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Sedimentary development and isotope analysis of deposits at the Cretaceous/Palaeogene transition in the Paraíba Basin, NE Brazil

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Abstract

New data are presented for three formations (Itamaracá, Gramame and Maria Farinha) and two boundaries (Campanian/Maastrichtian and Maastrichtian/Danian) in the Olinda Sub-basin of the Paraíba Basin. Currently accepted facies models, sequence stratigraphy characterizations, and stable-isotope data of carbon and oxygen are reviewed. The carbonate cement of the Itamaracá Formation sandstones shows carbon- and oxygen-isotope ratios consistent with a shallow-marine depositional environment: $\delta^{18}O$ ranges from -0.8 to –2.7‰ PDB, and $\delta^{13}C$ ranges from +1 to +2‰ PDB. Within the Itamaracá Formation, a maximum flooding surface at the Campanian/Maastrichtian transition has been identified. During the Maastrichtian, a Highstand System Tract was deposited, which shows an increase in temperature and marine bioproductivity as recorded by stable-isotope values ($\delta^{18}O$ from –3 to –5‰ PDB, and $\delta^{13}C$ values of –1.2, -0.3, 0.1 and +2.3‰ PDB). Just below the K/Pg boundary, the O-isotope signal indicates three warming phases, alternating with four cooling phases.

Keywords: NE Brazil, Cretaceous/Palaeogene boundary, carbon isotopes, oxygen isotopes

Introduction

The Paraíba Basin is located along the Atlantic margin of NE Brazil, and comprises the coastal area between the Pernambuco Shear Zone in the south and the Mamanguape Fault in the north. The basin is characterized by a nearly continuous sedimentary succession that was deposited during the Late Campanian, the Maastrichtian and the Palaeocene. The low economic potential of the onshore and offshore continental margin between the Pernambuco Shear Zone (PESZ) and the Touros High (TH) implies that it is a poorly studied region. It appears though that its tectonic characteristics differ from those of the neighbouring Potiguar and Pernambuco (Mohriak et al., 1995, 1998) marginal basins (Fig. 1A), as well as from coeval offshore basins along the African continental margin along the central segment of the South Atlantic Ocean (Moulin et al., 2005).

We follow here the interpretation that the marginal area between the PESZ and the Patos Shear Zone (PASZ) corresponds to the coastal Paraíba Basin and that the area from the PESZ to the TH corresponds to the East Platform of the Potiguar Basin (Fig. 1). This interpretation is based primarily on stratigraphical and sedimentological evidence presented by, among others, Mabesoone & Alheiros (1993), Feitosa et al. (2002), Barbosa et al. (2003) and Barbosa (2007).

According to Lima Filho et al. (1998), Barbosa et al. (2003), Barbosa (2007), and Souza (2006), the Beberibe Formation (Santonian?-Campanian), the Itamaracá Formation (Campanian-Maastrichtian), the Gramame Formation (Maastrichtian), and the Maria Farinha Formation (Palaeocene-Eocene?) are found in the coastal area between the PESZ and the PASZ.

In the present contribution, we present facies models, a sequence-stratigraphic analysis and C- and O-isotope geochemistry results for the upper three of these four sedimentary formations of the Paraíba Basin: the Itamaracá Fm. (calcareous sandstones and limestones), the Gramame Fm. (limestones and marls) and the Maria Farinha (limestones and marls), and

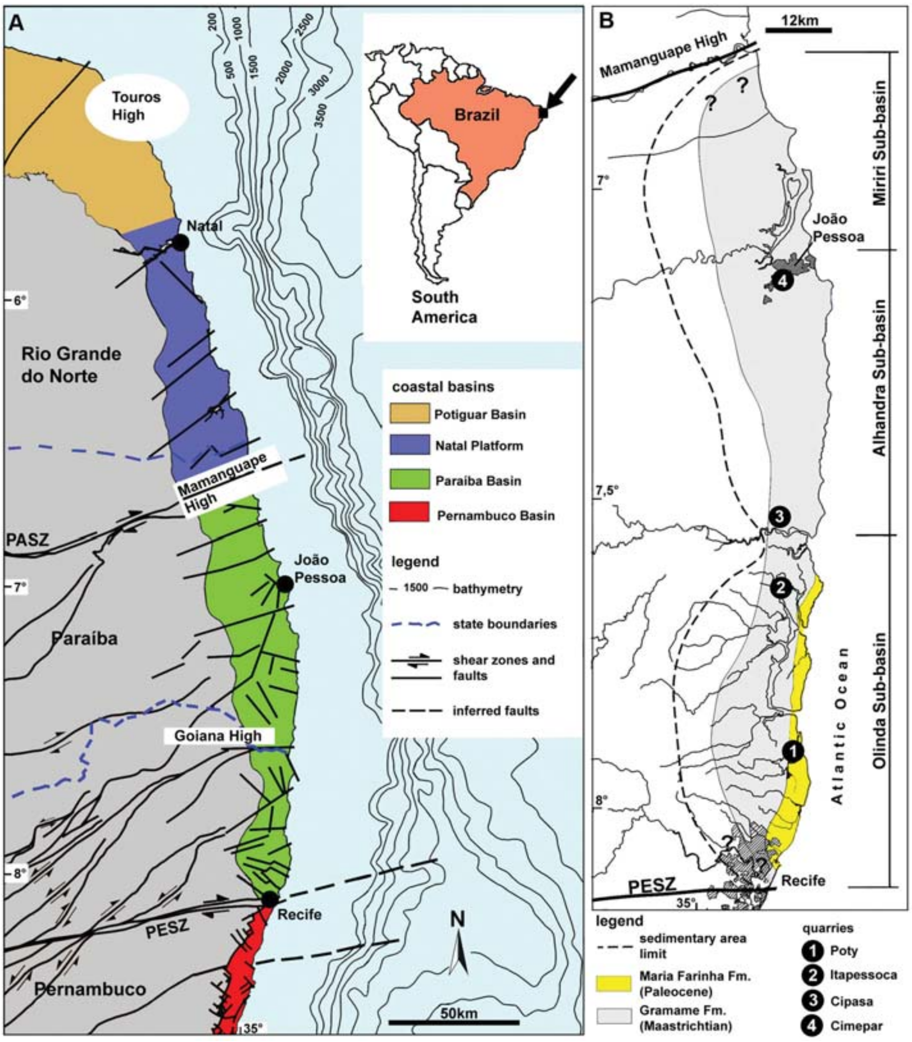

Fig. 1. Location maps. **A:** Location of the Paraiba Basin in northeastern Brazil. **B:** Detail of the Paraíba Basin, showing its division into sub-basins, its Maastrichtian-Danian carbonate deposits and locations of investigated quarries.

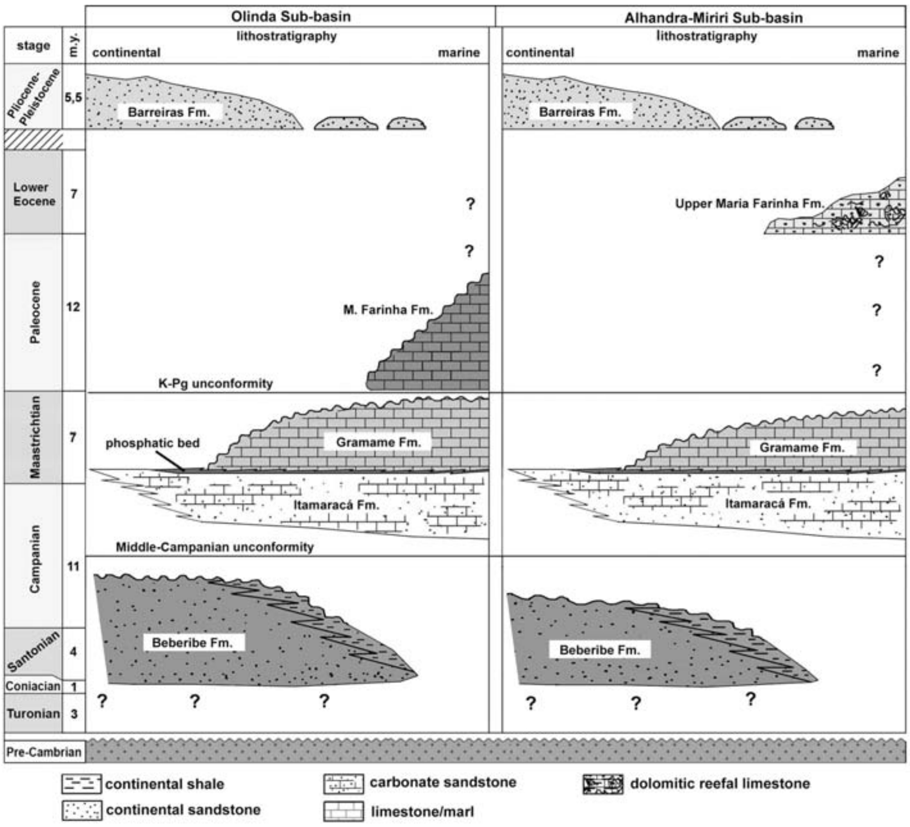

Fig. 2. Stratigraphy of the onshore Paraíba Basin, showing the distribution of the units over the various sub-basins, the infill of which was influenced mainly by tectonic events during the Late Cretaceous.

for the boundaries that separate the Itamaracá and Gramame Formations (Campanian/Maastrichtian) and the Gramame and Maria Farinha Formations (Maastrichtian/Danian = K/Pg) (see Fig. 2).

The unconformity that coincides with the K/Pg boundary is only preserved in the Olinda Sub-basin (Fig. 1B). Since the work of Alvarez et al. (1980) on the origin of the Cretaceous/Palaeogene boundary event, much additional evidence that corroborates their impact theory has been found. For example: iridium anomalies in the K/Pg contact layer elsewhere in the world, and the discovery of a large-scale impact crater in the subsurface of the Yucatan Peninsula (Mexico). In South America, preserved successions that include the actual K/Pg boundary are known from the Paraíba coastal basin (Albertão, 1993; Sial et al., 2001, 2003; Barbosa & Neumann, 2004) and the Yacoraite region of the Neuquen Basin, Argentina (Sial et al., 2001, 2003).

C- and O-isotope studies of the K/Pg boundary layers have previously been analyzed by several researchers (Sial et al., 1993; Ferreira et al., 1996; Barbosa et al., 2005; Sabino et al., 2005, Nascimento-Silva et al., 2008). All these authors have suggested an enrichment of carbon near the K/Pg boundary and a marked break after this limit. Also, the C- and O-isotope behavior in the Cretaceous-Palaeogene boundary registered in the Poty quarry is similar to that observed elsewhere in the world.

The objective of the present contribution is a short reconstruction of the geological development of the study area just before, during and just after the K/Pg transition. This is done on the basis of a combination of changes in the sedimentological development and analysis of the carbon and oxygen isotopes.

Characteristics of the Paraíba Basin

The Paraíba Basin (Fig. 1) is subdivided into three sub-basins: Olinda (South), Alhandra (middle) and Miriri (Morth). The Olinda Sub-basin is bounded in the South by the PESZ, and in the North by the Goiana High (a NE–SW trending basement high that strikes toward the coast, north of Goiana City). It has a semicircular form, and it contains the area where the basin is widest. Only in this sub-basin, a relatively continuous Maastrichtian-Palaeocene carbonate succession has been preserved. Little work, though, has been done on these deposits, with the exception of exposures in the Poty Quarry and at Ponta do Funil. The Poty Quarry (outcrops and cores) contains the best studied K/Pg transitional beds in South America.

Material and methods

For the present study, four quarries (Poty, Itapessoca, Cipasa and Cimepar) and one drill core (Poty Quarry) were studied and sampled (Fig. 1B). Fifty-three thin sections were made from selected samples collected in these quarries; they were studied petrographically to identify the sedimentary lithofacies and microfacies. In addition, cathodoluminescence (CL) analysis was done on the thin sections to evaluate authigenic cement types. Additionally, 165 samples, spaced 30 cm apart, from a 52 m drill core made at the Poty Quarry, were analyzed for C and O isotopes, using McCrea´s (1950) method. The sampled core includes Late Campanian, Maastrichtian and Danian carbonates. Based on the stable-isotope results, 25 samples were chosen for major and trace chemistry analyses by XRF. The elements that were analyzed include Sr, Mn, Mg, Ca and Rb. These elemental analyses were carried out in order to strengthen the interpretation of the isotope results and to verify that the stable-isotope signal was not significantly altered by diagenesis.

Formations under investigation

Itamaracá Formation

The Itamaracá Formation consists of carbonate-cemented sandstones and shales that were interpreted by previous researchers to have formed in shallow lagoons that experienced some estuarine influences. This unit represents a rapid transgressive pulse over the basin. This transgressive event was driven mainly by tectonic subsidence, which affected this region of north-eastern Brazil during the Late Campanian (Barbosa & Lima Filho, 2006; Barbosa et al., 2004, 2007). At the top of this succession, a phosphate-rich, sandy carbonate bed is present. Based on gamma-ray logs and sedimentological profiles that indicate the end of the transgressive cycle and the beginning of a carbonate domain, this phosphate-rich level is interpreted as a maximum flooding surface (MFS). Within the basin, the thickness of this phosphatic bed varies between 50 cm and 6 m. This phosphatic layer (Maastrichtian) marks the Campanian/Maastrichtian boundary.

The Campanian/Maastrichtian boundary has been studied mainly in cores. In cores, these easily weathered, silty, carbonate-rich phosphate deposits are easily observed; in outcrops, the phosphatic bed is rarely well-exposed. It represents the MFS of the transgressive system tract (Barbosa & Lima Filho, 2006; Barbosa et al., 2004, 2007).

Gramame and Maria Farinha Formations

Both formations consist of shoaling-upward cycles that consist of dark- to light-grey to yellowish, fine- to medium-grained, marly limestones alternating with marl beds (Fig. 3). These lithologically monotonous deposits are characterised by even, laterally continuous, planar bedding that clearly extends beyond the scale of the outcrops (Fig. 3).

These carbonate deposits were deposited on a shallow carbonate platform that was dominated by low-energy carbonate muds. Bioclasts are common and some terrigenous influx was also present. In some intervals, reworked bioclasts are concentrated, which is inferred to represent bottom winnowing during storms. These tempestite layers also contain burrows dominated by the genus *Thalassinoides*.

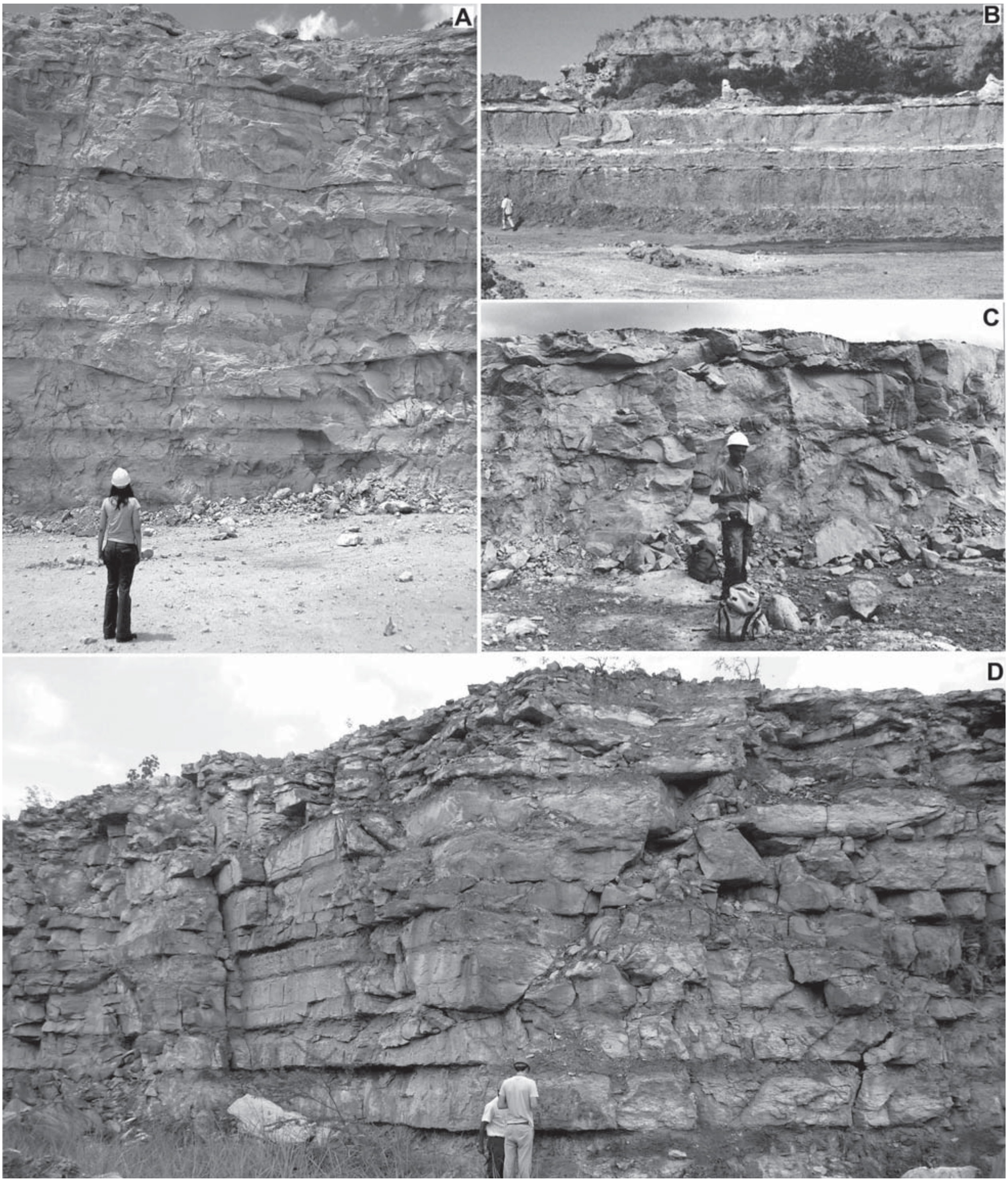

Fig. 3. Main sites where deposits of the Gramame and Maria Farinha Formations can be analysed for their carbonate-platform environment and its depositional architecture. **A:** Cipasa; **B:** Poty; **C:** Cimepar; **D:** Itapesocca.

Boundaries under investigation

The K/Pg boundary

The top of the Gramame Formation is separated from the Maria Farinha Formation by a conglomeratic bed that marks the K/Pg boundary. This carbonate conglomerate was observed both in wells and in outcrops in the Olinda Sub-basin (Fig. 1B). The origin of this conglomerate is still being debated and is under intensive study. It has been variously interpreted as an impact-generated tsunami deposit, a storm deposit, a tectonic conglomerate, or a sea-level low-stand (Stinnesbeck & Keller, 1996; Barbosa et al., 2006). Preliminary results of recent Pernambuco/Princeton research indicate that it represents an erosional unconformity that formed due to a fast sea-level fall that occurred during the Early Danian (Fig. 4A). This conglomerate marks the top of the high-stand system tract and the beginning of a regressive event, which affected the basin during the Palaeocene (Fig. 4B).

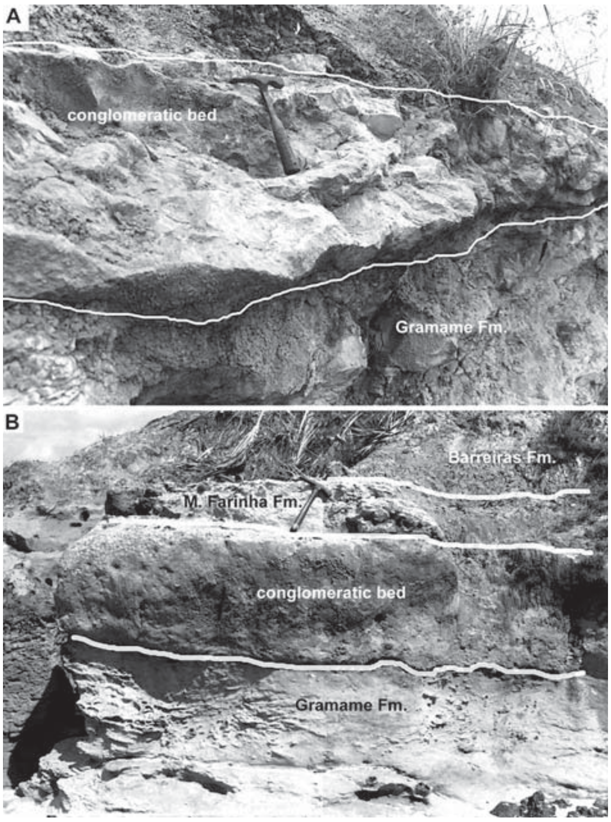

Fig. 4. The conglomeratic bed which separates the Gramame and Maria Farinha Formations. **A:** Poty quarry; **B:** Ponta do Funil.

A detailed study of the conglomerate layer was conducted at the Poty Quarry to analyse the relationship between the microfacies and stable-isotope data below and above the K/Pg boundary. The detailed stratigraphic section with the K/Pg boundary (Fig. 5) at the Poty Quarry shows the seven carbonate beds that were identified. These carbonate rocks have also been sampled, and the thin sections have been petrographically studied using an optical microscope. The photomicrographs of the beds in the K/Pg section are shown in Figure 6. They reveal that the carbonates deposited until the Late Maastrichtian are mudstones, wackstones and packstones. In the early Danian, an erosional event occurred, and carbonates of Maastrichtian and Danian age became reworked, forming a conglomeratic bed that represents the K/Pg boundary in the Paraíba Basin. This change in lithology corresponds with a marked negative excursion in the $\delta^{13}C$ values. The photomicrographs of the carbonates just above the boundary show the same microlithofacies (mudstones, wackestones and packstones) as those deposited during the late Maastrichtian, but with a different faunal fossil content. The ammonites disappear whereas the nautiloids become the most important cephalopods and the characteristic elements of the Maria Farinha Formation. The microfauna of the Gramame Formation is abundant, with planktonic foraminifers constituting 70–90% of the total, among which various species of *Globotruncana* (zone of *G. contuse* and *G. stuarti*). Among the abundant microfossils of the Maria Farinha Formation dominate the benthonic foraminifers, chiefly nodosarids; the planktonic ones constitute only 1–5% of the total (Mabesoone, 1994).

C- and O-isotope characteristics of the Cretaceous/Palaeogene carbonates

The Mn/Sr ratios of the samples are all below 1.0 (Fig. 7), and therefore indicate that we

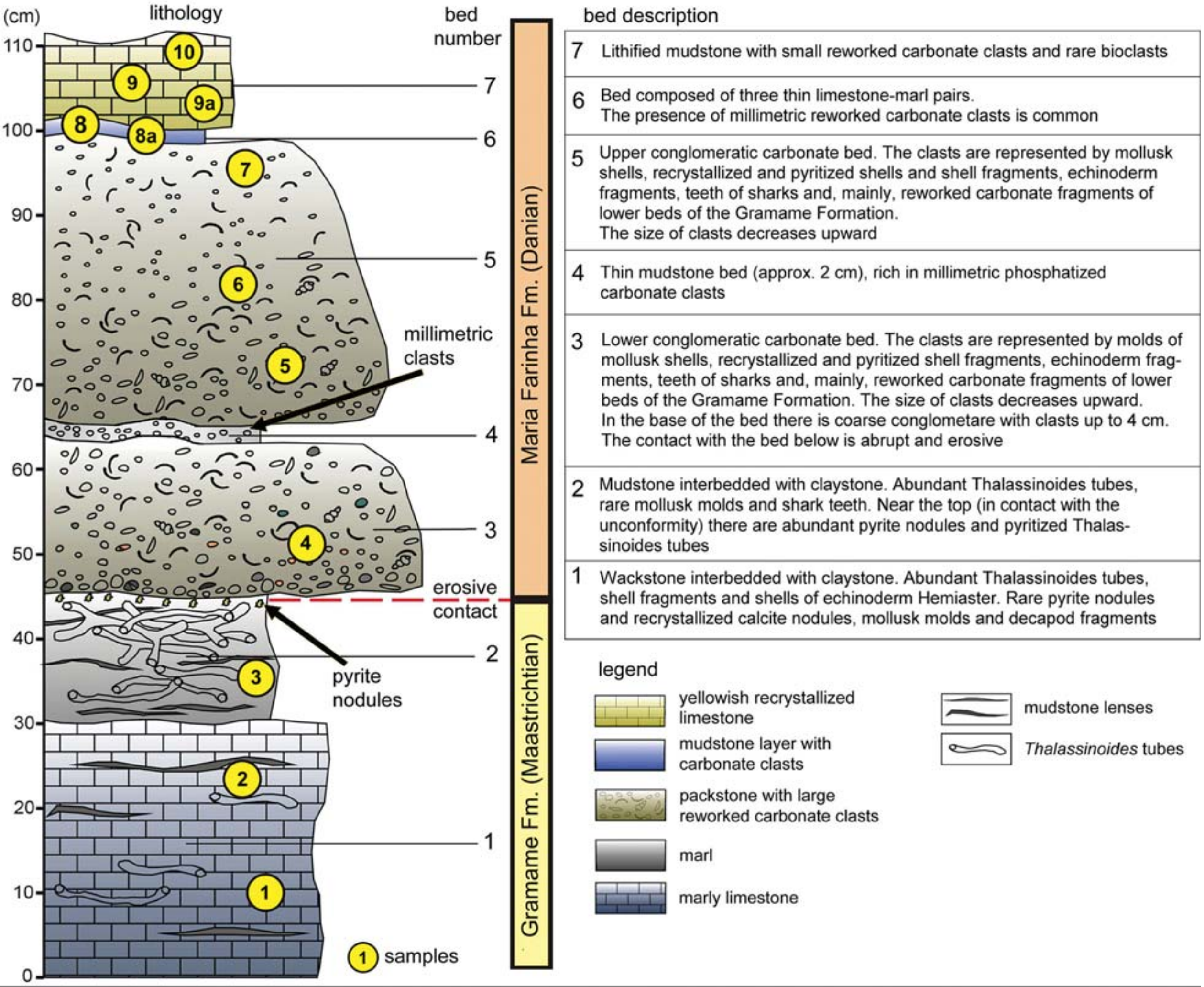

Fig. 5. Detailed stratigraphic section of K/Pg boundary in the Poty quarry with description of the beds.

are dealing with largely primary isotopic signals (cf. Kaufman et al., 1993). Positive $\delta^{13}C$ values, ranging from +1 to +2‰ PDB, characterize all samples from the Campanian Itamaracá Formation. However, negative values (–1.2, -0.3 and 0.1‰ PDB) characterize the samples taken from the Campanian-Maastrichtian boundary beds.

The Maastrichtian samples show a clear, positive trend in the δ13C data that persists until the early Danian, reaching values of +2.3‰ PDB for the upper Maastrichtian. Superimposed on this trend are two negative peaks in the middle Maastrichtian (–1.8% and 0.6‰ PDB, respectively).

In the early Danian, a small positive excursion occurs with values around +2‰ PDB, which is followed by a sharp drop to +1‰ PDB. This negative excursion occurs above the K/Pg transition.

The oxygen-isotope signature indicates a cool climate during the late Campanian (0.8–2.7‰ PDB), and a warmer phase during the early Maastrichtian (–3 to –5 ‰ PDB). Subsequently, the temperature decreased gradually during the middle and late Maastrichtian, as indicated by oxygen values of around –2‰ PDB. However, a succession of negative and positive peaks appears to have occurred during the late Maastrichtian. These peaks might be related to climatic variations such as those described by Keller (2001, 2005) and Keller et al. (2003, 2004a,b), which were inferred to reflect multiple impacts prior to the main Yucatan event.

Just above the K/Pg boundary layer, the SiO_2 content increases (from 23.0% to 37.6%)

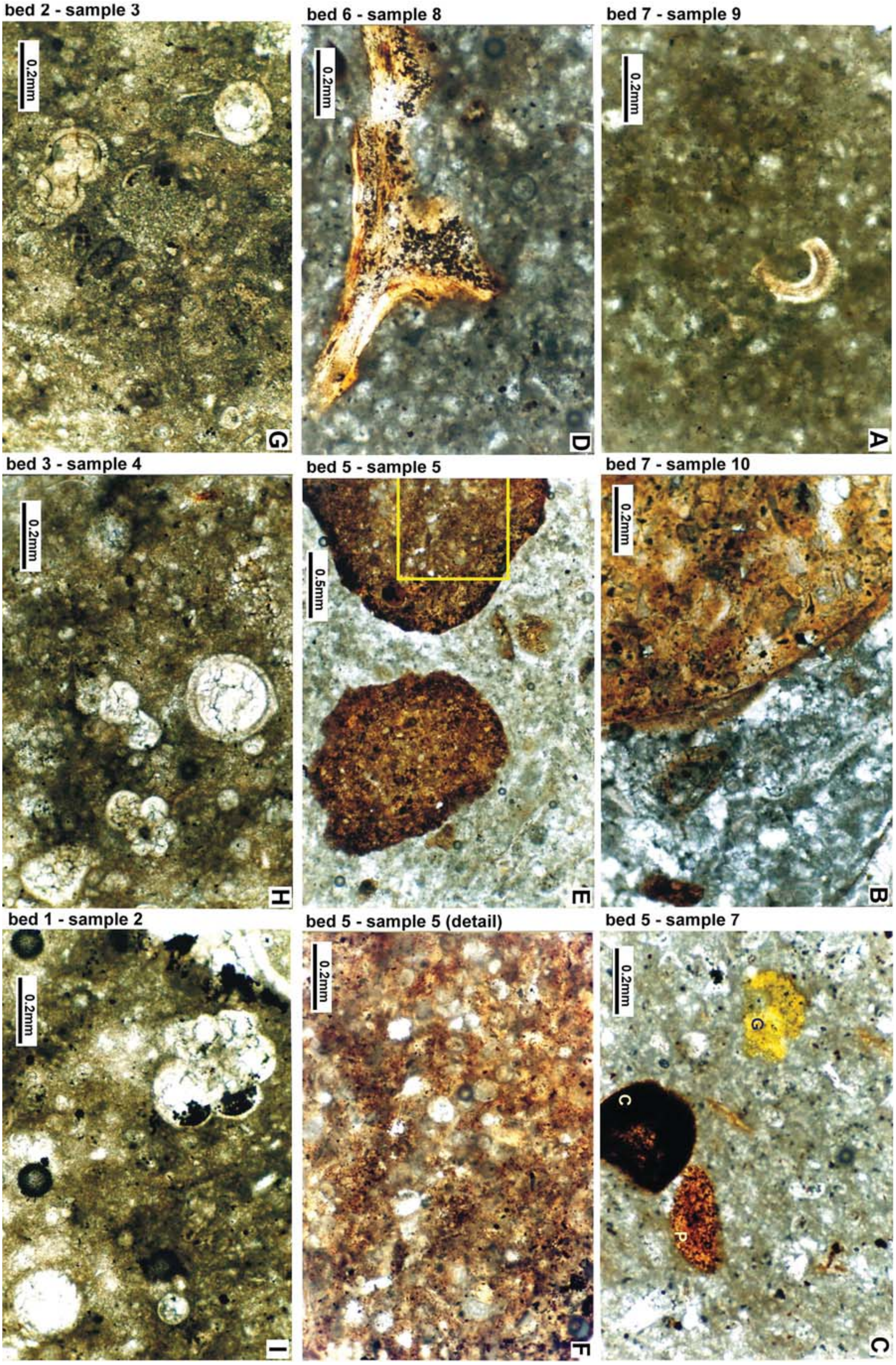
bed 2 - sample 3
0.2mm
G
bed 6 - sample 8
0.2mm
D
bed 7 - sample 9
0.2mm
A
bed 3 - sample 4
0.2mm
H
bed 5 - sample 5
0.5mm
E
bed 7 - sample 10
0.2mm
B
bed 1 - sample 2
0.2mm
I
bed 5 - sample 5 (detail)
0.2mm
F
bed 5 - sample 7
0.2mm
G
C
P
C

Fig. 6 (left). Photomicrographs of the carbonate microfacies across the K/Pg section in the Poty quarry. **A:** Mudstone with an echinoderm spine as bioclast. **B:** Packstone with intraclasts in the upper part of the bed. The intraclasts are rounded similar to those in beds 3, 4, 5 and 6. The brown color in the intraclast is phosphate and the green areas are glauconite. **C:** Upper part of the conglomeratic bed. The intraclast sizes indicate grading. Fine grains are present in the matrix of the lower part of the bed 5; in the upper part, coarser grains gradually decrease. G = glauconite, P = phosphate nodules, C = pyritisized carbonate clasts. **D:** Wackstone-mudstone rich in calcispheres and foraminifers with a large fish-bone fragment. **E:** Conglomeratic bed. Wackestone-packstone with dispersed intraclasts. The average size of the intraclasts in this part of the bed is centimetre. **F:** Detail of an intraclast. The yellowish and brownish microclasts are phosphatized. The black coloured microclasts are pyritized. **G:** Wackestone-mudstone with some sparry calcite infilling the foraminifer and calcisphere tests. Algae cysts and calcisphere are partially pyritized. **H:** Wackestone very rich in calcispheres and planktic foraminifers. **I:** Wackestone showing a detail of partially pyritized planktic foraminifer test.

and the amount of Al_2O_3 increases from 6.8% to 15.2%. This is interpreted to result from an increase in the amount of terrigenous siliciclastic material preserved in the basin due to a sea-level fall. This change in sea level is believed to result from a drop in temperature in the wake of the global greenhouse event which occurred at the K/Pg boundary, as suggested by Keller (2005).

Conclusions

The late Campanian Itamaracá Formation formed in a shallow-marine environment. There is a maximum flooding surface at the transition to the Gramame Formation (Campanian-Maastrichtian). Samples right above this level are enriched in phosphates (3.46–5.28% P_2O_5) and have positive $\delta^{13}C$ values (from 0.0 to +1.9‰ PDB), suggesting an increase in marine bioproductivity, likely related to a sea-level high-stand event.

The Gramame Formation is composed of alternating limestones and marls, and contains abundant bioturbation (biomicrite), intervals of fossiliferous limestone (wackestone) and *Thalassinoides* ichnofacies. At the contact between the Gramame and Maria Farinha Formations (Maastrichtian/Danian boundary), a

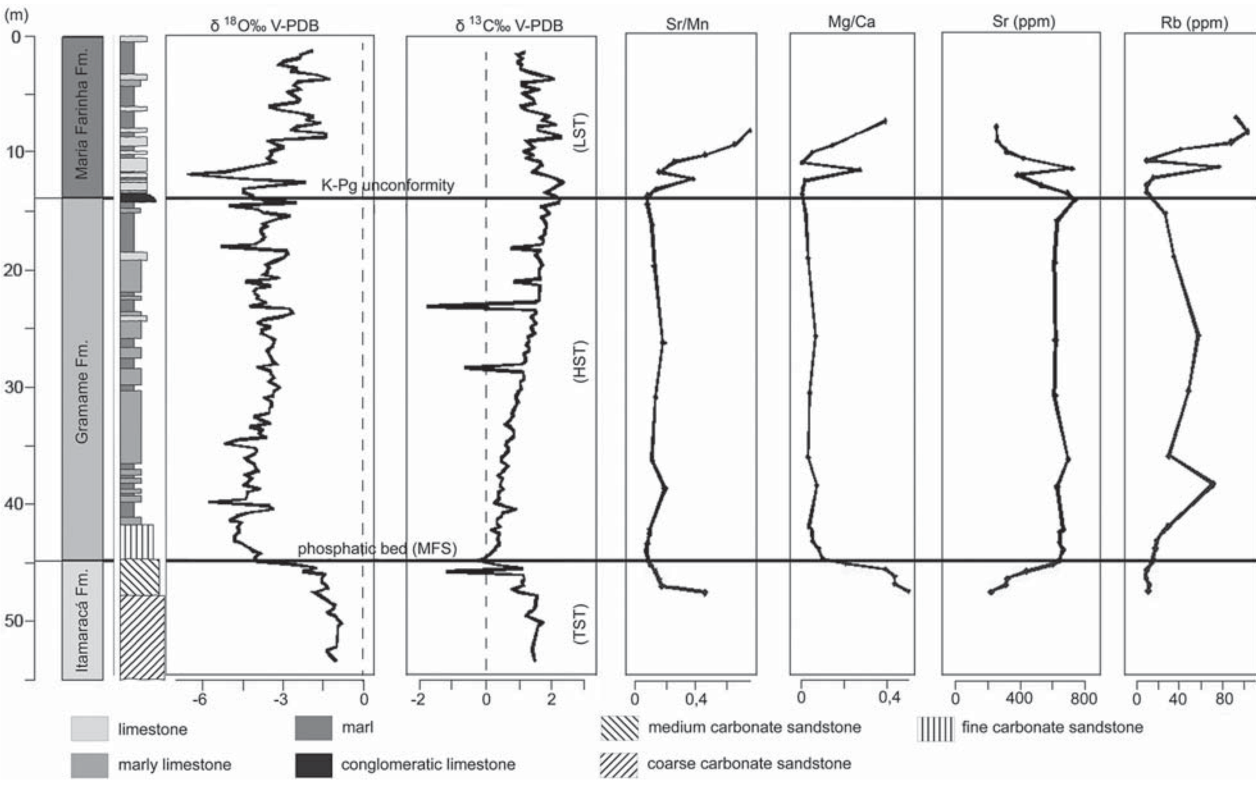

Fig. 7. Trends in oxygen and carbon isotopes, and Mn/Sr, Mg/Ca, Sr and Rb values in the Poty Quarry.

conglomerate occurs that is composed of grey limestone with reworked clasts varying in size from millimetres to several centimetres. This conglomerate layer is possibly associated with an erosive event in the earliest Danian.

The Maria Farinha Formation is also composed of alternating limestones and marls, with significant bioturbation (primarily *Thalassinoides*). Towards the top of the Marinha Farinha Formation, an increase in terrigenous siliciclastic material in the carbonate platform was observed, indicating the occurrence of a regional marine regression. This observation, in combination with contemporaneous physiographic and faunal changes (i.e. more shallow-marine animals) in the Paraíba Basin, strongly suggests that the upper Maria Farinha Formation represents a Lowstand System Tract.

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