriids + globoconusids, parvularugoglobigerinids, chiloguembelenids, and "others" (eoglobigerinids, globanomalinids, truncorotaliids).

of approximately 15 kyr in duration. This is inferred because chiloguembelinids are already relatively common, which is typical of the middle and upper part of the Acmezone DanAZ2.

(5) *Sections without Danian sediments overlaying the K/Pg deposit*: The K/Pg deposit (CCU) correlation for the El Peñón and Los Ramones sections (Northeastern Mexico), ant the Cacarajícara, Peñalver-La Habana, Minas, and Santa Isabel sections (West and West-Central Cuba) is illustrated in Fig. 16. Like the El Tecolote section (Fig. 12), these sections either lack Danian sediments directly overlaying the CCU, or they have not been adequately dated with planktic foraminifera. They are included to provide a more complete regional view of the K/Pg deposits in Mexico and Cuba.

(6) *Within the Chicxulub structure and large hiatus sections*: M0077A (extended section) and Yaxcopoil-1 (Chicxulub structure), and La Ceiba (Central Mexico), La Trinitaria B (Southeastern Mexico), and Fomento (Central Cuba). Their Danian acmecorrelation is illustrated in Fig. 17. With the exception of M0077A as previously mentioned, this correlation suggests that all these sections contain large K/Pg-Danian hiatus, ranging from approximately 600 kyr in La Ceiba and Fomento, 650 kyr in Yaxcopoil-1, and 2500 kyr in La Trinitaria B. At Fomento, a condensed level overlying the CCU is recognized, which probably records the Achrozones Dan1, Dan2, Dan3, and Dan4a-b, although they occur condensed and mixed. The extended section of M0077A has been studied to analyze the acmestratigraphic record of the middle-upper Danian, and it is therefore used here as the reference section for this interval. Its acmestratigraphic record is similar to that identified in Zumaia and Caravaca (Spain) for the ≥100 μm size fraction (Arenillas and Arz, 2009).

According to this regional distribution of the K/Pg-Danian hiatus, no significant correlation exists between the hiatus's presence or its duration and the paleogeographic and paleobathymetric context of each section. This lack of correlation points to the complexity of the post-impact depositional environments across the studied American K/Pg sections. It is, however, worth noting that two distinct types of K/Pg-Danian hiatuses were observed based on duration: those lasting around 10 kyr, and those lasting around 600 kyr. The former appears to be strongly related to the DCB deposition, which took place during the 10 kyr-long post-K/Pg climate warming, a factor that may have affected its emplacement mechanisms. Regarding the latter, it is not possible to link it to a specific climatic or environmental cause, so it could be related

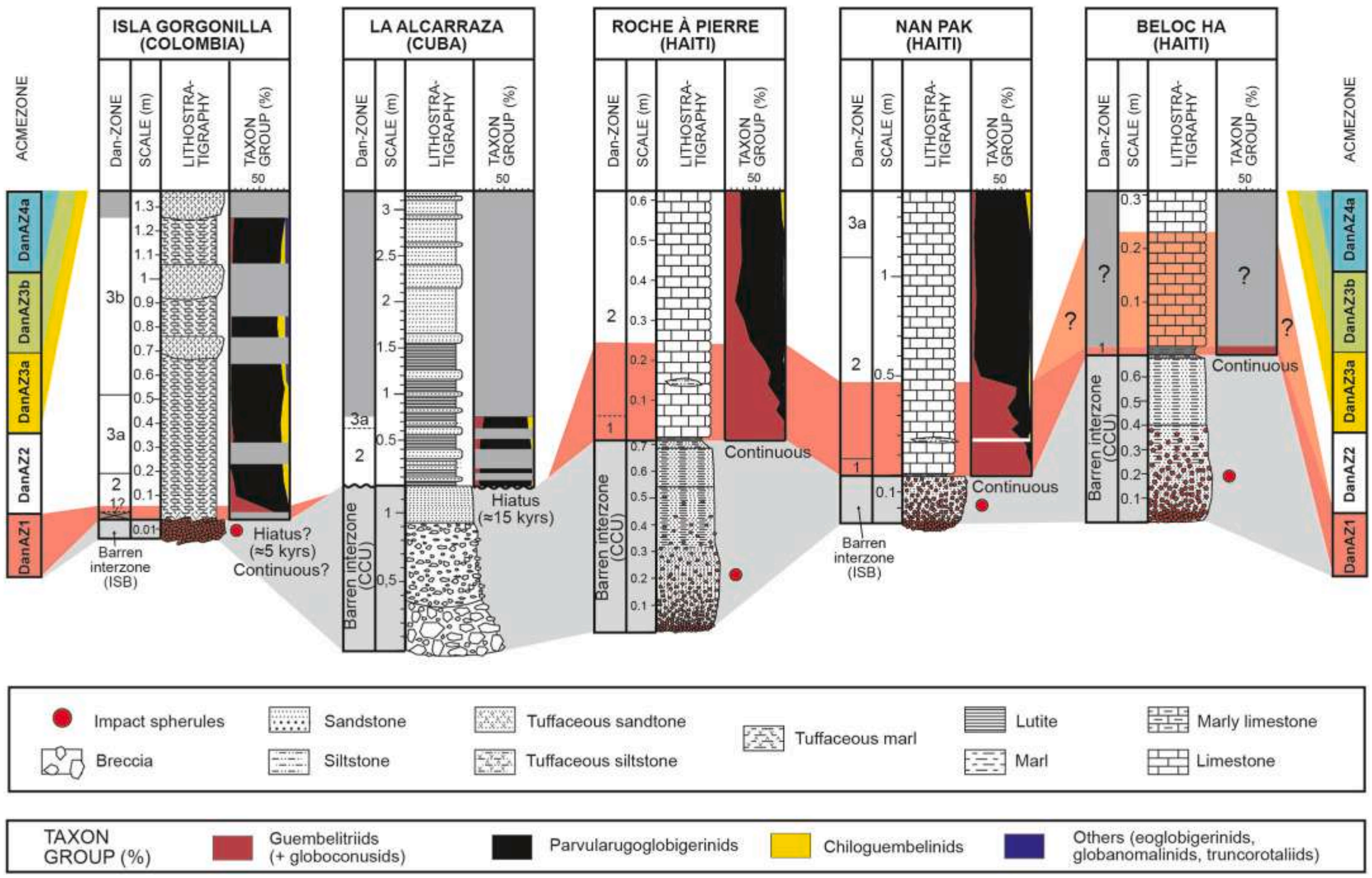

Fig. 15. Biochronocorrelation with planktic foraminifera of the K/Pg deposits and Danian pelagic sediments of Isla Gorgonilla/Gorgonilla Island (Colombia), La Alcarraza (Cuba), and Roche à Pierre, Nan Pak and Beloc HA (Haiti), applying the DanAZ-acmezonation. Estimation of the duration in kyr of K/Pg-Danian hiatuses, where present. Taxon Group (%) = cumulative relative abundance of taxa or taxon groups: guembelitriids + globoconusids, parvularugoglobigerinids, chiloguembelenids, and 'others' (eoglobigerinids, globanomalinids, truncorotaliids).

to regional tectonic causes.

6. Discussion

6.1. Applicability of the Dan- and DanAZ scales

To check the applicability of the new Dan- and DanAZ-scales for global biochronocorrelation, we compared the results obtained in the studied localities across the Gulf of Mexico, the Caribbean, and the Colombian Pacific regions with those obtained in sections from the western Tethyan and the North-East Atlantic regions, such as El Kef, Aïn Settara and Elles (Tunisia), Caravaca, Agost and Zumaia (Spain), and Bottaccione (Gubbio, Italy) (see Arenillas et al., 2004, 2021; Metsana-Oussaid et al., 2019; Gilabert et al., 2022). The latter include the reference sections for the original definition of the Dan- and DanAZ-scales (Arenillas et al., 2021), as well as of the acmestratigraphic AZP-scale (Arenillas and Arz, 2009). The original Dan- and DanAZ-scales of Arenillas et al. (2021) only covered the lower Danian (to the lower part of Biozone Dan4c, or Biozone P1c of Wade et al., 2011). At least for this interval, the biostratigraphic distribution (both qualitative and quantitative) of the planktic foraminiferal species and groups was verified to be consistent across the studied Tethyan and Atlantic localities, and also across some Gulf of Mexico and Caribbean localities, such as Bochil, La Lajilla, and Moncada. These consistent stratigraphic distribution patterns have also been identified in the American localities analyzed in this work, further corroborating the validity of both scales for global biochronocorrelation across the lower Danian.

Metsana-Oussaid et al. (2019) studied in detail for the first time the qualitative planktic foraminiferal stratigraphy in two Algerian K/Pg sections, Sidi Ziane and Djebel Zakhamoune (Médéa, northern Algeria), spanning from the uppermost Maastrichtian to the middle-upper Danian. This study allowed us to review the middle-upper Danian biostratigraphical scales, and time-calibrate the main key bioevents through graphic bio-magnetostratigraphic correlations comparing the Bottaccione (Gubbio) section in Italy, the Agost and Caravaca sections in southern Spain, and Kalaat Senan section in Tunisia. Kalaat Senan includes two localities: Aïn Settara for the lower Danian, and Sidi Nasseur for the middle-upper Danian. After reviewing the qualitative planktic foraminiferal stratigraphy, they proposed an achrostratigraphic scale for the Danian (to the lower part of Biozone Dan5, or Biozone P2 of Wade et al., 2011) that basically coincides with the Dan-scale proposed in this work (Fig. 11). The only difference is that the Subbiozone Dan4d was elevated to the category of biozone (*Acarinina trinidadensis* Zone), as defined by Bolli (1957), Tourmakine and Luterbacher (1985) and Arenillas and Molina (1997). As a result, Metsana-Oussaid et al. (2019) concluded that the Sidi Ziane and Djebel Zakhamoune sections had a K/Pg-Danian hiatus of about 600 kyr, affecting the lower Danian from the Biozone Dan1 to the Subbiozone Dan4b. Nevertheless, they were able to analyze in the Algerian sections the middle-upper Danian interval (from the Subbiozone Dan4c to the Biozone Dan5), reaching the conclusion that the qualitative stratigraphic distributions of the planktic foraminiferal species in these sections were similar to that identified in the Tunisian, Spanish, and Italian reference sections (see references in Metsana-Oussaid et al., 2019). We have been able to confirm that the planktic foraminiferal stratigraphic distributions identified in the American localities spanning the middle-upper Danian, mainly M0077,

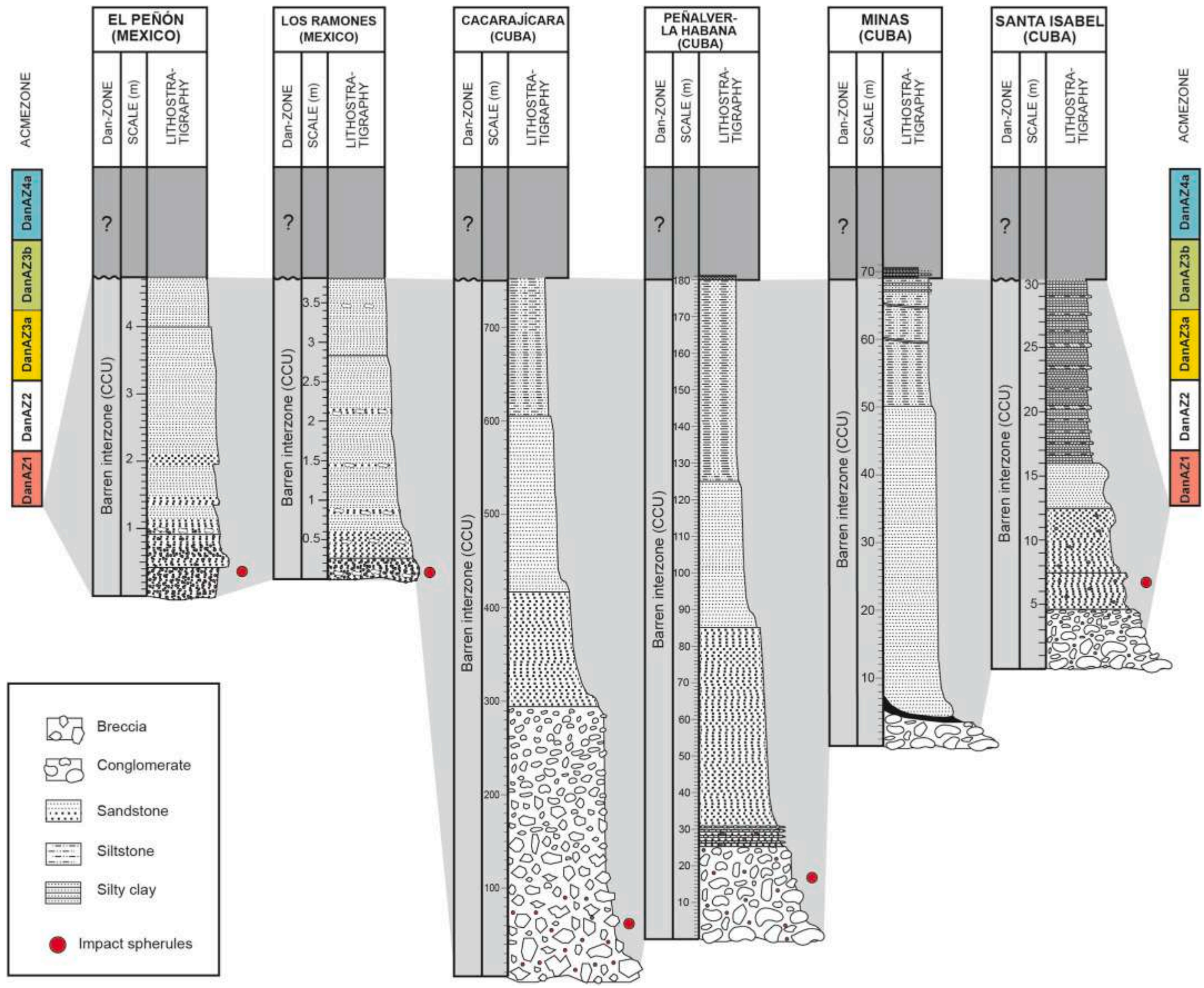

Fig. 16. Correlation of the K/Pg deposits of El Peñón and Los Ramones (Mexico), and Cacarajícara, Peñalver-La Habana, Minas and Santa Isabel (Cuba). There are no dated Danish pelagic sediments outcropping at these localities.

are also consistent with those identified across the western Tethyan and North-East Atlantic regions.

Arenillas and Arz (2009) proposed an acmestratigraphic scale with planktic foraminifera for the entire Paleocene, which they called AZP-acmezonation, but this was never published in a peer-reviewed journal. We have rescued this proposal from oblivion because, although established with a different methodology (quantitative studies in the ≥100 μm size fraction instead of in the ≥63 μm size fraction), it has a significant equivalence with the DanAZ-acmezonation for the middle-upper Danian. Arenillas and Arz (2009) used as reference sections those of Zumaia and Caravaca (Spain), where they identified similar quantitative biostratigraphic patterns in planktic foraminifera to those identified in the analyzed American K/Pg sections, mainly M0077.

These comparisons between American, Tethyan, and North Atlantic regions lead us to the subsequent inference that the new Dan- and DanAZ-scales are applicable worldwide across low and mid-latitudes, and in oceanic and outer neritic environments. To confirm the global validity of the middle-upper Danian biozones of both scales (mainly the DanAZ-scale), it will be necessary to study and compare the qualitative and quantitative stratigraphic distribution patterns of planktic foraminifera in other localities and regions. Furthermore, to confirm the global application of these scales, it will be necessary to quantitatively study locations from other regions, such as the North Pacific, South Atlantic, and regions at higher latitudes.

6.2. *Comparative resolution of the Dan- and DanAZ-scales with the most standardized ones*

The resolution of the most standardized Danian biozonations with planktic foraminifera are very low, mainly for the middle-upper Danian. Thus, for example, the planktic foraminiferal zonation of Toumarkine and Luterbacher (1985) only considered three biozones between the K/Pg boundary and the Dan4/Dan5 boundary (first 3100 kyr of the Danian), or four if the basal Biozone P0 of Smit (1982) is included (Fig. 11). In this scale, only two biochronohorizons (or key biohorizons) were available for this interval, which in updated taxonomic terms were the boundaries between the *Parvularugoglobigerina eugubina/Parasubbotina pseudobulloides* Biozones, and *Parasubbotina pseudobulloides/Acarinina trinidadensis* Biozones. This means that the average resolution of the biozones was 1033 kyr, not counting the short-duration Biozone P0 of Smit (1982). The planktic foraminiferal zonation of Wade et al. (2011), which is currently the most standardized, did not represent

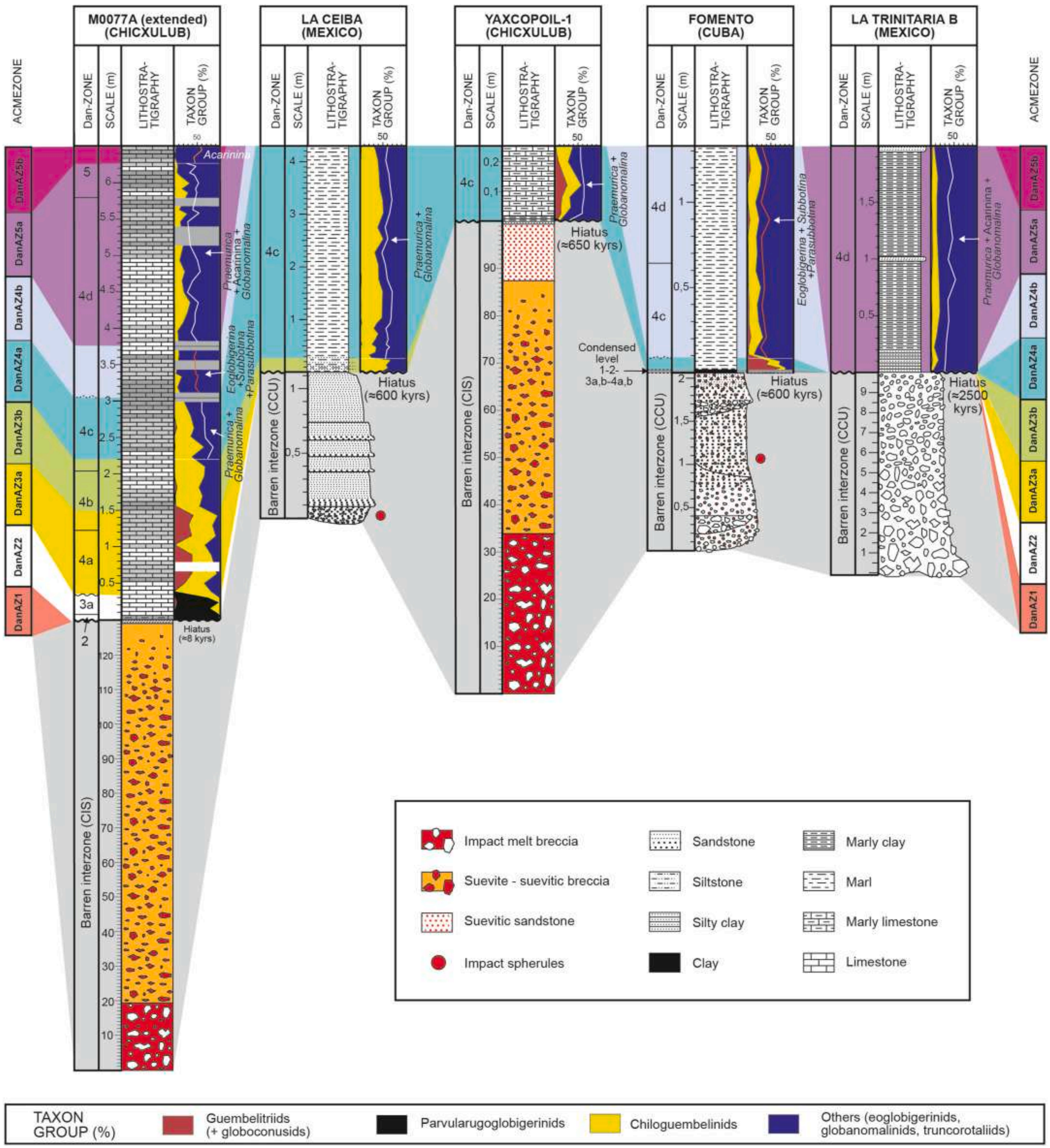

Fig. 17. Biochronocorrelation with planktic foraminifera of the K/Pg deposits and Danian pelagic sediments of Site M0077A-extended and Site Yaxcopoil-1 (within the Chicxulub structure), La Ceiba and La Trinitaria B (Mexico), and Fomento (Cuba), applying the DanAZ-acmezonation. Estimation of the duration in kyr of K/Pg-Danian hiatuses, where present. Taxon Group (%) = cumulative relative abundance of taxa or taxon groups: guembelitriids + globoconusids, parvularugoglobigerinids, chiloguembelenids, and "others" (eoglobigerinids, globanomalinids, truncorotaliids). Relative abundance curves (white and orange) of index taxa of the subacmezones of DanAZ4 and DanAZ5.

a significant advance in the resolution of the planktic foraminiferal stratigraphic scale for the Danian, since for the first 3100 kyr of the Danian it only considered three biochronohorizons (not counting the P0/Pα boundary): the Pα/P1a, P1a/P1b, and P1b/P1c boundaries (Fig. 11). The resolution of biozones at this scale was increased slightly to 775 kyr, with the Biozone P1c spanning as long as ~2100 kyr in estimated duration.

The integration of both Dan- and DanAZ-scales allows for a much higher biochronological resolution than the previous more standardized scales for the Danian. The achrostratigraphic Dan-scale alone already considers seven biochronohorizons: the Dan1/Dan2, Dan2/Dan3a, Dan3a/Dan3b, Dan3b/Dan4a, Dan4a/Dan4b, Dan4b/Dan4c, and Dan4c/Dan4d boundaries (the Dan4d/Dan5 boundary and Achrozone Dan5 are excluded as the upper boundary of Dan5 remains uncalibrated in the present study). Not counting the short-duration Achrozone Dan1 (≈P0 of Smit, 1982), the mean resolution of Dan-scale biozones is 442 kyr. The biozone resolution is much higher for the first 68 kyr of the Danian, with an average of only 17 kyr including the Achrozone Dan1. For the next 3000 kyr of the Danian, the resolution drops to 750 kyr on average. For its part, the DanAZ-scale considers six biochronohorizons for the 3320 kyr of the Danian: the DanAZ1/DanAZ2, DanAZ2/DanAZ3a, DanAZ3a/DanAZ3b, DanAZ3b/DanAZ4a, DanAZ4a/DanAZ4b, and DanAZ4b/DanAZ5a boundaries (the DanAZ45a/DanAZ5b boundary and Subacmezone DanAZ5b are excluded as the upper boundary of DanAZ5b remains uncalibrated in the present study). Not counting the short-duration Acmezone DanAZ1, the resolution of their DanAZ-acmezones is 553 kyr. The combination of both scales allows the recognition of up to 15 biochronohorizons and an average resolution of up to 221 kyrs for the first 3320 kyr of the Danian, being of very high resolution of 11 kyrs for the first 68 kyrs, and of 361 kyrs for the next 3250 kyr of the Danian. This resolution is much higher than that achieved with magnetostratigraphic data (∼700 kyrs in average) across the Danian (Table 3), and similar to that achieved with short and long eccentricity cycles (∼100 and ∼400 kyrs, respectively), or even with precession cycles (∼21 kyrs) in the case of the lowermost Danian.

Increasing the resolution of the planktic foraminiferal chronological scale will allow us to establish more accurate age models across the Danian in the studied localities, particularly where cyclostratigraphic data needed for astrochronological age models are unavailable. These more precise biochronological scales will not only allow us to assess the stratigraphic continuity of the Danian sections or estimate the temporal duration of K/Pg-Danian hiatuses (if present), but also to more accurately place in the studied sections the stratigraphic position of the multiple events recognized during the Danian. These events include not only isotopic events, such as the one recorded in the DCB (post-K/Pg warming event), the event Dan-C2, the event Lower C29n (LC29n), the multiple events MLDME (Middle–Lower Danian Multiple Event), or the event Middle C27r (MC27r), but also other geochemical events (Hg, Te, and other trace elements) related to the Deccan Traps volcanic pulses (see Coccioni et al., 2012, Gilabert et al., 2025; Baumann et al., 2025).

7. Conclusions

The qualitative and quantitative biostratigraphic study with planktic foraminifera of thirty American K/Pg localities across the Gulf of Mexico, the Caribbean, and the Colombian Pacific regions, and the biochronocorrelation of their Danian sediments directly overlying the Chicxulub impact-related Cretaceous/Paleogene boundary deposits (K/Pg deposits), yields the following conclusions.

(1) Among the localities studied, only Bochil and Guayal (Mexico), Moncada (Cuba), Beloc HA, Nan Pak and Roche à Pierre (Haiti), and probably Isla Gorgonilla (Colombia) exhibit stratigraphic continuity between the K/Pg deposits and the first Danian sediments deposited under normal conditions.
(2) Localities such as Site M0077A (within the Chicxulub structure), El Mimbral, El Mulato, La Lajilla, Coxquihui, Chilil, Soyaló, Felipe Ángeles and Vistahermosa (Mexico), Loma Capiro and La Alcarraza (Cuba), and Chemal (Guatemala) contain small hiatuses affecting the first normal Danian sediments (K/Pg-Danian hiatuses), with durations approximately ranging from 8 to 15 kyr.
(3) Localities such as Yaxcopoil-1 (within the Chicxulub structure), La Ceiba and La Trinitaria B (Mexico), and Fomento (Cuba) contain large K/Pg-Danian hiatuses, with durations approximately ranging from 600 kyr to 2500 kyr.
(4) Other localities, including El Tecolote, El Peñón, Los Ramones, Cacarajícara, Peñalver-La Habana, Minas, and Santa Isabel, either lack Danian sediments directly overlying the K/Pg deposits, or these overlying sediments could not be dated using planktic foraminifera.

Qualitative and quantitative biostratigraphic studies using planktic foraminifera across the analyzed American K/Pg sections allowed us to extend the lower Danian Dan- and DanAZ-scales of Arenillas et al. (2021) to the middle-upper Danian. This extension has resulted in the proposal and definition of five achrozones for the Dan-scale: Dan1, Dan2, Dan3 (subdivided into Dan3a and Dan3b), DanAZ4 (subdivided into Dan4a, Dan4b, Dan4c, and Dan4c), and DanAZ5, and five acmezones for the DanAZ-scale: DanAZ1, DanAZ2, DanAZ3 (subdivided into DanAZ3a and DanAZ3b), DanAZ4 (subdivided into DanAZ4a and DanAZ4b), and DanAZ5 (subdivided into DanAZ5a and DanAZ5b). A comparation of the results obtained in the studied American regions with those previously obtained in the most expanded and complete K/Pg sections of the western Tethyan and North-East Atlantic regions yields the following conclusions.

(1) The qualitative and quantitative biostratigraphic distribution patterns of planktic foraminiferal species and groups are consistent across both sets of regions.
(2) The proposed biostratigraphic/biochronological scales are consequently applicable worldwide across low and mid-latitudes, and in oceanic and outer neritic environments.
(3) The integration of both Dan- and DanAZ-scales allows for a much higher biochronological resolution than the more standardized ones for the first 3300 kyr of the Danian, with an average resolution of up to 221 kyrs, being of very high resolution (11 kyrs) for the first 68 kyrs of the Danian, and of 361 kyrs for the next 3250 kyr of the Danian.

CRediT authorship contribution statement

Ignacio Arenillas: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Vicente Gilabert:** Writing – review & editing, Visualization, Methodology, Investigation, Conceptualization. **Iván Aparicio:** Writing – review & editing, Investigation. **Hermann D. Bermúdez:** Writing – review & editing, Investigation, Conceptualization. **Liliana Bolívar:** Writing – review & editing, Investigation. **Thierry Calmus:** Writing – review & editing, Investigation. **Daniel Ferrer:** Writing – review & editing, Investigation, Conceptualization. **José M. Grajales-Nishimura:** Writing – review & editing, Investigation, Conceptualization. **Carlos L. Liesa:** Writing – review & editing, Visualization, Investigation, Conceptualization. **Kenya E. Núñez-Cambra:** Writing – review & editing, Investigation. **Ligia Pérez-Cruz:** Writing – review & editing, Investigation. **Reinaldo Rojas-Consuegra:** Data curation, Writing – review & editing. **María del Carmen Rosales-Domínguez:** Writing – review & editing, Investigation. **Ana R. Soria:** Writing – review & editing, Visualization, Investigation, Conceptualization. **Jaime Urrutia-Fucugauchi:** Writing – review & editing, Investigation, Conceptualization. **José A. Arz:** Writing – review & editing, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsames.2026.105959.

Data availability

Data will be made available on request.

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