



ELSEVIER

Contents lists available at ScienceDirect

## Comptes Rendus Palevol

www.sciencedirect.com



General palaeontology, systematics and evolution (Biostratigraphy)

## Integrated biostratigraphy based on planktonic foraminifera and dinoflagellates across the Cretaceous/Paleogene (K/Pg) transition at the Izeh section (SW Iran)



*Biostratigraphie intégrée du passage Crétacé/Paléogène basée sur les foraminifères planctoniques et les événements des dinoflagellés de la coupe d'Izeh (Sud-Ouest de l'Iran)*

Bijan Beiranvand<sup>a</sup>, Dalila Zaghib-Turki<sup>b,\*</sup>, Ebrahim Ghasemi-Nejad<sup>c</sup>

<sup>a</sup> Petroleum Geology Department, Exploration & Production Division, Research Institute of Petroleum Industry, Western side of Azadi Sport Complex, P.O Box 14857-3311 Tehran, Islamic Republic of Iran

<sup>b</sup> Université de Tunis El Manar, faculté des sciences de Tunis, campus universitaire, 2092 Tunis, Tunisia

<sup>c</sup> Geological School, Science Place, University of Tehran, Tehran, Islamic Republic of Iran

## ARTICLE INFO

## Article history:

Received 4 June 2013

Accepted after revision 1<sup>st</sup> October 2013

Available online 5 February 2014

Handled by Philippe Taquet

## Keywords:

K/Pg boundary

Biostratigraphy

Planktonic foraminiferal biozonation

Dinocyst events

Izeh section

Zagros Basin

Iran

## ABSTRACT

The present work is based on semi-quantitative study carried on detailed sampling (samples are spaced by 5, 10 and 15 cm close to the boundary) of an essentially continuous and expanded section crossing the Cretaceous–Paleogene (K/Pg) boundary in Iran. By this work, we attempt to detail biostratigraphy based on planktonic foraminifera biozones and correlate biozones and subzones with dinocyst events. The entire Cretaceous–Paleogene interval contains rich, diversified and well-preserved planktonic foraminifera and dinoflagellate cyst assemblages. Four planktonic foraminiferal biozones have been recognized across the Cretaceous–Paleogene transition (K/Pg): *Abathomphalus mayaroensis* Biozone including *Plummerita hantkeninoides* Subzone from the Late Maastrichtian and *Guembelitra cretacea* (including *Hedbergella holmdelensis* and *Parvularugoglobigerina longiapertura* subzones), *Parvularugoglobigerina eugubina* Biozone and *Parasubbotina pseudobulloides* Biozone belonging to the Early Danian. These biozones have been correlated with four dinocyst biozones: the *Manumiella seelandica* Biozone belonging to the Late Maastrichtian and the *Alisocysta reticulata*, *Senoniasphaera inornata* and *Damassadinium californicum* biozones from the Early Danian. At this section, like at the El Kef section (GSSP for the K/Pg) and the auxiliary sections, an Ir anomaly is detected indicating the K/Pg boundary. This geochemical anomaly coincides also with mass extinctions of planktonic foraminifera species. The extinct species are in particular the large, complex tropical and subtropical taxa dwelling in subsurface and lower photic water. The mass extinctions at the Izeh section occurred over a succinct period of time similar to the K/Pg type section at El Kef (Tunisia). These sudden mass extinctions indicate a catastrophic pattern event occurring at the Maastrichtian/Danian boundary. In contrast the organic-walled dinocysts were less affected by the mass extinction and most species crossed the K/Pg boundary without showing mass

\* Corresponding author.

E-mail addresses: [dalila.turki@yahoo.fr](mailto:dalila.turki@yahoo.fr), [dalila.zaghib@fst.rnu.tn](mailto:dalila.zaghib@fst.rnu.tn) (D. Zaghib-Turki).

and sudden extinctions. Nevertheless, they showed changes in their assemblages' structure beyond the K/Pg boundary. Especially, *Manumiella seelandica* and *M. druggii*, typical species of Antarctic Maastrichtian dinocysts assemblages, occur in coeval deposits at the Izeh section; they persist through the Lower Danian and, like in Tunisia (e.g., El Kef section, Ellès section) show an obvious increase in relative abundance.

© 2013 Académie des sciences. Published by Elsevier Masson SAS. All rights reserved.

## R É S U M É

### Mots clés :

Limite K/Pg  
Biostratigraphie  
Biozotation des foraminifères  
planctoniques  
Évènements des dinokystes  
Coupe d'Izeh  
Bassin de Zagros  
Iran

Le présent travail est basé sur un échantillonnage serré effectué dans la coupe d'Izeh, située dans le bassin de Zagros, dans le Sud-Ouest de l'Iran. Au total, 25 échantillons sont étudiés. Ceux qui ont été prélevés au niveau de la limite Crétacé/Paléogène sont espacés de 5, 10 et 15 cm. Cette coupe contient d'abondants foraminifères planctoniques bien conservés, ainsi que divers kystes de dinoflagellés. L'étude biostratigraphique détaillée des foraminifères planctoniques révèle que cette coupe est bien continue et complète dans son intervalle de passage Crétacé/Paléogène (K/Pg) et que toutes les biozones et sous-zones caractérisant cet intervalle sont développées : la zone à *Abathomphalus mayaroensis*, y compris la sous-zone à *Plummerita hantkeninoides* du Maastrichtien terminal ; la zone à *Guembeltria cretacea* du Danien basal, avec ses deux sous-zones celle à *Hedbergella holmdelensis* et celle à *Parvularugoglobigerina longiapertura* ; la zone à *Parvularugoglobigerina eugubina* et la zone à *Parasubbotina pseudobulloides* du Danien inférieur. Ces différentes zones et sous-zones ont pu être corrélées avec les différents événements enregistrés de dinokystes : celui déterminant la zone à *Manumiella seelandica* du Maastrichtien et ceux caractérisant les zones successives à *Alisocysta reticulata*, à *Senoniasphaera inornata* et à *Damassadinium californicum* du début du Danien. L'analyse semi-quantitative des foraminifères planctoniques révèle que ce groupe de foraminifères a subi des extinctions spécifiques en masse à la limite K/Pg, coïncidant avec une anomalie d'iridium (Ir) bien confirmée sur le plan géochimique. Les espèces éteintes sont principalement les globotruncanidés à test caréné et les grands hétérohélécidés. De tels taxa sont caractéristiques des eaux marines photiques intermédiaires des domaines tropical et subtropical. Les extinctions en masse dans cette coupe d'Izeh sont soudaines et de durée succincte. Elles sont similaires à celles de la coupe El Kef en Tunisie (stratotype de la limite K/Pg) et des autres coupes complètes dans leur intervalle de passage Crétacé/Paléogène. De telles extinctions spécifiques étant survenues à une échelle globale à la limite Maastrichtien/Danien déterminent un bioévénement de type catastrophique. En revanche, les dinokystes à paroi organique ont été moins touchés par l'extinction de masse et la plupart des espèces ont traversé la limite K/Pg sans montrer d'extinctions en masse et soudaines. Néanmoins, ils ont montré des changements dans la structure de leurs assemblages au-delà de la limite K/Pg. Surtout, *Manumiella seelandica* et *M. druggii* typiques des assemblages maastrichtiens du domaine antarctique sont bien présentes dans la coupe d'Izeh ; elles persistent dans le Danien inférieur et, comme en Tunisie, notamment dans les coupes d'El Kef et d'Ellès, elles ont montré une nette augmentation d'abondance relative.

© 2013 Académie des sciences. Publié par Elsevier Masson SAS. Tous droits réservés.

## 1. Introduction

The El Kef section (Tunisia) is the Global Stratigraphic Section and Point (GSSP) that defines the Cretaceous/Paleogene boundary (K/Pg). It corresponds to the base of a dark clay layer with a thin rusty reddish oxidized layer with abnormally high Iridium content, as at the Gubbio section in Italy (Alvarez et al., 1980), and an increase in spinels rich in nickel (see Molina et al., 2006, 2009 and references therein). It coincides with a sudden catastrophic mass extinction, which strongly affected the planktonic foraminifera. This mass extinction defines the top of the *Abathomphalus mayaroensis* Biozone and the *Plummerita hantkeninoides* Subzone. It is now generally accepted that this major bioevent is linked to the global Cretaceous/Paleogene boundary event. This event is due to the meteorite impact (as characterized by geochemical anomalies) causing a major crisis and an almost complete turnover in the assemblages across the boundary. The

Izeh section is supposed to record all these characteristics within the Cretaceous–Paleocene transition.

Elsewhere in Caravaca (Spain) and El Kef (Tunisia), the K/Pg planktonic foraminiferal bioevent was studied in detail by Smit (1977, 1979, 1982, 1990, 1994). According to his opinion most of Cretaceous species disappeared at the K/Pg boundary, but a few species crossed the boundary. These latter are considered to be reworked. Smit also noted that the mass extinction was of short duration. Consequently he concluded that the K/Pg mass extinction event was sudden, catastrophic and the consequence of a large extraterrestrial bolide impact (Kyte, 1998; Smit, 1990, 1997). However, others (Keller, 1988, 1989a,b, 1994, 1996, 2008, 2011; Keller et al., 1994, 1995, 1998, 2008, 2009, 2012; Preisinger et al., 1993) have again and again questioned the catastrophic nature of the mass extinction at the K/Pg boundary and they argued that the pattern of the mass extinction in the terminal Maastrichtian is gradual. They noticed that 2/3 of the species are already in decline

during the Late Maastrichtian and become extinct prior to or at the K/Pg boundary, whereas 1/3 of them survived into the Danian. Consequently, Keller and her collaborators defended that such gradual pattern of extinction cannot be attributed to the global effect of the asteroid impact. Nevertheless, a considerable number of authors did not accept such a gradual pattern of extinction (e.g., Arenillas et al., 2002; Arz et al., 2004; Canudo, 1997; Gallala and Zaghbib-Turki, 2010; Ginsburg, 1997a,b; Koutsoukos, 1996; Lipps, 1997; Masters, 1997; Molina et al., 1998; Olsson, 1997; Orue-Etxebarria, 1997; Schulte et al., 2010; Smit, 1997; Zaghbib-Turki et al., 2000, 2001).

In contrast, deep-water benthic foraminifers were less influenced by the K/Pg boundary event, but their diversity and abundance decreased temporarily (see, e.g., Alegret et al., 2001, 2003, 2004, 2005; Coccioni and Galeotti, 1998; Coccioni and Marsili, 2007).

Other pelagic groups which are calcareous (e.g., coccolithophorids) and non calcareous (e.g., dinoflagellates and radiolarians), were less affected by this crisis. Thus many species of them crossed the K/Pg boundary with apparently no major changes in their diversity and abundance (Bown, 2005; Elliot et al., 1994; Hollis, 1996; Sarkis et al., 2002).

The K/Pg boundary is marked by an important decrease in the abundance of calcareous nannoplankton, the increase of Cretaceous-survivor species (e.g., *Cyclagelosphaera reinhardtii*) together with the cysts of the calcareous dinoflagellate *Thoracosphaera operculata*. The simultaneous first appearances of *Cyclagelosphaera alta* and *Biantholithus sparsus* indicate the Earliest Danian (Bernaola and Monechi, 2007; Westerhold et al., 2008).

Despite the fact that the Cretaceous–Paleocene is well exposed in outcrops in the central part of the Zagros Basin and the abundance and the good preservation of planktonic foraminifera within the studied section at Izeh, no detailed biostratigraphic study of the K/Pg interval in the Southwest of Iran has yet been published. To fill this gap, we sampled a well-exposed section located some 25 km northwest of the village of Izeh (Fig. 1) with the aim to undertake a detailed study of the distribution of the planktonic foraminifera and dinocysts and high-resolution biostratigraphical analysis across the Cretaceous–Paleogene transition interval. In addition, the relationship between the planktonic foraminiferal zonation and the distribution of organic-walled dinoflagellate cysts (dinocyst events) has been studied.

## 2. Geological setting and stratigraphy

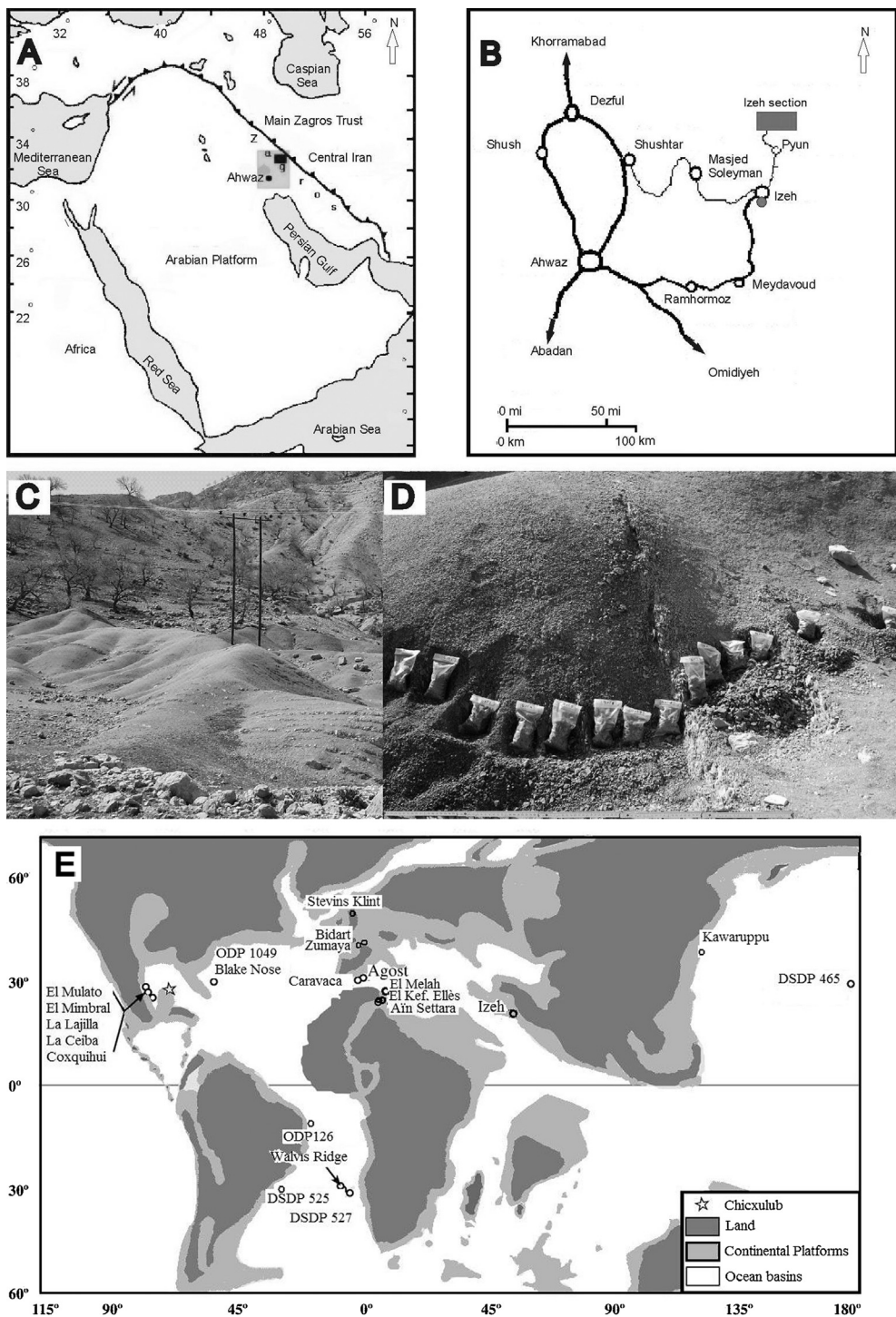
The studied section is located in the region of Izeh (Fig. 1), in the central part of the Zagros Basin, which is the northernmost part of the Arabian Platform constituting the southeastern margin of the Tethys palaeo-ocean. Development of the Zagros Basin began in the Late Cretaceous (Turonian to Maastrichtian) due to fore-deep subsidence preceding the continental closure along the Zagros Suture. This closure resulted in collision of the western Iranian and Afro-Arabian plates (Gealey, 1988). In the Zagros Basin, the Gurpi Formation constitutes the upper part of the Uppermost Turonian–Middle Maastrichtian progradational–retrogradational megasequence,

as well as the basal strata of the overlying Uppermost Maastrichtian–Upper Eocene megasequence (Alavi, 2004; James and Wynd, 1965; Koop and Stoneley, 1982; Motiei, 2003; Murris, 1980; Ziegler, 2001). The Gurpi Formation consists of dark gray marly shale (Turonian–Middle Maastrichtian in the lower part of the Formation), which is overlain by gray marls with interbedded clayey limestones of the Emam Hassan Member (Middle Maastrichtian), and the dark gray shaly marls (Upper Maastrichtian to Paleocene, in the upper part). These distinctive lithostratigraphical units represent depositional environments ranging from middle shelf to upper slope as indicated by the rich macro- and microfaunas (Hemmati-Nasab et al., 2008). In the studied area, the Gurpi Formation is considered to be a continuous stratigraphical succession through the Campanian–Paleogene interval. It overlies the Ilam Formation with minor disconformities and is covered conformably by the sandy to silty purple shales of the Lowermost Pabdeh Formation top. The K/Pg boundary lies within the upper part of the marly Gurpi Formation, at 275.82 m from its base. It is within the dark gray shaly marls unit composing the upper part of the formation, at about 68 m above the Emam Hassan Member. It is also at 61.2 m below the base of the Pabdeh Formation including three successive units:

- lower marly shales;
- middle clayey limestone;
- upper shaly marls.

## 3. Material and methods

A total of 25 samples were collected, carefully for micropaleontological analyses from 2.8 m below to 1.5 m above the K/Pg boundary at the Izeh section. The section was sampled at 5, 10, 15 cm intervals close to the K/Pg boundary. Half of the collected samples were processed for foraminiferal study, following the standard method of Neumann (1967) and others. The samples have been soaked in water for several days and then washed through 200, 120, 63  $\mu\text{m}$  and 36  $\mu\text{m}$  sieve series with tap water and dried in an oven at 50 °C. One half of the each residue has been scanned for planktonic foraminifera species; the distribution interval of each recognized species is specified. For the semi-quantitative analyses, the planktonic foraminiferal assemblages have been counted in representative splits in the size fraction larger than 63  $\mu\text{m}$  using a microsplitter in order to obtain, nearly 300 specimens from each sample (see Table 1). Additional foraminiferal specimens are selected for scanning electron microscopy (SEM, see Figs. 5–7). The rest of the same samples were processed for palynostratigraphy following the standard palynological technique described in Wood et al. (1996). After HCl and HF treatment, the residues were sieved on 20  $\mu\text{m}$  filters. Heavy liquid separation (using  $\text{ZnCl}_2$ ) was carried out on all samples, and five slides were prepared from each sample. At least three slides per sample were scanned until approximately 200 specimens (including debris) are identified and counted into larger than 20  $\mu\text{m}$  sized fraction, as listed in Table 2.



**Fig. 1.** Geographic (A, B) and palaeogeographic maps (E\*) location of the Izeh Section (B, SW Iran) and panoramic (C) and detailed (D) outcrop photos the boundary.

**Fig. 1.** Localisation de la coupe d'Izeh (Sud-Ouest de l'Iran) sur les cartes géographique (A, B) et paléogéographique (E\*), photos panoramique (C) et de détail (D) de l'affleurement de la limite Crétacé/Paléogène.

The palaeogeographic map is after *Denham and Scotese (1987)* and *Scotese, 2001*.

**Table 1**

Relative abundance of planktonic foraminiferal species in the Izeh section.

**Tableau 1**

Abondance relative des espèces de foraminifères planctoniques dans la coupe d'Izeh.

	Gu- 113	Gu- 114	Gu- KT-01	Gu- KT-02	Gu- KT-03	Gu- KT-04	Gu- KT-05	Gu- KT-06	Gu- KT-07	Gu- KT-08	Gu- KT-09	Gu- KT-10	Gu- KT-11
<i>A. mayaroensis</i>	1	1	1	0	1	0	0	0	1	1	0	1	1
ABATHOMPHALUS	1	1	1	0	1	0	0	0	1	1	0	1	1
<i>A. blowi</i>	5	3	2	3	5	6	3	3	5	6	4	3	5
<i>A. cretacea</i>	1	1	2	1	1	1	2	3	3	2	1	1	2
ARCHAEOGLOBIGERINA	6	4	4	4	6	7	5	6	8	8	5	4	7
<i>C. midwayensis</i>	0	0	0	0	0	0	0	0	0	0	0	0	0
CHILOGUEMBELINA	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>C. contusa</i>	1	1	1	1	1	1	0	1	0	0	1	0	0
CONTUSOTRUNCANA	1	1	1	1	1	1	0	1	0	0	1	0	0
<i>E. fringa</i>	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>E. eobulloides</i>	0	0	0	0	0	0	0	0	0	0	0	0	0
EOGLOBIGERINA	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>G. compressa</i>	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>G. imitata</i>	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>G. planocompressa</i>	0	0	0	0	0	0	0	0	0	0	0	0	0
GLOBANOMALINA	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>G. daubjergensis</i>	0	0	0	0	0	0	0	0	0	0	0	0	0
GLOBOCONUSA	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>G. aegyptiaca</i>	3	2	2	1	1	1	2	1	1	2	1	2	1
<i>G. arca</i>	1	1	1	1	1	2	1	1	1	1	2	1	1
<i>G. falsostuarti</i>	1	1	1	1	1	1	1	1	1	1	1	1	1
<i>G. mariei</i>	1	1	1	2	1	1	1	2	1	1	1	1	1
GLOBOTRUNCANA	6	5	5	5	4	5	5	5	4	5	5	5	4
<i>G. havanensis</i>	5	1	2	3	1	4	1	4	1	1	1	1	0
<i>G. petaloidea</i>	4	5	6	6	9	10	9	8	6	6	4	7	5
GLOBOTRUNCANELLA	9	6	8	9	10	14	10	12	7	7	5	8	5
<i>G. conica</i>	1	1	1	1	1	1	1	1	1	1	1	1	1
<i>G. dupeublei</i>	1	1	1	1	1	1	1	1	1	1	1	1	1
<i>G. subspinosa</i>	1	1	1	1	1	1	1	1	1	1	1	1	1
<i>G. stuarti</i>	1	1	1	1	1	1	1	1	1	1	1	1	1
<i>G. stuartiformis</i>	0	0	1	1	1	1	1	1	1	1	1	1	1
GLOBOTRUNCANITA	4	4	5	5	5	5	5	5	5	5	5	5	5
<i>G. irregularis</i>	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>G. cretacea</i>	2	3	1	1	0	0	3	2	2	3	0	0	1
<i>G. trifolia</i>	0	0	0	0	0	0	0	0	0	0	0	0	0
GUEMBELITRIA	2	3	1	1	0	0	3	2	2	3	0	1	1
<i>H. holmdelensis</i>	5	6	9	9	10	17	9	13	10	10	8	13	12
<i>H. monmouthensis</i>	5	9	7	4	3	5	9	3	6	3	5	3	6
HEDBERGELLA	10	15	16	13	13	22	18	16	16	13	13	16	18
<i>H. dentata</i>	10	11	10	5	9	10	10	8	13	12	10	8	14
<i>H. globulosa</i>	73	65	59	38	39	47	41	53	55	50	36	51	48
<i>H. labellosa</i>	9	7	10	6	9	9	14	10	10	13	8	10	6
<i>H. navarroensis</i>	13	12	20	18	17	22	30	21	26	19	22	17	17
<i>H. pulchra</i>	5	9	1	4	9	7	7	13	3	6	3	6	3
<i>H. punctulata</i>	3	1	2	1	3	3	1	1	1	2	3	1	3
<i>H. striata</i>	22	27	14	12	11	10	10	8	12	13	17	11	11
HETEROHELIX	135	132	116	84	97	108	113	114	116	115	99	104	102
<i>P. pseudobulloides</i>	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>P. varianta</i>	0	0	0	0	0	0	0	0	0	0	0	0	0
PARASUBBOTINA	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Pv. eugubina</i>	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>Pv. longiapertura</i>	0	0	0	0	0	0	0	0	0	0	0	0	0
PARVULARUGOGLOBIGERINA	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>P. brazoensis</i>	1	1	1	1	1	1	2	3	2	2	0	1	1
<i>P. carseyae</i>	1	3	3	1	1	2	3	1	1	1	1	2	1
PLANOGLOBULINA	2	4	4	2	2	3	5	4	3	3	1	3	2
<i>P. hantkeninoides</i>	0	0	0	4	4	2	1	3	4	5	3	6	4
<i>P. reicheli</i>	9	8	6	8	6	9	10	6	9	7	10	8	10
PLUMMERITA	9	8	6	12	10	11	11	9	13	12	13	14	14
<i>P. pseudoinconstans</i>	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>P. inconstans</i>	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>P. taurica</i>	0	0	0	0	0	0	0	0	0	0	0	0	0
PRAEMURICA	0	0	0	0	0	0	0	0	0	0	0	0	0
<i>P. costulata</i>	22	27	21	24	30	26	21	25	26	30	27	25	30
<i>P. excolata</i>	5	9	10	13	15	14	11	11	14	13	18	9	18
<i>P. hariaensis</i>	3	3	4	1	2	2	2	3	3	3	2	1	3
<i>P. palpebra</i>	0	0	0	1	1	2	1	1	1	1	1	1	2





Table 1 (Continued)

	Gu- KT-12	Gu- KT-13	Gu- KT-14	Gu- KT-15	Gu- KT-16	Gu- KT-17	Gu- KT-18	Gu- KT-19	Gu- KT-20	Gu- 116	Gu- 117	Gu- 118
HETEROHELIX	143	116	115	55	54	61	75	69	68	83	12	4
<i>P. pseudobulloides</i>	0	0	0	0	0	0	0	0	0	0	0	26
<i>P. varianta</i>	0	0	0	0	0	0	0	0	0	0	5	3
PARASUBBOTINA	0	0	0	0	0	0	0	0	0	0	5	29
<i>Pv. eugubina</i>	0	0	0	0	0	47	57	52	58	60	41	0
<i>Pv. longiapertura</i>	0	0	0	0	6	12	11	7	0	0	0	0
PARVULARUGOGLOBIGERINA	0	0	0	0	6	59	68	59	58	60	41	0
<i>P. brazoensis</i>	3	0	1	0	0	0	0	0	0	0	0	0
<i>P. carseyae</i>	1	2	1	0	0	0	0	0	0	0	0	0
PLANOGLOBULINA	4	2	2	0	0	0	0	0	0	0	0	0
<i>P. hantkeninoides</i>	3	6	8	0	0	0	0	0	0	0	0	0
<i>P. reicheli</i>	9	5	3	0	0	0	0	0	0	0	0	0
PLUMMERITA	12	11	11	0	0	0	0	0	0	0	0	0
<i>P. pseudoinconstans</i>	0	0	0	0	0	0	0	0	0	0	9	14
<i>P. inconstans</i>	0	0	0	0	0	0	0	0	0	0	0	15
<i>P. taurica</i>	0	0	0	0	0	3	3	2	3	2	15	17
PRAEMURICA	0	0	0	0	0	3	3	2	3	2	24	46
<i>P. costulata</i>	21	30	29	29	35	10	13	15	17	12	0	0
<i>P. excolata</i>	8	14	7	0	0	0	0	0	0	0	0	0
<i>P. hariaensis</i>	3	1	3	0	0	0	0	0	0	0	0	0
<i>P. palpebra</i>	1	1	1	0	0	0	0	0	0	0	0	0
PSEUDOGUMBELINA	33	46	40	29	35	10	13	15	17	12	0	0
<i>P. elegans</i>	12	18	17	0	0	0	0	0	0	0	0	0
<i>P. intermedia</i>	0	0	0	0	0	0	0	0	0	0	0	0
PSEUDOTEXTULARIA	12	18	17	0	0	0	0	0	0	0	0	0
<i>R. fruticosa</i>	1	1	1	0	0	0	0	0	0	0	0	0
<i>R. powelli</i>	1	1	1	0	0	0	0	0	0	0	0	0
RACEMIGUEMBELINA	2	2	2	0	0	0	0	0	0	0	0	0
<i>R. hexacamerata</i>	3	2	1	0	0	0	0	0	0	0	0	0
<i>R. macrocephala</i>	2	1	3	0	0	0	0	0	0	0	0	0
<i>R. milamensis</i>	17	8	10	0	0	0	0	0	0	0	0	0
<i>R. rugosa</i>	3	3	3	0	0	0	0	0	0	0	0	0
RUGOGLOBIGERINA	25	14	17	0	0	0	0	0	0	0	0	0
<i>S. trivialis</i>	0	0	0	0	0	0	0	0	0	0	2	3
<i>S. triloculinoides</i>	0	0	0	0	0	0	0	0	0	0	0	26
SUBBUTINA	0	0	0	0	0	0	0	0	0	0	2	29
<i>T. scotti</i>	4	8	3	0	0	0	0	0	0	0	0	0
TRINITELLA	4	8	3	0	0	0	0	0	0	0	0	0
<i>W. hornerstowensis</i>	0	0	0	1	2	1	0	3	2	1	0	4
WOODRINGINA	0	0	0	1	2	1	0	3	2	1	0	4
SUM	272	256	244	204	209	204	225	228	231	260	246	265

#### 4. Biostratigraphy

Several biostratigraphic subdivisions (zonations) based on planktonic foraminifera for the Cretaceous–Paleogene transition interval, have been proposed (e.g., Berggren, 1972; Berggren and Miller, 1988; Berggren and Pearson, 2005; Berggren et al., 1985; Blow, 1969, 1979; Bolli, 1966; Canudo et al., 1991; Herm et al., 1981; Keller, 1988; Molina et al., 1996; Smit, 1982; Toumarkine and Luterbacher, 1985).

The present study is based on the zonations of Zaghbib-Turki et al. (2000), Arenillas et al. (2004), Gallala et al. (2009), and Gallala and Zaghbib-Turki (2010), established for middle and lower latitudes.

Fig. 2 compares some of the more frequently used biozonations for the Maastrichtian–Danian transition. Four main planktonic foraminiferal zones are recognized in the studied section:

- *Abathomphalus mayaroensis* Zone (including the *Plummerita hantkeninoides* Subzone);

- *Guembelitra cretacea* Zone (including the *Hedbergella holmdelensis* Subzone and the *Parvularugoglobigerina longiapertura* Subzone);
- *Parvularugoglobigerina eugubina* Zone;
- *Parasubbotina pseudobulloides* Zone.

The planktonic foraminiferal assemblages in the Izeh section are very similar to those of the well-known Tunisian section at El Kef (i.e., the GSSP for the K/Pg boundary).

On the other hand, age assignments of the dinoflagellate assemblages reported here are based on comparison with worldwide ranges of individual taxon with emphasis on low to mid latitude records (Williams et al., 2004). It was done in combination with a detailed planktonic foraminiferal stratigraphy from the Izeh section. Several local and worldwide biostratigraphical biozonations based on dinoflagellate cysts have been proposed (Brinkhuis and Zachariasse, 1988; Brinkhuis et al., 1998; Costa and Manum, 1988; Lentin and Williams, 1980; Mao and Mohr, 1992; Powell, 1992; Williams and Bujak, 1985; Williams et al., 1990).





Table 2 (Continued)

Dinoflagellates species	Gu-KP-13	Gu-KP-14	Gu-KP-15	Gu-KP-16	Gu-KP-17	Gu-KP-18	Gu-KP-19	Gu-KP-20	Gu-116	Gu-117	Gu-118
<i>Achomosphaera neptunii</i>	1	2	0	1	0	2	1	0	2	1	3
<i>A. ramulifera</i>	0	0	0	0	0	0	0	1	0	0	1
<i>A. regiensis</i>	0	0	0	0	0	0	0	0	0	1	1
<i>A. sagena</i>	0	0	2	0	0	1	0	2	1	0	0
<i>Alisocysta reticulata</i>	0	0	1	1	2	5	4	2	3	1	2
<i>Alisogymnium euclaense</i>	0	0	0	1	0	0	2	0	0	2	1
<i>Alterbidinium acutulium</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Areoligera coronate</i>	0	0	0	0	0	0	1	0	0	2	0
<i>Cannosphaeropsis utinensis</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Cannosphaeropsis passio</i>	0	0	0	0	0	0	0	0	0	0	1
<i>Carpatella cornuta</i>	1	0	0	1	0	0	0	0	1	1	0
<i>Cerodinium deibelii</i>	1	0	2	1	0	0	3	0	2	1	1
<i>Cerodinium striatumb</i>	0	0	0	0	0	0	2	0	1	0	0
<i>Cerodinium pannuceom</i>	0	2	0	0	0	0	0	0	1	0	0
<i>Cerodinium wardenense</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Cordosphaeridium fibrospinosum</i>	0	0	0	0	0	0	0	0	0	0	2
<i>Damassadinium californicum</i>	0	0	0	0	0	0	0	0	3	2	4
<i>Dapsilidinium cf. pastilum</i>	0	0	0	0	0	0	0	0	0	0	3
<i>Deflandrea coronate</i>	0	0	0	0	0	0	0	0	0	1	0
<i>Deflandrea oebisfeldensis</i>	0	2	0	0	0	0	0	0	1	0	0
<i>Deflandrea phosphoritica</i>	0	0	0	0	0	0	0	0	0	0	1
<i>Dinogymnium acuminatum</i>	3	0	0	0	0	0	2	0	0	1	2
<i>Dinogymnium longicorne</i>	1	0	0	2	0	0	1	0	0	0	1
<i>Glaphyrocysta perforata</i>	1	2	0	0	0	0	1	0	3	2	0
<i>Glaphyrocysta assamica</i>	2	5	0	1	0	0	0	0	0	3	7
<i>Godavariella venkatachala</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Hafniasphaera fluens</i>	0	0	0	1	0	0	0	0	0	2	0
<i>Heterosphaeridium difficile</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Hystrichodinium pulchrum</i>	0	1	0	0	0	0	3	0	0	1	0
<i>Hystrichokolpoma bulbosum</i>	0	2	0	0	0	0	0	0	3	0	1
<i>Hystrichokolpoma proprium</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Hystrichosphaeridium tubiferum</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Impagidinium pentahedrias</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Isabelidinium cretaceum</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Kleithriasphaeridium loffrense</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Lacrymodinium warrenii</i>	0	0	0	0	0	0	2	0	1	0	0
<i>Lanternosphaeridium reinhardtii</i>	0	1	0	1	0	0	0	0	2	0	0
<i>Manumiella druggii</i>	0	3	0	2	0	0	1	0	0	1	1
<i>Manumiella seelandica</i>	0	2	0	1	0	1	1	0	0	2	1
<i>Operculodinium centrocarpum</i>	0	0	0	0	0	0	0	0	0	0	1
<i>Operculodinium divergence</i>	0	0	0	0	0	0	0	0	0	0	2
<i>Palaeocystodinium australinum</i>	0	0	0	1	0	0	2	0	0	1	0
<i>Palaeocystodinium golzowense</i>	0	0	0	0	0	0	0	0	0	0	1
<i>Palaeocystodinium lidiae</i>	1	0	0	0	0	0	0	0	0	0	0
<i>Palaeoperidinium pyrophorum</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Phelodinium magnificum</i>	0	0	1	2	0	1	0	0	3	2	1
<i>Phelodinium tricuspis</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Satyrodinium haumuriense</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Senoniasphaera inornata</i>	0	0	0	1	0	0	1	0	1	1	0
<i>Spinidinium densispinatum</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Spiniferites ancoriferus</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Spiniferites cornutus</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Spiniferites ovatus</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Spiniferites porosus</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Spiniferites ramosus</i>	6	0	4	5	0	3	0	0	7	9	7
<i>Tanyosphaeridium xanthiopyxides</i>	0	0	0	0	0	0	0	0	0	0	0
<i>Tectatodinium rugulatum</i>	0	0	0	0	0	0	0	0	0	1	0
<i>Ynezidinium pentahedrias</i>	0	0	0	0	0	0	0	0	0	0	2
Total of 58 species from 36 genera											

Especially a widely accepted worldwide standard zonation has been proposed by Brinkhuis and Powell, 2004 in Gradstein et al., 2004 (see also Geologic Time Scale, therein). The microfossils from the Izeh section that we have recognized include 61 planktonic foraminiferal species and 57 dinocyst taxa. The important planktonic foraminiferal and dinocyst taxa are illustrated on Figs. 4–7.

#### 4.1. Planktonic foraminifera

##### 4.1.1. *Abathomphalus mayaroensis* Total Range Zone

The *Abathomphalus mayaroensis* Biozone, as defined by Bolli (1966), is the stratigraphic interval represented by the total range of the nominate index species. It characterizes the Upper Maastrichtian in low latitude regions as well as in the Tethyan palaeogeographic realm. The Upper

Age (Ma)	Period System Stage	Chrono-stratigraphy	Polarity	This Study	Arz and Molina, 2001 Arenillas et al., 2004 Gallala et al., 2009	Zaghib-Turki et al., 2000	Berggren et al., 1995 Berggren & Pearson 2005	Keller 1988; Keller et al., 1995	Smit, 1982; Smit & Romein, 1985	Bolli, 1966; Toumarkine & Luterbacher 1985
63	Paleogene Paleocene	Early Danian	C28n <sub>1</sub> - C28n <sub>2</sub>	<i>P. pseudobulloides</i> <i>Pv. eugubina</i> <i>Pv. longiper.</i> <i>P. hantkeninoides</i> <i>A. mayaroensis</i> , <i>P. hantken.</i> <i>G. gansseri</i>	<i>Subbotina triloculinoidea</i> <i>Eoglobigerina trivialis</i> <i>E. simplicissima</i> <i>Pv. sabina</i> <i>Pv. longiapertura</i> <i>H. holmdelensis</i>	<i>Parasubbotina pseudobulloides</i> <i>Pv. eugubina</i> <i>Gc. conusa</i>	<i>S. triloculinoidea</i> <i>Gl. compressa</i> <i>P. eugubina</i> - <i>S. triloculinoidea</i> <i>Pv. eugubina</i> <i>Gt. cretacea</i>	<i>P1b</i> <i>P1a</i> <i>P1a</i> <i>P1a(1)</i> <i>P0</i>	<i>P1b</i> <i>P1c</i> <i>P1c(1)</i> <i>P1c(2)</i> <i>P0</i>	<i>Globigerina pseudobulloides</i> <i>Globigerina eugubina</i>
64										
65	Cretaceous Late	Late Maastrichtian	C30	<i>Abathomphalus mayaroensis</i> <i>R. hantkeninoides</i> <i>R. fructifera</i>	<i>Psg. hantkeninoides</i> <i>P. hantkeninoides</i>	<i>Abathomphalus mayaroensis</i> <i>P. hantken.</i>	<i>Abathomphalus mayaroensis</i> <i>Abathomphalus mayaroensis</i>	<i>Abathomphalus mayaroensis</i> <i>Abathomphalus mayaroensis</i> <i>P. hantken.</i>	<i>Abathomphalus mayaroensis</i> <i>Abathomphalus mayaroensis</i> <i>P0</i>	<i>Abathomphalus mayaroensis</i> <i>Abathomphalus mayaroensis</i>
66										
67										

Fig. 2. Correlation between different proposed planktonic foraminiferal biozonations schemes for the Late Maastrichtian–Early Danian and the main recorded bioevents in the Izeh section (Smit and Romein, 1985).

Fig. 2. Corrélation entre les différentes biozonations basées sur les foraminifères planctoniques du Maastrichtien supérieur/Danien inférieur et les principaux bioévénements enregistrés dans la coupe d'Izeh.

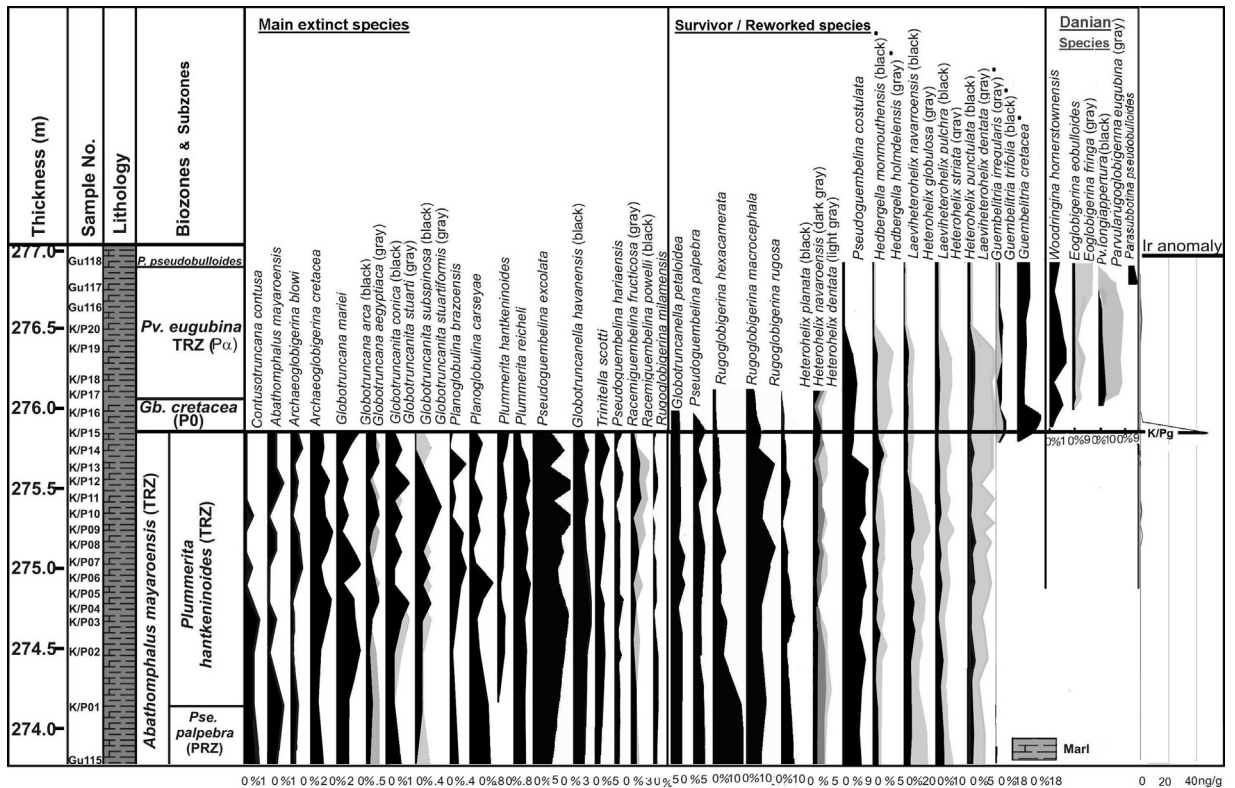


Fig. 3. Relative abundance of planktonic foraminifera species at K/Pg boundary in the Izeh section (species marked by filled circle are the most plausible survivors).

Fig. 3. Abondance relative des espèces de foraminifères planctoniques dans la coupe d'Izeh (les espèces marquées par un cercle plein représentent les plus plausibles survivantes).

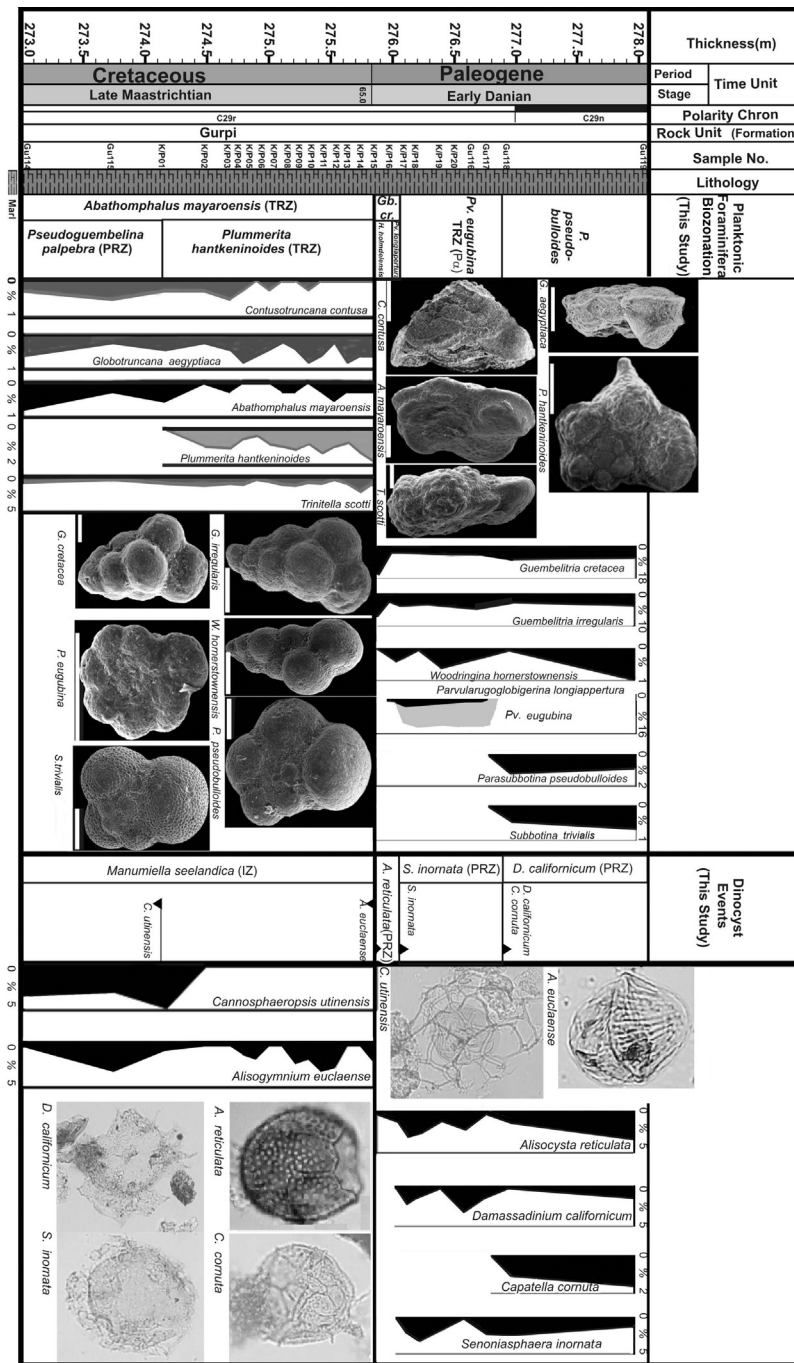
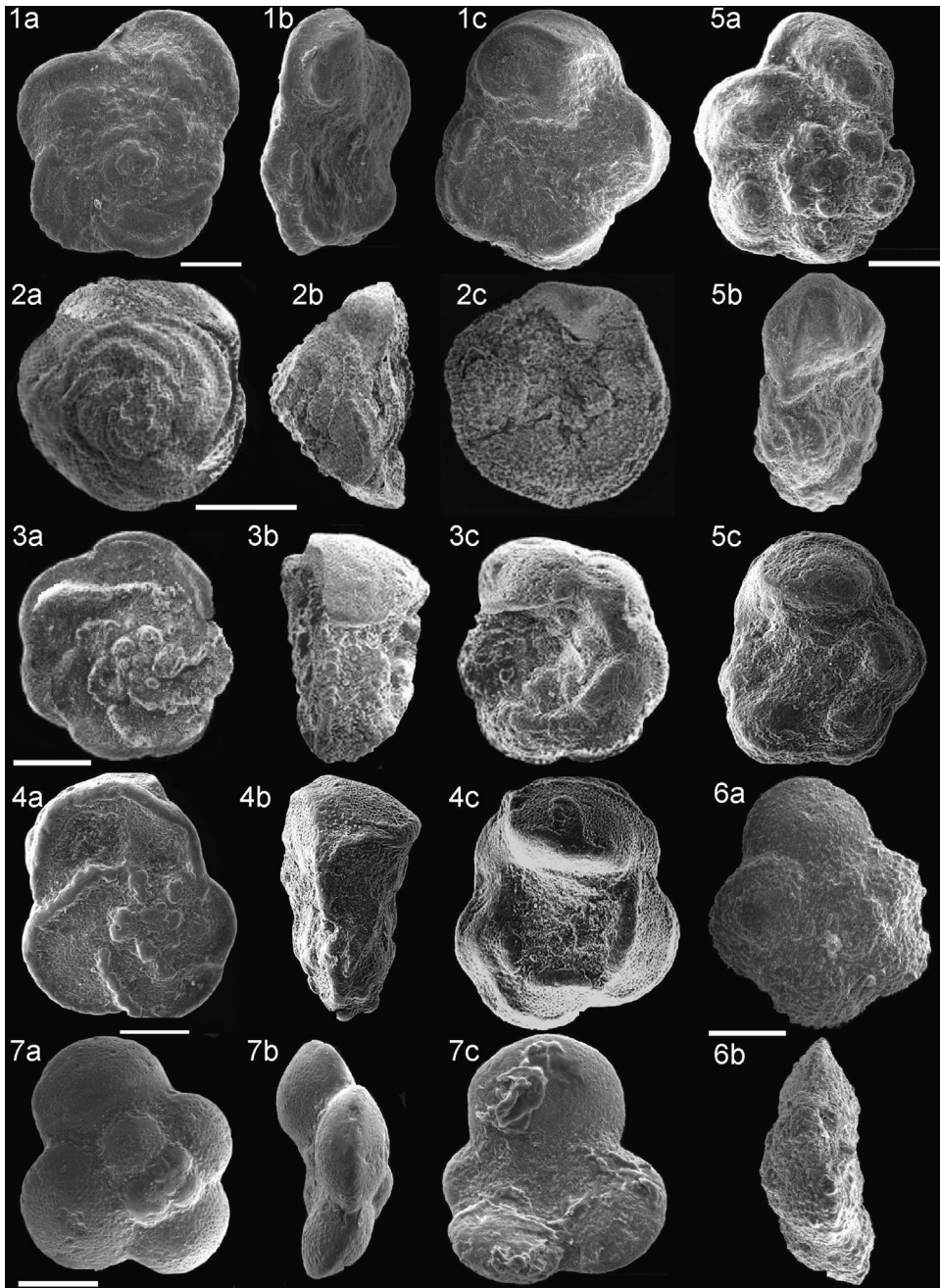


Fig. 4. Relative abundance of the key planktonic foraminifera and dinocyst elements across the K/Pg boundary in the Izeh section.  
 Fig. 4. Abondance relative des principaux foraminifères planctoniques et dinocystes dans l'intervalle du passage K/Pg de la coupe d'Izeh.

boundary of the zone coincides with the K/Pg boundary in many sections from diverse areas (e.g., Berggren, 1969; Blow, 1979; Bolli, 1957, 1966; Caron, 1985; Herm et al., 1981; Luterbacher and Premoli Silva, 1964; Smit, 1982). However, it has been shown that *A. mayaroensis* is very sporadic in low latitude regions, e.g., in Blake Nose (Huber et al., 2002) and Demerara Rise (MacLeod et al., 2007) and it may become extinct prior to the K/Pg boundary

(Abramovich et al., 1998; Keller, 1988, 1989a; Molina et al., 1998). There, the supposed absence of *A. mayaroensis* means its scarcity. Based on a very intensive study of the Uppermost Maastrichtian samples of the Ellès section, Zaghbib-Turki et al. (2000, 2001) could prove the presence of *A. mayaroensis*, although it may be very rare, up to the top of the Maastrichtian. The same observation was confirmed in the El Kef section and Bidart section (Gallala, 2010;



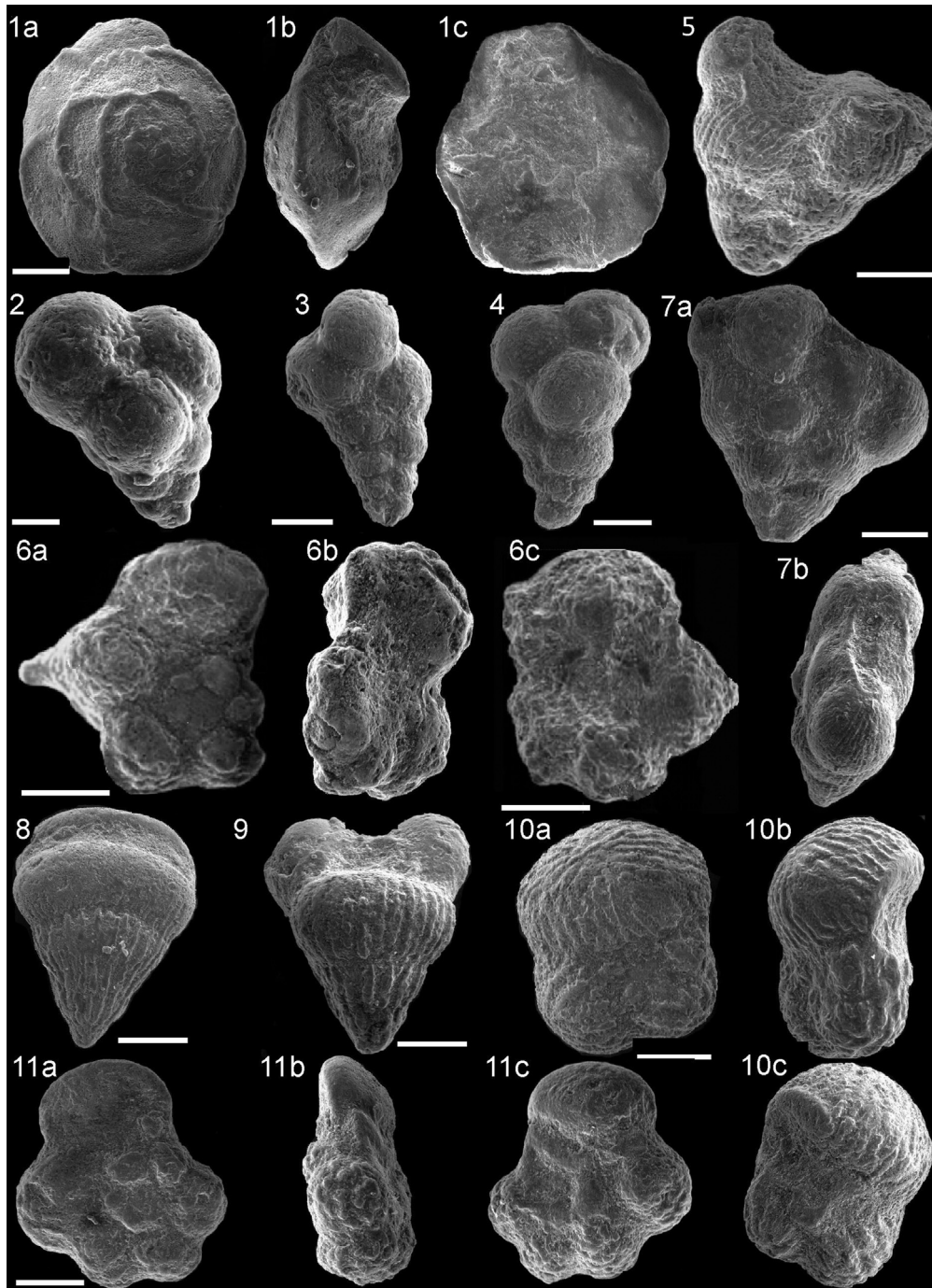


**Fig. 5.** 1a–c – *Abathomphalus mayaroensis* (Bolli), Gu-92; 2a–c – *Contusotruncana contusa* (Cushman), Gu-72; 3a–c – *Gansserina gansseri* (Bolli), Gu-40; 4a–c – *Globotruncana aegyptiaca* (Nakkady), Gu-19; 5a–c – *Globotruncana bulloides* Vogler, Gu-5; 6a–b – *Globotruncanella havanensis* (Voorwijk), Gu-3; 7a–c – *Globotruncanella petaloidea* (Gandolfi), Gu-39. a = spiral view (in trocho-, plano and pseudospiral species) and/or lateral view (in bi-, tri- and multiserial species); b = edge view; c = umbilical view. All scale bars = 100  $\mu$ m.

**Fig. 5.** 1a–c – *Abathomphalus mayaroensis* (Bolli), Gu-92; 2a–c – *Contusotruncana contusa*, (Cushman), Gu-72, 3a–c – *Gansserina gansseri* (Bolli), Gu-40; 4a–c – *Globotruncana aegyptiaca* (Nakkady), Gu-19, 5a–c – *Globotruncana bulloides* Vogler, Gu-5; 6a–b – *Globotruncanella havanensis* (Voorwijk), Gu-3; 7a–c – *Globotruncanella petaloidea* (Gandolfi), Gu-39. a = vue spirale (chez les espèces à test trocho-, plano et pseudospiralé) et/ou vue laterale (chez les espèces à test bi-, tri- et multiserialé); b = vue de profil; c = vue ombilicale. Toutes les barre d'échelle représentent = 100  $\mu$ m.

Gallala and Zaghbib-Turki, 2010; Gallala et al., 2009). However, *A. mayaroensis* is absent or sporadic in high latitudes (Blow, 1979; Huber, 1992; Keller, 1989a,b) and it is absolutely absent in relatively shallow-water deposits, due to the unfavorable environmental conditions (Brinkhuis and

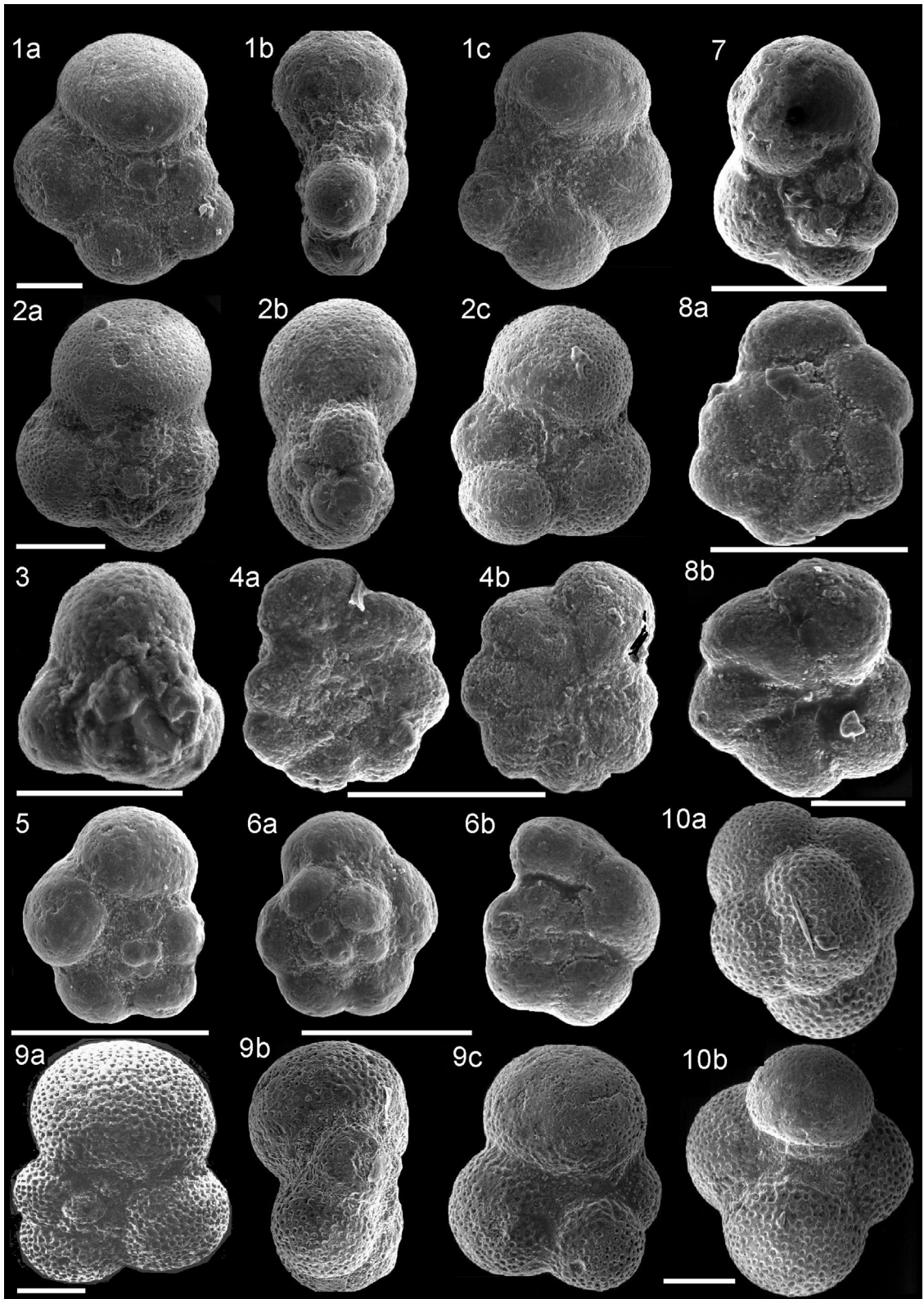
Zachariasse, 1988). Thus, in the absence of *A. mayaroensis*, *Plummerita hantkeninoides* or *Pseudoguembelina hariaensis* can be used to characterize the Uppermost Maastrichtian (defined by the total range of the nominate taxa; e.g., Gallala and Zaghbib-Turki, 2010; Gallala et al., 2009;



**Fig. 6.** 1a–c – *Globotruncanita stuarti* (de Lapparent), Gu-68; 2 – *Guembelitra cretacea* (Cushman), Gu-114; 3 – *Guembelitra danica* (Hofker), Gu-116; 4 – *Guembelitra irregularis* (Morozova), Gu-116; 5 – *Planoglobulina carseyae* (Plummer), Gu-113; 6a–c – *Plummerita hantkeninoides* (Brönnimann), Gu-115; 7a–b – *Pseudoguembelina hariaensis* (Nederbragt), Gu-94; 8 – *Pseudotextularia elegans* (Rzehak), Gu-112; 9 – *Pseudotextularia intermedia* (de Klasz), Gu-84; 10a–c – *Rugoglobigerina macrocephala* (Brönnimann), Gu-42; 10a–c – *Tritinella scotti* (Brönnimann), Gu-92. a = spiral view (in trocho-, plano and pseudospiral species) and/or lateral view (in bi-, tri- and multiserial species); b = edge view; c = umbilical view. All scale bars = 100  $\mu\text{m}$ .

**Fig. 6.** 1a–c – *Globotruncanita stuarti* (de Lapparent), Gu-68; 2 – *Guembelitra cretacea* (Cushman), Gu-114; 3 – *Guembelitra Danica* (Hofker), Gu-116; 4 – *Guembelitra irregularis* (Morozova), Gu-116; 5 – *Planoglobulina carseyae* (Plummer), Gu-113; 6a–c – *Plummerita, hantkeninoides* (Brönnimann), Gu-115; 7a–b – *Pseudoguembelina hariaensis* (Nederbragt), Gu-94; 8 – *Pseudotextularia elegans* (Rzehak), Gu-112; 9 – *Pseudotextularia intermedia* (de Klasz), Gu-84, 10a–c – *Rugoglobigerina macrocephala* (Brönnimann), Gu-42; 10a–c – *Tritinella Scotti*, (Brönnimann), Gu-92. a = vue spirale (chez les espèces à test trocho-, plano et pseudospiralé) et/ou vue laterale (chez les espèces à test bi-, tri- et multisérié); b = vue de profil; c = vue ombilicale. Toutes les barre d'échelle représentent = 100  $\mu\text{m}$ .





Ion, 1993; Keller et al., 1995; Molina et al., 1996, 1998; Pardo et al., 1996). Detailed studies of the heterohelicids (Arenillas et al., 2004; Arz and Molina, 2001; Bernaola and Monechi, 2007; Gallala, 2010; Gallala and Zaghbib-Turki, 2010; Nederbragt, 1991; Tantawy et al., 2001) in Upper Maastrichtian outcrop sedimentary successions in the Tethyan Realm, indicate that within *A. mayaroensis* TRZ two successive subzones can be distinguished: the *Racemoguembelina fruticosa* Subzone and the *Pseudoguembelina hariaensis* Subzone (Figs. 2, 3 and 5).

In the Izeh section both the zonal and subzonal index species are present in all the Maastrichtian samples investigated in this study. Therefore, the *P. hantkeninoides* Subzone is used to characterize the Uppermost Maastrichtian part of the *Abathomphalus mayaroensis* Biozone. *A. mayaroensis* is present but rare in all the Maastrichtian samples below the K/Pg boundary, *P. hantkeninoides* and *Psg. hariaensis* are slightly more frequent in the interval samples Gu-K/P02–Gu-K/P14 (collected between ca 274.5 and 275.82 m from the base of the Gurpi Formation).

#### 4.1.2. *Guembelitra cretacea* Partial Range Zone (P0)

This biozone was originally defined by Smit (1982) as the partial range of *Gt. cretacea* from the mass extinction of most of the Cretaceous species to the first appearance of *Globigerina minutula*. It was emended by Keller (1988) as the interval from the last occurrence of *P. hantkeninoides* to the first occurrence of *Parvularugoglobigerina eugubina*. It is equivalent of Biozone P0 of Berggren et al. (1995). The relevant planktonic foraminiferal assemblage (Figs. 3 and 6) contains a large number of species found in the Latest Cretaceous strata (e.g., *Hedbergella* spp., *Globigerinelloides* spp. and *Heterohelix* spp.). Nevertheless, the specimens of these possible survivors from these Cretaceous taxa are all tiny, like as those of the species, which appear in the basal Danian (e.g., *Eoglobigerina fringa*, *E. eobulloides* and *Woodringina hornerstownensis*). In this way, Huber et al. (2002), using carbon isotope, concluded that similar basal Danian specimens from the North Atlantic are reworked. The authors noted that in the basal Danian most of the Cretaceous taxa above the K/Pg boundary have  $\delta^{13}\text{C}$  values identical to those of Maastrichtian taxa and in contrast the true basal Danian co-occurring specimens have distinctive lighter  $\delta^{13}\text{C}$  values.

At the Izeh section, the interval corresponding to the basal Danian *Guembelitra cretacea* Zone is 25-cm thick. It consists of gray clayey shale and marl rich in organic matter. It contains common Maastrichtian species, which are generally fragmented, partly dissolved and/or not filled by iron oxide. These altered specimens are considered to be

reworked. The first specimens of Danian taxa are small and very rare. In the Izeh section, the first occurrence of *Parvularugoglobigerina longiapertura* is observed in Gu-K/P16 sample (at 275.95 m from the base of the Gurpi Formation). It allows the *Guembelitra cretacea* Zone to be subdivided into two biosubzones: *Hedbergella holmdelensis* Subzone and *Parvularugoglobigerina longiapertura* Subzone. In this fauna, the individuals are rare and tiny in size as at the El Kef section (Zaghbib-Turki observations) and the Bidart section (Gallala and Zaghbib-Turki, 2010).

#### 4.1.3. *Parvularugoglobigerina eugubina* Total Range Zone

This Early Danian TRZ is defined originally by Luterbacher and Premoli Silva (1964) as the total range of the nominate species. The base of this zone is defined by the lowermost occurrence (LO) of *Pv. eugubina*. Its top is defined by the highest occurrence (HO) of the nominate taxon. The P $\alpha$  biozone of Berggren and Miller (1988) includes the *Parvularugoglobigerina longiapertura* Subzone and the *Parvularugoglobigerina eugubina* Zone defined herein.

The lowest and highest occurrences of *Pv. eugubina* at the Izeh section are observed respectively at about 276.10 m and 276.95 m from the base of the Gurpi Formation. *Pv. eugubina* differs from *Pv. longiapertura*. Thus, *Pv. eugubina* has less compressed test, with less chambers in the last whorl and less pronounced elongate comma-shaped primary aperture. Throughout the *Pv. eugubina* Zone stratigraphic interval, this marker species becomes the most frequent fossil. It shows a considerable variability in size, number of chambers, and height of spire. In the lower part of the zone, the planktonic foraminiferal assemblage still contains small and unkeeled Late Cretaceous forms, especially heterohelicids, globigerinelloids and hedbergellids. In the *Parvularugoglobigerina eugubina* biozone, *Pv. longiapertura* specimens become progressively larger in size.

In the Izeh section, the interval attributed to the *Pv. eugubina* Zone is 85 cm thick and consists of bluish gray clayey limestone rich in organic material (Figs. 3 and 7).

#### 4.1.4. *Parasubbotina pseudobulloides* Partial Range Zone

Leonov and Alimarina (1961) introduced *Globorotalia* (*Turborotalia*) *pseudobulloides*-*Globorotalia daubjergensis* Zone (these taxa are attributed later respectively to *Parasubbotina* and *Globoconusa*, see Olsson et al., 1999). According to Leonov and Alimarina (*idem.*), the biozone covers the stratigraphical interval between the lowest occurrence (LO) of *G. pseudobulloides* and the LO of *Globorotalia uncinata* (attributed recently to *Praemurica*). Later,

**Fig. 7.** 1a–c – *Parasubbotina pseudobulloides* (Plummer), Gu-120; 2a–c – *Parasubbotina varianta* (Subbotina), Gu-127; 3 – *Globoconusa daubjergensis* (Brönnimann), Gu-116; 4a–b – *Parvularugoglobigerina longiapertura* (Blow), Gu-116; 5 – *Praemurica pseudoconstans* (Blow), Gu-117; 6a–b – *Praemurica inconstans* (Subbotina), Gu-117; 7 – *Globanomalina planocompressa* (Shutskaia), Gu-117; 8a–b – *Parvularugoglobigerina eugubina* (Luterbacher and Premoli Silva), Gu-116; 9a–c – *Subbotina triloculinoides* (Plummer), Gu-128; 10a–b – *Subbotina trivialis* (Subbotina), Gu-118. a = spiral view (in trocho-, plano and pseudospiral species) and/or lateral view (in bi-, tri- and multiserial species); b = edge view; c = umbilical view. All scale bars = 100  $\mu\text{m}$ .

**Fig. 7.** 1a–c – *Parasubbotina pseudobulloides* (Plummer), Gu-120; 2a–c – *Parasubbotina varianta* (Subbotina), Gu-127; 3 – *Globoconusa daubjergensis* (Brönnimann), Gu-116; 4a–b – *Parvularugoglobigerina longiapertura* (Blow), Gu-116; 5 – *Praemurica pseudoconstans* (Blow), Gu-117; 6a–b – *Praemurica inconstans* (Subbotina), Gu-117; 7 – *Globanomalina planocompressa* (Shutskaia), Gu-117; 8a–b – *Parvularugoglobigerina eugubina* (Luterbacher et Premoli Silva), Gu-116; 9a–c – *Subbotina triloculinoides* (Plummer), Gu-128; 10a–b – *Subbotina trivialis* (Subbotina), Gu-118. a = vue spirale (chez les espèces à test trocho-, plano et pseudospiralé) et/ou vue laterale (chez les espèces à test bi-, tri- et multisérié); b = vue de profil; c = vue ombilicale. Toutes les barre d'échelle représentent = 100  $\mu\text{m}$ .

Bolli (1966) renamed it as the *Globigerina pseudobulloides* PRZ. Berggren and Miller (1988), as well as Berggren et al. (1995) defined the zone as the interval from the extinction datum of *Pv. eugubina* to the first appearance of *Praemurica uncinata*. This zonal concept is also adopted by Zaghbib-Turki et al. (2000). Moreover, these authors noted that the upper part of this zone is marked by the LO of “*Turborotalia*” *trinidensis* (synonym of *Praemurica inconstans*).

Finally, Arenillas et al. (2004) and Gallala and Zaghbib-Turki (2010) subdivided this zone into the *Eoglobigerina trivialis* and *Subbotina trilocolinoides* sub-zones. In the studied section, the diversity of planktonic foraminifera increases progressively with *Chiloguembelina* spp., *Woodringina* spp., *Eoglobigerina* spp., *Parasubbotina* spp., *Globanomalina* spp., and *Praemurica* spp., which are the most frequent taxa. However, their abundances remain low. The zone covers a stratigraphical interval with a thickness of 4 m. Only its lowermost part is detailed in the present work.

#### 4.2. Dinocysts

The overall aspect of the organic-walled dinoflagellate cysts (dinocysts) assemblages from the studied section is similar to that reported from low latitudes (e.g., Brinkhuis and Leereveld, 1988; Fensome et al., 1993; Habib and Miller, 1989; Hoek et al., 1996; Jain and Millepied, 1975; Masure et al., 1998; Mohamed et al., 2012; Oboh-Ikuenobe et al., 1998; Oloto, 1989; Rauscher and Doubinger, 1982; Sarkis et al., 2002; Schrank, 1987; Yepes, 2001). The most important useful dinocyst events in the section are:

- lowest occurrence of *Manumiella seelandica*, *Alisocysta reticulata*, *Senoniasphaera inornata*, *Carpatella cornuta*, *Damassadinium californicum*;
- highest occurrence of *Cannosphaeropsis utinensis* and *Alisogymnium euclaense*.

Based on dinocysts distribution and LO and HO events (Table 2, Fig. 4), at the Izeh section, the Lower Danian is marked by the simultaneous LOs of *Damassadinium californicum*, *Senoniasphaera inornata* and *Carpatella cornuta*. In summary, characteristic assemblages allow four main dinocyst zones to be distinguished. These zones may be correlated with the planktonic foraminiferal zones established herein.

The stratigraphic value of dinocysts is enhanced by calibration with the well-established planktonic foraminiferal zonation. This ideal situation has been demonstrated for the Gurpi Formation, which provides both an excellent planktonic foraminiferal chronostratigraphic framework and well recorded dinocyst bioevents (see Table 2, Fig. 4). Distribution and age assignments of the identified taxa are primarily based on the dinoflagellate cyst biozonations established from the low to middle latitudes of the Northern Hemisphere. It was done in combination with a comparison to the global ranges of individual species. Finally the resulting biozonation has been correlated with the detailed planktonic foraminiferal biozonation recorded from the section.

##### 4.2.1. *Manumiella seelandica* PRZ

This Partial Range Zone (PRZ) covers the biostratigraphical interval between the LO of *M. seelandica* at the base and the LO of *Alisocysta reticulata* and HO of *Alisogymnium euclaense* at the top. Williams et al. (2004) proposed the LO of *Alisocysta reticulata* and the HO of *Alisogymnium euclaense* as the main events of the basal Danian in the middle latitudes of the Northern Hemisphere. At the Izeh section, the relevant assemblage is diversified and it is mainly composed of the nominate zonal species. This index species is associated with *M. druggii*, *Achomosphaera neptunii*, *Alisogymnium euclaense*, *Cerodinium deibelii*, *Deflandrea oebisfeldensis*, *Dinogymnium longicorne*, *Glaphyrocysta perforate*, *Glaphyrocysta assamica*, *Hystrichodinium pulchrum*, *Hystrichokolpoma bulbosum*, *Spiniferites ramosus*. The *Manumiella seelandica* Zone is correlated with the upper part of the *A. mayaroensis* planktonic foraminiferal biozone and it is Late Maastrichtian in age. The relevant stratigraphic interval spans ca 15 m (from 260 m to 275.82 m) within the lowermost part of the dark gray marly shale of the Gurpi Formation (Table 2, Fig. 4). Only the uppermost 2.82 m of the biozone are detailed in the present work.

##### 4.2.2. *Alisocysta reticulata* PRZ

The *Alisocysta reticulata* PRZ covers the interval bounded by the LO of *A. reticulata* at the base and the LO of *Senoniasphaera inornata* at the top. The LO of *A. reticulata* indicates the base of the Danian (Williams et al., 2004). At the Izeh section, the relevant assemblage is diverse and is mainly composed of *Achomosphaera sagen*, *Cerodinium deibelii*, *Dinogymnium longicorne*, *Glaphyrocysta assamica*, *Glaphyrocysta assamica*, *Lanternosphaeridium reinhardtii*, *Palaeocystodinium australinum*, *Phelodinium magnificum*, *Senoniasphaera inornata* and *Spiniferites ramosus*. The *Alisocysta reticulata* PRZ may be correlated with the *Gt. cretacea* PRZ (PO) planktonic foraminiferal biozone defining the Earliest Danian. This stratigraphic interval deposition consists of the following 25 cm (from 275.85 m to 276.10 m) of dark gray marly shale of the Gurpi Formation (Fig. 4).

##### 4.2.3. *Senoniasphaera inornata* PRZ

This partial range zone covers the interval between the LO of *Alisocysta reticulata* and the LOs of *Damassadinium californicum* and *Carpatella cornuta*. The LO of *C. cornuta* indicates Lower Danian (Habib et al., 1996; Moshkovitz and Habib, 1993; Williams et al., 2004), as does the LO of *D. californicum* (Williams et al., 2004). At the Izeh section, the assemblage is very diverse. It is marked by the persistence of *Alisocysta reticulata*, which is associated mainly with *A. sagen*, *Cerodinium deibelii*, *Phelodinium magnificum* and *Spiniferites ramosus*. The *Senoniasphaera inornata* Zone is approximately correlated with the Early Danian planktonic foraminiferal *Parvularugoglobigerina eugubina* Zone (as defined in the present work). It spans 82 cm (from 276.10 m to 276.92 m) within the Gurpi Formation (Fig. 3).

##### 4.2.4. *Damassadinium californicum* CRZ

This concurrent range biozone corresponds to the stratigraphic interval between the LO of both *D. californicum* and *C. cornuta* taxa at the base and the LO of

*Cordosphaeridium inodes* and HO of *Dinogymnium acuminatum* at the top. Throughout this biozone the diversity of the dinocyt assemblage is very high. At least 24 palynomorphs are present, including *D. californicum*, *C. cornuta*, *Achomosphaera* spp., *Alisocysta reticulata*, *Alisogymnium euclaense*, *Cannosphaeropsis passio*, *Cerodinium deibelii*, *Cordosphaeridium fibrospinum*, *Dapsilidinium pastilum*, *Deflandrea phosphoritica*, *Dinogymnium acuminatum*, *Dinogymnium longicorne*, *Glaphyrocysta assamica*, *Operculodinium* spp., *Spiniferites ramosus*, *Ynezidinium pentahedrias*. The abundance of *D. californicum* fluctuates above Gu-118. A similar behavior of this taxon has been previously reported from the Paleocene of China, Tunisia and Israel (Brinkhuis and Leereveld, 1988; Brinkhuis and Zachariasse, 1988; Eshet et al., 1992; Sung et al., 1978). The *D. californicum* Biozone is equivalent to the *Carpatella cornuta* Zone (IZ) of Costa and Manum (1988) and Powell (1992). In the Gurpi Formation this biozone spans ~12 m (from 276.87 to 289 m). Its lower part, detailed herein, may be correlated with the Early Danian planktonic foraminiferal *Parasubbotina pseudobulloides* Subzone (Fig. 3).

### 5. Bioevents at and beyond the K/Pg boundary

In the Zagros Basin most of the Gurpi Formation represents continuous deposition in an open marine environment. The upper part of the formation indicates sedimentation in an outer shelf environment (Fig. 1E). In most of the outcrops of the Gurpi Formation in southwestern Iran, a hiatus spanning the Cretaceous/Paleocene boundary interval is observed (Ghasemi-Nejad et al., 2006; James and Wynd, 1965; Motiei, 2003; Sampo, 1969; Setudehnia, 1972, 1978; Wynd, 1965). However, the Izeh section exhibits a continuous and well-preserved transition across the boundary.

The K/Pg boundary is exposed at 275.82 m from the base of the Gurpi Formation. It is marked and overlain by a few millimeters thick rust-colored ferruginous layer. This layer composed of reddish hematitic and goethitic laminae containing very low percentage of CaCO<sub>3</sub>. It is marked by an abnormal high values of Ir (an abrupt enrichment from 0 to 4.3 ppb: unpublished data) and Ni (from 0 to 0.24 ppm, unpublished data).

Therefore, all the main criteria defining the K/Pg boundary are recorded at the Izeh section, including the mass extinction of planktonic foraminifera and spike in iridium (see Figs. 3 and 4). The mass extinctions affected particular species of planktonic foraminifera, and especially the keeled globotruncanids and large heterohelicids like at the other sections showing a complete and continuous Cretaceous–Paleogene transition interval. However, the Cretaceous species crossing the K/Pg boundary are commonly unkeeled globotruncanids, hedbergellids, globigerinelloids and small heterohelicids. Among these latter, we note that:

- the species may be identical or different from section to other. To ensure that such species is reworked or it is a real survivor, it needs eventually to realize stable isotopic analysis on each individual specimen of these species and

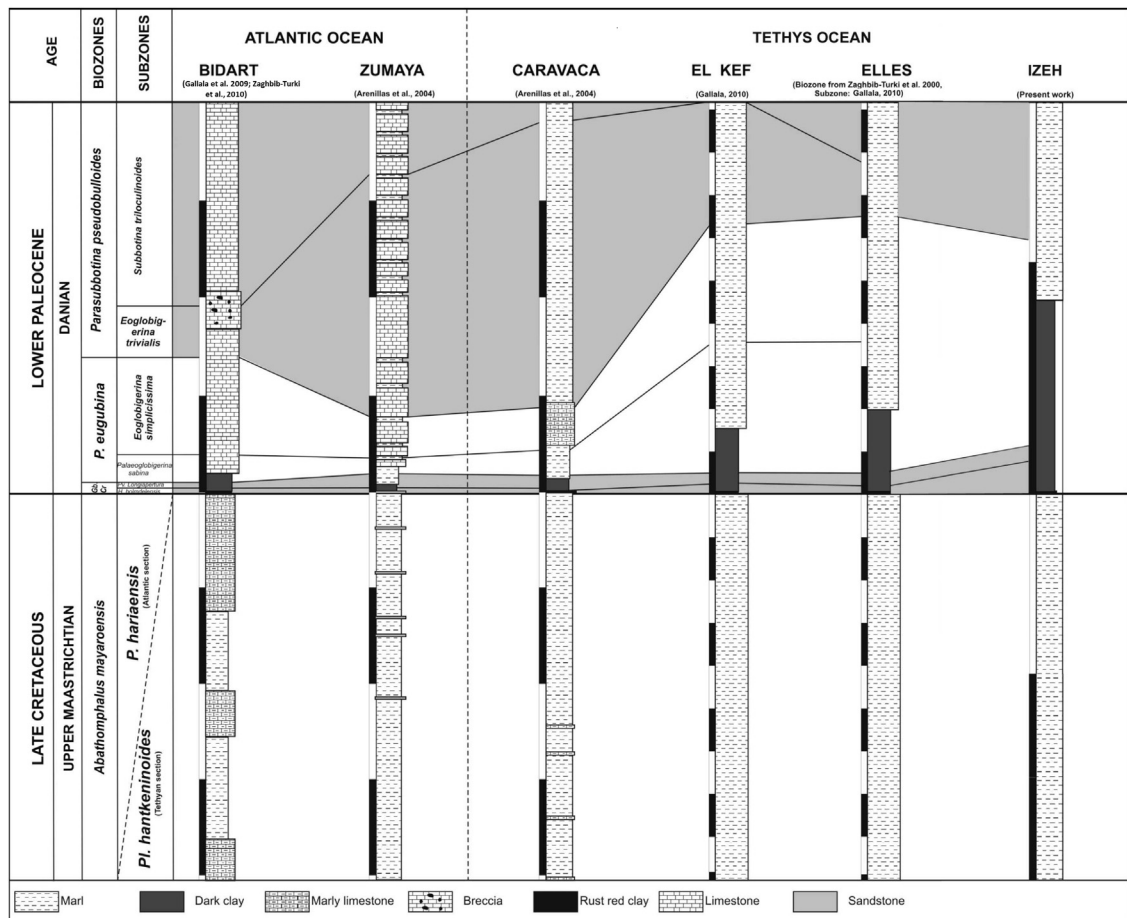
compare their values below and above the K/Pg boundary;

- except the guembeltriids, which are long time survivors (up to the *Parasubbotina pseudobulloides* Subzone), for the other species the survivorship duration may be similar or different.

Besides, in the Izeh section no Cretaceous species was extinct below the K/Pg boundary and both *Archaeoglobigerina blowi* and *A. cretacea* became extinct at the K/Pg boundary. In contrast, in the El Kef section (Gallala, 2010) and the Agost and the Zumaya sections these species became extinct at few decimeters below the K/Pg boundary (Gallala, 2010; Molina et al., 1998). In the Bidart section only *A. cretacea* became extinct below the K/Pg boundary (Gallala and Zaghbib-Turki, 2010; Gallala et al., 2009).

The major crisis affecting the planktonic foraminifera was caused by the sudden environmental deterioration induced by the meteorite impact, which generated climate change and trophic starvation in the ocean superficial waters (Hallam, 1984; Hildebrand et al., 1991; McLean, 1991; MacLeod et al., 1997; Huber et al., 2002; Schulte et al., 2010, among others). At least two thirds of the Maastrichtian planktonic foraminifera species became extinct within the first few centimeters above the K/Pg boundary (higher they are poorly preserved and probably reworked). The Upper Maastrichtian planktonic foraminiferal assemblages of the Izeh section are characterized by the highest diversity (43 species) observed in the entire studied interval (Table 1 and Fig. 3). They are dominated by cosmopolitan species dwelling in near surface and intermediate photic water depths (e.g., *Heterohelix globulosa*, *Rugoglobigerina pennyi*; see Abramovich et al., 2003). Small biserial species (heterohelicids and pseudoguembelinids) are frequent (e.g., *Heterohelix globosa* and *H. navarroensis* represent respectively 19% and 8%; see Fig. 3). Planispiral (globigerinelloids) and simple trochospiral species (hedbergellids and globotruncanellids) are also common, particularly *Hedbergella monmouthensis* and *Hedbergella holmdelensis*. These taxa are all relatively small and morphologically simple. The triserial heterohelicids species (*Guembeltria* spp.) are common just below the K/Pg boundary (approximately 28%); this may be due to burrowing organisms which reworked the Lowermost Danian material. Large, complex and tropical-subtropical taxa are less abundant than the cosmopolitan ones, but they are very diverse. For hedbergellids (i.e., *Hedbergella monmouthensis* and *H. holmdelensis*), which have been reported to cross the K/Pg boundary in several middle to lower latitude sections (Keller et al., 1995), their relative abundance decreases progressively towards bipolar and eventually austral habitats just prior to their extinction. *H. monmouthensis*, *H. holmdelensis* and *Heterohelix globulosa*, which dominated the Uppermost Maastrichtian planktonic foraminiferal assemblages, are as abundant in the Lowermost Danian as in the Maastrichtian. *H. globulosa* exhibits a similar pattern of decrease toward higher latitudes just before they disappeared from the Danian assemblages, while others (e.g., *Pseudoguembelina palpebra*, *P. costulata*, *Rugoglobigerina hexacamerata*, *R. macrocephala*, *Pseudotextularia elegans*) became extinct at the K/Pg boundary in middle and low





**Fig. 8.** Correlation between the thicknesses of the biozones at the IZEH section, the El Kef section (Global Stratigraphic Section and Point [GSSP] for the K/Pg boundary) and the auxiliary sections (Bidart, Zumaya, Caravaca and Ellès).

**Fig. 8.** Corrélation entre les épaisseurs des biozones dans les coupe d'IZEH, d'El Kef (GSSP de la limite K/Pg) et les coupes auxiliaires (Bidart, Zumaya, Caravaca et Ellès).

latitudes, as in Tethyan region (Obaidalla, 2005). Simple and double-keeled trochospiral of the genera *Globotruncana*, *Globotruncanita*, *Gansserina*, *Contusotruncana* and *Abathomphalus* are generally rare in the Uppermost Maastrichtian, except *Globotruncana arca* and *Globotruncana aegyptiaca*, which are common. The unkeeled and rugose trochospiral species, e.g., *Rugoglobigerina rugosa*, *R. macrocephala* and *Plummerita hantkeninoides*, are more common than the keeled taxa. The large biserial helerochelicids belonging to *Pseudotextularia*, e.g., *Pt. intermedia* and *Pt. elegans*, are also common. However, the multiserial heterohelicids (e.g., *Planoglobulina* spp., *Racemiguembelina* spp. and *Gublerina* spp.), as well as high trochospiral keeled species, i.e., *Contusotruncana* spp. are rare. The index species of the *Abathomphalus mayaroensis* Biozone is also rare, and in the Uppermost Maastrichtian becomes increasingly rare. The index species of the *Plummerita hantkeninoides* Subzone is slightly more frequent within the Uppermost Maastrichtian sediments (Fig. 3). Thus, this subzonal index species allows further characterization of the terminal Maastrichtian biozonation. Moreover, the high diversity of the generic and specific composition of the

Uppermost Maastrichtian assemblages in the IZEH section suggests optimal mesotrophic and oxygenated tropical to subtropical marine conditions. The Lower Danian *Guembelitra cretacea* PRZ, *Parvularugoglobigerina eugubina* TRZ and *Parasubbotina pseudobulloides* PRZ at the IZEH section are less expanded than at the El Kef and Ellès sections (see Fig. 8) and they are similarly developed as other continuous and complete sections known in the Tethyan region and elsewhere (e.g., El Melah, Aïn Settara, Zumaya, Bidart). Through these biozones, the planktonic foraminiferal species content is very similar to that of El Kef and Ellès sections in Tunisia. As in the other sections with a complete K-Pg transition, the assemblages of the *Gt. cretacea* Zone are poorly diversified and the specimens are all tiny, and species richness appears to be similar to that in the low and middle latitude Tethyan sections (Coccioni and Luciani, 2006; Gallala et al., 2009; Gallala and Zaghbib-Turki, 2010; Molina et al., 1998; Zaghbib-Turki et al., 2000). The basal Danian planktonic foraminiferal assemblages are dominated by guembelitriids (e.g., *Gt. cretacea* and *Gt. trifolia*), which are the most frequent "Cretaceous-survivor" of the K/Pg boundary. As compared to



the other sections (Fig. 8), the *G. cretacea* Zone interval is expanded but without exceeding 25 cm in thickness of dark clayey. It covers the K/Pg boundary indicated by a few millimeters thick rust-colored ferruginous layer composed of reddish hematitic and goethitic laminae and lacking fossils. Within the lower part (over 13 cm) of the *G. cretacea* Zone especially the “Cretaceous-survivors” co-occurring with reworked species are present. The foraminifera species restricted to the Danian, which are of the genera *Eoglobigerina*, *Woodringina* and *Parvularugoglobigerina*, appear few centimeters above the K/Pg boundary. Most of the globotruncanids and large heterohelicids represented by altered tests (i.e., broken, dissolved and/or not filled by iron oxide) are probably reworked. However the small heterohelicids associated with tiny hedbergellids are better preserved. They are the main survivors crossing the K/Pg boundary event.

At the Izeh section, the *Pv. eugubina* Biozone is recognizable by the LO of *Pv. eugubina* at the base and the HO of *Pv. eugubina* and/or the LO of *Ps. pseudobulloides* at the top. Throughout this zone the assemblage still contains Cretaceous-survivors.

The assemblages of the *Ps. pseudobulloides* Zone are dominated by biserial species belonging to *Chiloguembelina* (15%) and *Woodringina* (30%). *Guembelitra cretacea* is frequent (18%) in the lower part of the zone. Thus, in the Early Danian the planktonic foraminiferal assemblages are very similar to those of Tunisian sections, e.g., at El Kef, Ellès and Ain Settara and Spanish sections, e.g., Zumaya, San Sebastian, Osinaga, Músquiz and the French section at Bidart (Arenillas et al., 1998, 2004; Gallala and Zaghbib-Turki, 2010; Keller, 1988; Zaghbib-Turki et al., 2000, 2001). Although, the *Ps. pseudobulloides* Zone is well developed in the Gurpi Formation, only its lower 85 cm have been investigated in the present work. Many species appearing in the *Guembelitra cretacea* and *Parvularugoglobigerina eugubina* biozones have short stratigraphical ranges. As elsewhere, increasing size, diversification of wall structure, and increasing species diversity are the main trends in the behavior of the planktonic foraminiferal species and assemblages within the *Ps. pseudobulloides* Biozone as recorded in the GSSP for the K/Pg boundary and the auxiliary sections.

The palynomorphs were less affected by mass extinctions and most species crossed the K/Pg boundary indicating that there was not a major crisis in the dinocysts. Nevertheless, there were major changes in dinocyst assemblage structure beyond the K/Pg boundary. The LO of *Manumiella seelandica*, *Phelodinium magnificum*, *Hystrichokolpoma bulbosum*, and *Cordosphaeridium fibrospinosum* are the main dinocyst events within The Upper Maastrichtian *Abathomphalus mayaroensis* Zone. The K/Pg boundary coincides with the boundary between the *Manumiella seelandica* PRZ and *Alisocysta reticulata* PRZ. The important LO events of *D. californicum*, *Carpatella cornuta*, *Cordosphaeridium gracile*, and the HO of *Dinogymnium acuminatum* characterize the *Damassadinium californicum/Carpatella cornuta* CRZ and *Cordosphaeridium gracile* PRZ occurring at the Danian.

In short, the recognized dinocyst assemblages from the Izeh section are similar to that from the El Kef section

containing several palynomorphs which indicate cold surface water (e.g., *Manumiella seelandica*) as described by Brinkhuis and Zachariasse (1988). Our organic-walled dinoflagellate semi-quantitative results are based on three slides per sample; it may that very rare dinocyst morphotypes are missed. In all the cases, in the Izeh section, the Danian samples do not contain reworked Cretaceous dinocysts. Mohamed et al. (2012) working on organic-walled dinocyst from the Cretaceous–Paleogene transition in Austria noted that the Lower Danian samples contain many Cretaceous dinoflagellates that they consider reworked. This was confirmed also by the enrichment of the Danian deposits in detrital lithology elements, lacking in the Izeh section.

The Cretaceous–Paleogene transition was a period of extremely stressful environmental conditions for many living organisms due to rapid and extreme climate fluctuations (Abramovich et al., 1998; Coccioni and Luciani, 2006; Hallam, 1984; Keller, 2003; Koeberl and MacLeod, 2002; Li and Keller, 1998a,b; Ryder et al., 1996; Sharpton and Ward, 1990). The climate change and trophic starvation conditions caused by the asteroid impact added to widespread volcanism (Arenillas et al., 2006; Gertsch et al., 2011; Keller et al., 2007 and references therein) generated high stress conditions and triggered the mass extinctions of tropical and subtropical species at the K/Pg boundary. This critical time of high stress environments is widely characterized by blooms of the opportunist *Guembelitra* species which have fast reproduction and very small size and may arise at any time of stressful environment [Albian, Cenomanian, Late Maastrichtian and Early Cenozoic (see Keller and Pardo, 2004; Leckie, 1987; Leckie et al., 1991, 1998)].

The Lowermost Danian *Guembelitra* bloom is associated with low productivity and rapid cooling induced by the asteroid collision (Abramovich and Keller, 2002; Keller, 2003). The post-K/Pg bloom of guembelitriids in the world ocean occurred both in shallow and deep-water environments, near shore, and in the open ocean, and at high and low latitudes (Abramovich et al., 2002, 2003; Hull et al., 2011; Liu and Olsson, 1992).

The relative abundance of *Spiniferites* shows a general increasing trend in relative abundance upward in the section (Firth, 1993; Schiøler et al., 1997). This also shows a complex signal. In the other hand, high abundances of the *Spiniferites* group are in most cases associated with high sea level and/or low energy (Firth, 1993; Schiøler et al., 1997). Harland (1983) considered the morphology of *Spiniferites ramosus* to be closely related to taxa observed in inner to outer neritic environments.

## 6. Conclusions

Our high-resolution biostratigraphical investigation confirms that the Izeh section from SW Iran, in the Zagros Basin, is complete and continuous across its Cretaceous–Paleocene transition interval and does not contain any stratigraphic hiatus. The planktonic foraminiferal biozones and subzones and dinocyst events characterizing the Uppermost Maastrichtian–Lower Danian interval are recorded and easily recognized by their well-preserved

index species. The K/Pg transition at the Izeh section is characterized by the following features:

- the uppermost part of the *Abathomphalus mayaroensis* Zone including the *Plummerita hantkeninoides* Subzone is well developed in Gurpi Formation. This interval of deposition is rich in diverse planktonic foraminifera with cosmopolitan and tropical-subtropical species (e.g., globotruncanids, large heterohelicids, e.g., *Pseudotextularia elegans*, see Fig. 6);
- the Uppermost Maastrichtian interval is immediately succeeded by a rusty colored thin barren layer, which is marked by an Ir anomaly;
- this rusty layer constitutes the base of a dark layer (boundary clay) that marks the Lowermost Danian and the mass extinction of most of the Cretaceous planktonic foraminifera;
- across this dark layer the planktonic foraminifera are scarce and tiny or poorly preserved;
- this assemblage includes the persistence of few Maastrichtian species from hedbergellids, heterohelicids and guembelitruids behaving as survivors;
- among these survivors, especially *Guembelitra cretacea* shows an obvious blooming.

The similarity of Izeh section with the other complete sections (in Tunisia, Spain, France, and other countries) in the model of planktonic foraminiferal species extinctions (mass extinctions and sudden loss of at least 43 of 61 species), coinciding with an Ir anomaly, confirms its catastrophic pattern compatible by an asteroid impact.

Minor differences in the assemblages may be due to their different specific composition background. The stressful conditions caused by the asteroid impact favor a bloom of the opportunist *Guembelitra* species and a few probable Cretaceous “survivors” (e.g., *Hedbergella holmdelensis*, *H. monmouthensis*, *Heterohelix globulosa*).

The palynomorphs were less affected by the catastrophic bioevent defined by sudden mass extinctions of species from diverse biological groups. Therefore and most dinocysts crossed the K/Pg boundary. Nevertheless, they showed changes in their assemblages’ structure beyond the K/Pg boundary. Of particular biostratigraphical importance, *Manumiella seelandica* and *M. druggii* typical species of Antarctic Maastrichtian dinocysts assemblages occur in coeval deposits at the Izeh section and they persist through the lower Danian. Like in Tunisia (e.g., El Kef section, Ellès section; see Brinkhuis and Leereveld, 1988; Brinkhuis and Powell, 2004; Brinkhuis and Zachariasse, 1988; Galeotti et al., 2004), these boreal palynomorphs show an obvious increase. Besides, *Alisocysta reticulata* and *Senoniasphaera inornata*, the Earliest Danian markers first occur respectively at the K/Pg boundary and at 25 cm above.

## Acknowledgments

This work was supported by the Research Institute of Petroleum Industry (RIPI). The authors thank S.S.Hendi, head of exploration research and development Department of RIPI for sustaining the project and to E.H.Tavakoli and H.Alinaghian for processing the samples. The authors

also thank Professor Mark Leckie from the University of Massachusetts Amherst and Associate Professor Edouardo Koutsoukos from the University of Heidelberg and the other anonym reviewers for their acceptance to review our manuscript and for their interesting suggestions and comments that led to improve the earliest version. They are especially grateful to Professor Leckie who also made linguistic corrections.

## Appendix A.

### Planktonic Foraminifera species

*Abathomphalus mayaroensis* Bolli, 1957  
*Archaeoglobigerina cretacea* d'Orbigny, 1840  
*A. blowi* Pessagno, 1967  
*Chiloguembelina midwayensis* Cushman, 1940  
*Contusotruncana contuse* Cushman, 1926  
*Eoglobigerina eobulloides* (Morozova, 1959)  
*E. fringa* (Subbotina, 1953)  
*Globanomalina compressa* (Plummer, 1926)  
*G. imitata* (Subbotina, 1953)  
*G. planocompressa* (Shutskaya, 1965)  
*Globoconusa daubjergensis* (Bronnimann, 1953)  
*Globotruncana aegyptiaca* Nakkady, 1960  
*G. arca* Cushman, 1926  
*G. falsostuarti* Sigal, 1952  
*G. mariei* Banner and Blow, 1960  
*Globotruncanella havanensis* Voorwijk, 1937  
*G. petaloidea* Gandolfi, 1955  
*Globotruncanita conica* White, 1928  
*G. dupeblei* Caron et al., 1984  
*G. subspinosa* (Pessagno, 1967)  
*G. stuarti* de Lapparent, 1918  
*G. stuartiformis*, 1955  
*Guembelitra cretacea* Cushman, 1933  
*G. irregularis* Morozova, 1961  
*G. trifolia* Morozova, 1961  
*Hedbergella holmdelensis* Olsson, 1964  
*H. monmouthensis* (Olsson, 1961)  
*Heterohelix dentata* Stenestad, 1968  
*H. globulosa* Ehrenberg, 1840  
*H. labellosa* Nederbragt, 1990  
*H. navarroensis* Loeblich, 1951  
*H. pulchra* Brotzen, 1936  
*H. punctulata* Cushman, 1938  
*H. striata* Ehrenberg, 1840  
*Parasubbotina pseudobulloides* (Plummer, 1926)  
*P. varianta* (Subbotina, 1955)  
*Parvulargyoglobigerina eugubina* (Luterbacher and Premoli Silva, 1964)  
*Pv. Longiappertura* Blow, 1979  
*Planoglobulina brazoensis* Martin, 1972  
*P. carseyae* Plummer, 1931  
*Plummerita hantkeninoides* Broennimann, 1952  
*P. reicheli* Broennimann, 1952  
*Praemurica pseudoconstans* Blow, 1979  
*P. inconstans* (Subbotina, 1953)  
*P. taurica* (Morozova, 1961)  
*Pseudoguembelina costulata* Cushman, 1938  
*P. excolata* Cushman, 1926  
*P. hariaensis* Nederbragt, 1990

*P. palpebra* Broennimann and Brown, 1953  
*Pseudotextularia elegans* Rzehak, 1891  
*P. intermedia* de Klasz 1953  
*Racemiguembelina fructifera* Egger, 1899  
*R. powelli* Smith and Pessagno, 1973  
*Rugoglobigerina hexacamerata* Broennimann, 1952  
*R. macrocephala* Broennimann, 1952  
*R. milamensis* Smith and Pessagno, 1973  
*R. rugosa* (Plummer, 1926)  
*Subbotina trivialis* (Subbotina, 1953)  
*S. trilocolinooides* (Plummer, 1926)  
*Trinitella scotti* Broennimann, 1952  
*Woodringina hornerstownensis* Olsson, 1960

**Dinocyts**  
*Achomospaera neptunii* (Eisenack, 1958)  
*A. ramulifera* (Deflandre, 1937)  
*A. regiensis* Corradin, 1973  
*A. sagena* Davey and Williams, 1966  
*Areoligera coronate* (Wetzel, 1933)  
*Cannosphaeropsis passio* de Verteuil and Norris, 1996  
*Carpatella cornuta* Grigorovich, 1969  
*Cerodinium deibelii*  
*Cerodinium striatumb* (Drugg, 1967)  
*Cerodinium pannuceom* (Stanley, 1965)  
*Cerodinium wardenense* Williams and Downie, 1966  
*Cordosphaeridium fibrospinosum* Davey and Williams, 1966  
*Damassadinium californicum* (Drug, 1967)  
*Dapsilidinium cf. pastilum*  
*Deflandrea coronate* McIntyre, 1975  
*Deflandrea coronate* McIntyre, 1975  
*Deflandrea oebisfeldensis* Albert, 1959  
*Deflandrea phosphoritica* Eisenack, 1958  
*Dinogymnium acuminatum* Evitt et al., 1967  
*Dinogymnium longicorne* (Vozzhennikova, 1967)  
*Glaphyrocysta perforata* Hultberg and Malmgren, 1985  
*Glaphyrocysta assamica* (Jain et al., 1975)  
*Godavariella venkatachala* Mehrotra and Sarjeant, 1987  
*Hafniasphaera fluens* Hansen, 1977  
*Heterosphaeridium difficile* (Manum and Cookson, 1964)  
*Hystrichodinium pulchrum* Deflandre, 1937  
*Hystrichokolpoma bulbosum* (Ehrenberg, 1838)  
*Hystrichokolpoma proprium* (Marheinecke, 1992)  
*Hystrichosphaeridium tubiferum* (Ehrenberg, 1938)  
*Impagidinium pentahedrias* (Damassa, 1979)  
*Isabelidinium cretaceum* (Cookson, 1956)  
*Kleithriasphaeridium loffrense* (Davey and Verdier, 1976)  
*Lacrymodinium warrenii* Albert et al., 1986  
*Lanternosphaeridium reinhardtii* Habib, 1993  
*Manumiella druggii* (Stover, 1974)  
*Manumiella seelandica* (Lange, 1969)  
*Operculodinium centrocarpum* (Deflandre and Cookson, 1955)  
*Operculodinium divergens* (Eisenack, 1958)  
*Palaeocystodinium australinum* (Cookson, 1956)  
*Palaeocystodinium golzowense* Alberti, 1931  
*Palaeocystodinium lidiae* (Corka, 1963)  
*Palaeoperidinium pyrophorum* (Ehrenberg, 1838)  
*Phelodinium magnificum* (Stanley, 1965)  
*Phelodinium tricuspis* (Wetzel, 1933)  
*Satyrodinium haumuriense* (Wilson, 1984)

*Senoniasphaera inornata* (Drugg, 1970)  
*Spinidinium densispinatum* Stanley, 1965  
*Spiniferites ancoriferus* Cookson and Eisenack, 1970  
*Spiniferites cornutus* Gerlach, 1961  
*Spiniferites ovatus* Matsuoka, 1983  
*Spiniferites porosus* (Manum and Cookson, 1964)  
*Spiniferites ramosus* (Ehrenberg, 1838)  
*Tanyosphaeridium xanthiopyxides* (Wetzel, 1933)  
*Tectatodinium rugulatum* (Hansen, 1977)  
*Ynezidinium pentahedrias* (Damassa, 1979)

## References

- Abramovich, S., Keller, G., 2002. High stress Late Maastrichtian paleoenvironment in Tunisia: inference from planktic foraminifera. *Paleogeogr., Palaeoclimatol., Paleoecol.* 178, 145–164.
- Abramovich, S., Keller, G., Adatte, T., Stinnesbeck, W., Hottinger, L., Stueben, D., Berner, Z., Ramanivosoa, B., Randriamanantenasoa, A., 2002. Age and paleoenvironment of the Maastrichtian to Paleocene of the Mahajanga Basin, Madagascar: a multidisciplinary approach. *Marine Micropaleontology* 47, 17–70.
- Abramovich, S., Almogi-Labin, A., Benjamini, C., 1998. Decline of the Maastrichtian pelagic ecosystem based on planktonic foraminifera assemblage change: implication for the terminal Cretaceous faunal crisis. *Geology* 26 (1), 63–66.
- Abramovich, S., Keller, G., Stüben, D., Berner, Z., 2003. Characterization of Late Campanian and Maastrichtian planktonic foraminiferal depth habitats and vital activities based on stable isotopes. *Paleogeogr., Palaeoclimatol., Paleoecol.* 202 (1–2), 1–29.
- Alavi, M., 2004. Regional stratigraphy of the Zagros fold-thrust belt of Iran and its proforeland evolution. *Am. J. Sci.* 304, 1–20.
- Alegret, L., Molina, E., Thomas, E., 2001. Benthic foraminifera at the Cretaceous-Tertiary boundary around the Gulf of Mexico. *Geology* 29, 891–894.
- Alegret, L., Molina, E., Thomas, E., 2003. Benthic foraminiferal turnover across the Cretaceous/Tertiary boundary at Agost (southeastern Spain): Paleoenvironmental inferences. *Mar. Micropaleontol.* 48, 251–279.
- Alegret, L., Kaminski, M.A., Molina, E., 2004. Paleoenvironmental recovery after the Cretaceous/Paleogene boundary crisis: evidence from the marine Bidart section (SW France). *Palaios* 19, 574–586.
- Alegret, L., Arenillas, I., Arz, J.A., Diaz, C., Grajales, M., Meléndez, A., Molina, E., Rojas, R., Soria, A.R., 2005. Cretaceous/Paleogene boundary deposits at Loma Capiro, central Cuba: evidence for the Chicxulub impact. *Geology* 33 (9), 721–724.
- Alvarez, L.W., Alvarez, W., Asaro, F., Michel, L.H.V., 1980. Extraterrestrial cause for the Cretaceous-Tertiary extinction: experimental results and theoretical interpretation. *Science* 208, 1095–1108.
- Arenillas, I., Alegret, L., Arz, J.A., Meléndez, A., Molina, E., Liesa, C., Soria, A.R., Cedillo-Pardo, E., Grajales-Nishimura, J.M., Rosales, M.C., 2002. Cretaceous/Tertiary boundary planktonic foraminiferal mass extinction and biochronology at La Ceiba, Bochil, México, and El Kef, Tunisia. *Geol. Soc. Am. Spec. Pap.* 356, 253–264.
- Arenillas, I., Arz, J.A., Molina, E., 1998. El límite Cretácico/Terciario de Zumaya, Osinaga y Musquiz (Pirineos): control bioestratigráfico y cuantitativo de hiatos con foraminíferos planctónicos. *Revista de la Sociedad Geológica de España* 11 (1–2), 127–138.
- Arenillas, I., Arz, J.A., Molina, E., 2004. A new high-resolution planktonic foraminiferal zonation and subzonation for the Lower Danian. *Lethaia* 37, 79–95.
- Arenillas, I., Arz, J.A., Grajales, M., Murillo, G., Álvarez, W., Camargo, A., Molina, E., Rosales, C., 2006. Chicxulub impact event is Cretaceous/Paleogene boundary in age: new micropaleontological evidence. *Earth Planet. Sci. Lett.* 249, 241–257.
- Arz, J.A., Molina, E., 2001. Planktonic foraminiferal quantitative analysis across the Campanian/Maastrichtian boundary at Tercis (Landes, France). In: Odin, G.S. (Ed.), *The Campanian-Maastrichtian stage Boundary: Characterization at Tercis les Bains (France): Correlation with Europe and other Continents*. IUGS Special Pub. (monograph Series 36; Developments in Palaeontology and Stratigraphy Series 19. Elsevier Sciences Publ, Amsterdam, pp. 338–348 (Chapter C5b).
- Arz, J.A., Alegret, L., Arenillas, I., 2004. Foraminiferal biostratigraphy and paleoenvironmental reconstruction at Yaxcopoil-1 drill hole (Chicxulub crater, Yucatan Peninsula). *Meteorit. Planet. Sci.* 39, 1099–1111.



- Berggren, W.A., 1969. Rates of evolution in some Cenozoic planktonic foraminifera. *Micropaleontology* 15 (3), 351–365.
- Berggren, W.A., 1972. Cenozoic biostratigraphy and paleobiogeography of the North Atlantic. In: Laughton, A.S., Berggren, W.A., et al. (Eds.), *Initial Rep. Deep Sea Drill. Proj.* 12, 965–975.
- Berggren, W.A., Miller, K.G., 1988. Paleocene tropical planktonic foraminiferal biostratigraphy and magnetobiochronology. *Micropaleontology* 34, 362–380.
- Berggren, W.A., Pearson, P.N., 2005. A revised tropical to subtropical Paleogene planktonic foraminiferal zonation. *J. Foraminiferal Res.* 35, 279–298.
- Berggren, W.A., Kent, D.V., Flynn, J.J., 1985. Paleogene geochronology and chronostratigraphy. In: Snelling, N.J. (Ed.), *The Chronology of the Geological Record*. *Geol. Soc. London Mem.* 10, 141–195.
- Berggren, W.A., Kent, D.V., Swisher, C.C., Aubrey, M.P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In: Berggren, W.A., Kent, D.V., Swisher, C.C., III, Aubrey, M.P., Hardenbol, J. (Eds.), *Geochronology, Time Scales and Global Stratigraphic Correlation*. *Spec. Publ.-SEPM (Soc. Sediment. Geol.)* 54, 129–212.
- Bernaola, G., Monechi, S., 2007. Calcareous nannofossil extinction and survivorship across the Cretaceous/Paleogene boundary at Walvis Ridge (ODP Hole 1262C, South Atlantic Ocean). *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 255 (1–2), 132–156.
- Blow, W.H., 1969. Late Middle Eocene to Recent planktonic foraminiferal biostratigraphy. In: Bronnimann, P., Renz, H.H. (Eds.), *Proceedings of the First International Conference on Planktonic Microfossils*. Geneva, pp. 199–422 (71).
- Blow, W.H., 1979. The Cainozoic Globigerinidae. In: Brill, E.J. (Ed.), *A study of the morphology, taxonomy, evolutionary relationship and the stratigraphical distribution of some Globigerinidae (mainly Globigerinacea)*. Leiden, Netherlands, 1413 pp.
- Bolli, H.M., 1957. The genera *Globigerina* and *Globorotalia* in the Paleocene–Lower Eocene Lizard Springs Formation of Trinidad. *U. S. Natl. Mus. Bull.* 215, 97–124.
- Bolli, H.M., 1966. Zonation of Cretaceous to Pliocene marine sediments based on planktonic foraminifera. *Boletino Informativo Asociacion Venezolana de Geologia. Minerariay Petroleo* 9, 3–32.
- Bown, P.B., 2005. Selective calcareous nannoplankton survivorship at the Cretaceous–Tertiary boundary. *Geology* 33 (8), 653.
- Brinkhuis, H., Leereveld, H., 1988. Dinoflagellate cysts from the Cretaceous–Tertiary boundary sequence of El Kef, northwest Tunisia. *Rev. Paleobot. Palynol.* 56, 5–19.
- Brinkhuis, H., Zachariasse, W.J., 1988. Dinoflagellate cysts, sea level changes and planktonic foraminifera across the Cretaceous–Tertiary boundary at El Haria, Northwest Tunisia. *Mar. Micropaleontol.* 13, 153–191.
- Brinkhuis, H., Powell, A.J., 2004. In: Gradstein, F.M., Ogg, J.G., Smith, A.G., Agterberg, F.P., Bleeker, W., Cooper, R.A., Davydov, V., Gibbard, P., Hinnov, L.A., House, M.R., Lourens, L., Luterbacher, H.P., McArthur, J., Melchin, M.J., Robb, L.J., Shergold, J., Villeneuve, M., Wardlaw, B.R., Ali, J., Brinkhuis, H., Hilgen, F.J., Hooker, J., Howarth, R.J., Knoll, A.H., Laskar, J., Monechi, S., Plumb, K.A., Powell, J., Raffi, I., Röhl, U., Sadler, P., Sanfilippo, A., Schmitz, B., Shackleton, N.J., Shields, G.A., Strauss, H., Van Dam, J., van Kolfschoten, T., Veizer, J., Wilson, D. (Eds.), *A Geologic Time Scale*. Cambridge University Press, Cambridge, 589 p.
- Brinkhuis, H., Bujak, J.P., Smit, J., Versteegh, G.J.M., Visscher, H., 1998. Dinoflagellate608 based sea surface temperature reconstructions across the Cretaceous–Tertiary boundary. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 141, 67–83.
- Canudo, J.L., 1997. El Kef blind test I: results. *Mar. Micropaleontol.* 29, 73–76.
- Canudo, J.L., Keller, G., Molina, E., 1991. Cretaceous/Tertiary boundary extinction pattern and faunal turnover at Agost and Caravaca, SE Spain. *Mar. Micropaleontol.* 17, 319–341.
- Caron, M., 1985. Cretaceous planktonic foraminifera. In: Bolli, H.M., Saunders, J.B., Perch-Nielsen, K. (Eds.), *Plankton Stratigraphy*. Cambridge University Press, Cambridge, pp. 11–86.
- Cocconi, R., Galeotti, S., 1998. What happened to small benthic foraminifera at the Cretaceous/Tertiary boundary? *Bull. Soc. geol. France* 169, 271–279.
- Cocconi, R., Luciani, V., 2006. Guembeltria irregularis bloom at the K–T boundary: morphological abnormalities induced by impact-related extreme environmental stress. In: Cockell, C. (Ed.), *Biological Processes Associated with Impact Events*. Springer, Berlin, pp. 179–196.
- Cocconi, R., Marsili, A., 2007. The response of benthic foraminifera to the K–Pg boundary biotic crisis at Elles (northwestern Tunisia). *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 255, 157–180.
- Costa, L.I., Manum, S., 1988. The description of the interregional zonation of the Paleogene (D1–D15) and the Miocene (D16–D20). *Geologisches Jahrbuch, Reihe A* 100, 321–330.
- Denham, C.R., Scotese, C.R., 1987. *Terra Mobilis*. A Plate Tectonic Program for the Macintosh. Geoimages, Austin Texas, USA.
- Elliot, D.H., Askin, R.A., Kyte, F.T., Zinsmeister, W.J., 1994. Iridium and dinocysts at the Cretaceous–Tertiary boundary on Seymour Island, Antarctica: implications for the K–T event. *Geology* 22, 675–678.
- Eshet, Y., Moshkovitz, S., Habib, D., Benjamin, C., Mogaritz, M., 1992. Calcareous nannofossil and dinoflagellate stratigraphy across the Cretaceous/Tertiary boundary at Hor Hahar. *Israel Mar. Micropaleontol.* 18, 199–228.
- Fensome, R.A., Taylor, F.J.R., Norris, G., Sarjeant, W.A.S., Wharton, D.I., Williams, G.L., 1993. A classification of living and fossil dinoflagellates. *Micropaleontol. Spec. Publ. Number* 7, 1–351.
- Firth, J.V., 1993. Dinoflagellate assemblages and sea level fluctuations in the Maastrichtian of Southwest Georgia. *Rev. Paleobot. Palynol.* 79, 179–204.
- Galeotti, S., Brinkhuis, H., Huber, M., 2004. Records of post-KT Boundary millennial scale cooling from western Tethys: a smoking gun for the impact winter hypothesis? *Geology* 32, 529–532.
- Gallala, N., 2010. *Micropaléontologie, biostratigraphie, paléocéologie et environnements de dépôt des foraminifères planctoniques et benthiques du passage Crétacé–Paléogène en Tunisie, Espagne et France*. Université de Tunis El Manar, Tunisie, Thèse, 441 p.
- Gallala, N., Zaghib-Turki, D., 2010. High-resolution biostratigraphy based on planktonic foraminifera across the Cretaceous/Paleogene (K/Pg) transition at the Bidart section (SW France). *Acta Geologica Polonica* 60 (2), 243–255.
- Gallala, N., Zaghib-Turki, D., Arenillas, I., Arz, J.A., Molina, E., 2009. Catastrophic mass extinction and assemblage evolution in planktonic foraminifera across the Cretaceous/Paleogene (K/Pg) boundary at Bidart (SW France). *Mar. Micropaleontol.* 72, 196–209.
- Gealey, W.K., 1988. Plate tectonic evolution of the Mediterranean–Middle East region. *Tectonophysics* 155, 285–306.
- Gertsch, B., Keller, G., Adatte, T., Garg, R., Prasad, V., Berner, Z., Fleitmann, D., 2011. Environmental effects of Deccan volcanism across the Cretaceous–Tertiary transition in Meghalaya, India. *Earth Planet. Sci. Lett.* 310 (2011), 272–285.
- Ghasemi-Nejad, E., Hobbi, M.H., Schiøler, P., 2006. Dinoflagellate and foraminiferal biostratigraphy of the Gurpi Formation (Upper Santonian–upper Maastrichtian), Zagros Mountains, Iran. *Cretaceous Res.* 27 (6), 828–835.
- Ginsburg, R.N., 1997a. An attempt to resolve the controversy over the end-Cretaceous extinction of planktonic foraminifera at El Kef, Tunisia using a blind test. Introduction: background and procedures. *Mar. Micropaleontol.* 29, 69–72.
- Ginsburg, R.N., 1997b. Perspectives on the blind test. *Mar. Micropaleontol.* 29, 101–103.
- Habib, D., Miller, J.A., 1989. Dinoflagellate species and organic facies evidence of marine transgression and regression in the Atlantic coastal plain. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 74, 23–47.
- Habib, D., Olsson, R.K., Liu, C., Moskovitz, S., 1996. High-resolution biostratigraphy of biotic extinction, and chaotic sedimentation at the Cretaceous/Tertiary sea level, low boundary in Alabama, north of the Chicxulub Crater. In: Ryder, G., Fastovsky, D., Gartner, S. (Eds.), *The Cretaceous/Tertiary event and other catastrophes in Earth history*. *Geol. Soc. Am. Spec. Pap.* 307, 243–252.
- Hallam, A., 1984. Humid and arid zones in the Jurassic and Cretaceous. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 47, 195–223.
- Harland, R., 1983. Distribution maps of recent dinoflagellate cysts in bottom sediments from the North Atlantic and adjacent seas. *Palaeontology* 26, 321–387.
- Hemmati-Nasab, M., Ghasemi-Nejad, E., Darvish-Zad, B., 2008. Palaeobathymetry of the Gurpi Formation Based on Planktonic and Benthic Foraminifera. *J. Sci., Islamic Repub. Iran* 34, 157–173.
- Herm, V.D., Hillebrandt, A., Perch-Nielsen, K., 1981. Die Kreide-Tertiär Grenze im Lattengebirge (nördliche Kalkalpen) in mikropaleontologischer sicht. *Geologica Bavarica* 82, 319–344.
- Hildebrand, A.R., Penfield, G.T., Kring, D.A., Pilkington, M., Camargo, A., Jabosen, S.B., Boynton, W., 1991. Chicxulub Crater: a possible Cretaceous/Tertiary boundary impact crater on the Yucatan Peninsula. *Mexico Geol.* 19, 867–871.
- Hoek, R.P., Eshet, Y., Almogi-Labin, A., 1996. Dinoflagellate cyst zonation of Campanian–Maastrichtian sequences in Israel. *Micropaleontology* 42 (2), 125–150.
- Hollis, C.J., 1996. Radiolarian faunal change through the Cretaceous–Tertiary transition of eastern Marlborough, New Zealand. In: MacLeod, N., Keller, G. (Eds.), *Cretaceous–Tertiary Mass*

- Extinctions: Biotic and Environmental Changes. W.W. Norton and Co., New York, London, pp. 173–204.
- Huber, B.T., 1992. Paleobiogeography of Campanian-Maastrichtian foraminifers in the high southern latitudes. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 92, 325–360.
- Huber, B.T., MacLeod, K.G., Norris, R.D., 2002. Abrupt extinction and subsequent reworking of Cretaceous planktonic Foraminifera across the Cretaceous-Tertiary boundary; evidence from the subtropical North Atlantic. In: Koeberl, C. and MacLeod K.G. (Eds.), *Catastrophic Events and Mass Extinctions: Impacts and Beyond*. GSA Spec. Pap. 356, 277–289.
- Hull, P.M., Norris, R.D., Bralower, T.J., Schueth, J.D., 2011. A role for chance in marine recovery from the end-Cretaceous extinction. *Nat. Geosci.* 4, 856–860.
- Ion, J., 1993. Upper Cretaceous planktonic foraminiferal biostratigraphy from the Carpathians and northern Dobrogea (Romania) related to macropaleontological zonation. *Rom. J. Stratigr.* 75, 41–53.
- Jain, K.P., Millepieid, P., 1975. Cretaceous microplankton from Senegal Basin, W. Africa. Part. II. Systematics and biostratigraphy. *Geology* 2, 126–171.
- James, G.A., Wynd, J.G., 1965. Stratigraphic nomenclature of the Iranian oil consortium agreement area. *Am. Assoc. Petrol. Geol. Bull.* 49, 2182–2245.
- Keller, G., 1988. Extinction, survivorship and evolution of planktonic foraminifera across the Cretaceous-Tertiary boundary at El Kef, Tunisia. *Mar. Micropaleontol.* 13, 239–263.
- Keller, G., 1989a. Extended period of extinctions across the Cretaceous/Tertiary boundary in planktonic foraminifera of continental shelf section: Implications for a impact and volcanism theories. *Geol. Soc. Am. Bull.* 101, 1408–1419.
- Keller, G., 1989b. Extended Cretaceous/Tertiary boundary extinctions and delayed population change in planktonic foraminifera from Brazos River, Texas. *Paleoceanography* 4, 287–332.
- Keller, G., 1994. Mass extinction and evolution patterns across the Cretaceous-Tertiary boundary. In: Molina, E. (Ed.), *Extincion y Registro fosil, Cuadernos Interdisciplinarios No. 5*. Universidad de Zaragoza, Zaragoza, Spain, pp. 165–200.
- Keller, G., 1996. The Cretaceous-Tertiary mass extinction in planktonic foraminifera: biotic constraints for catastrophe theories. In: Macleod, N., Keller, G. (Eds.), *Cretaceous-Tertiary Mass Extinction: Biotic and Environmental Changes*. W.W. Norton & Co., New York–London, pp. 49–84.
- Keller, G., 2003. Biotic effects of impacts and volcanism. *Earth Planet. Sci. Lett.* 215, 249–264.
- Keller, G., 2008. Cretaceous climate, volcanism, impacts, and biotic effects. *Cretaceous Res.* 29, 754–771, <http://dx.doi.org/10.1016/j.cretres.2008.05.030>.
- Keller, G., 2011. The Cretaceous-Tertiary mass extinction: theories and controversies. *SEPM Spec. Publ.* 100, 7–22.
- Keller, G., Pardo, A., 2004. Disaster opportunists Guembeltridae: index for environmental catastrophes. *Mar. Micropaleontol.* 53, 83–116.
- Keller, G., Stinnesbeck, W., Lopez-Oliva, J.G., 1994. Deposition and biotic effects of the Cretaceous/Tertiary Boundary at Mimbrel, NE Mexico. *Palaios* 9, 144–157.
- Keller, G., Li, L., MacLeod, N., 1995. The Cretaceous/Tertiary Boundary stratotype section at El Kef, Tunisia: how catastrophic was the mass extinction? *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 119, 221–254.
- Keller, G., Adatte, T., Stinnesbeck, W., Stuben, D., Kramer, U., Berner, Z., Li, L., Salis Perch-Nielsen, K., 1998. The Cretaceous-Tertiary transition in the shallow Saharan platform of southern Tunisia. *Geobios* 30, 951–975.
- Keller, G., Adatte, T., Berner, Z., Harting, M., Baum, G., Prauss, M., Tantawy, A., Stuben, D., 2007. Chicxulub impact predates K–T boundary: new evidence from Brazos, Texas. *Earth Planet. Sci. Lett.* 255, 339–356.
- Keller, G., Adatte, T., Gardin, S., Bartolini, A.S., Bajpal, S., 2008. Main Deccan volcanism phase near K–T boundary: evidence from the Krishna-Godavari Basin, SE India. *Earth Planet. Sci. Lett.* 268, 293–311.
- Keller, G., Adatte, T., Berner, Z., Pardo, A., Lopez-Oliva, J.G., 2009. New evidence concerning the age and biotic effects of the Chicxulub impact in NE Mexico. *J. Geol. Soc. London* 166, 393–411.
- Keller, G., Adatte, T., Bhowmick, P.K., Upadhyay, H., Dave, A., Reddy, A.N., Jaiprakash, B.C., 2012. Nature and timing of extinctions in Cretaceous-Tertiary planktic foraminifera preserved in Deccan intertrappean sediments of the Krishna-Godavari Basin, India. *Earth Planet. Sci. Lett.* 211–221.
- Koeberl, C., MacLeod, K., 2002. Impacts and beyond. *Geol. Soc. Am. Boulder, Spec. Pap.* 356, 1–749.
- Koop, W.J., Stoneley, R., 1982. Subsidence history of Middle East Zagros Basin, Permian to recent. *Phil. Trans. R. Soc. London* 306, 149–157.
- Koutsoukos, E.A.M., 1996. The Cretaceous–Paleogene boundary at the Poty section, NE Brazil: Foraminiferal record and sequence of events – a review. In: Jardinié, S., Klasz, I., Debenay, J.-P. (Eds.), *In: Géologie de l’Afrique et de l’Atlantique sud*, C.R. Coll. Angers, 16–20 juillet 1994. *Bull. Cent. Rech. Explor.-Prod. Elf-Aquitaine* 16, 413–431.
- Kyte, F.T., 1998. A meteorite from the Cretaceous/Tertiary boundary. *Nature* 396, 237–239 (in Russian with extensive English summary).
- Leckie, R.M., 1987. Paleocology of mid-Cretaceous planktonic foraminifera: a comparison of open ocean and epicontinental sea assemblages. *Micropaleontology* 33, 164–176.
- Leckie, R.M., Schmidt, M.G., Finkelstein, D., Yuretich, R., 1991. Paleoceanographic and paleoclimatic interpretations of the Mancos Shale (Upper Cretaceous), Black Mesa Basin, Arizona. In: Mattons, J. D., Eaton, J. G. (Eds.), *Stratigraphy, depositional environments, and sedimentary tectonics of the western margin, Cretaceous Western Interior Seaway*. *Geol. Soc. Am. Spec. Pap.* 260, 139–152.
- Leckie, R.M., Yuretich, R., West, O.L.O., Finkelstein, D., Schmidt, M.G., 1998. Paleocyanography of the southwestern Western Interior sea during the time of the Cenomanian-Turonian boundary (Late Cretaceous). In: *Stratigraphy and paleoenvironments of the Cretaceous Western Interior Seaway, USA*. SEPM (Society for Sedimentary Geology). *Concepts Sediment. Paleontol.* 6, 101–126.
- Lentin, J.K., Williams, G.L., 1980. Dinoflagellate provincialism with emphasis on Campanian Peridiniaceans. *American Association of Stratigraphic Palynologists Foundation Contributions, Series 7.*, pp. 46.
- Leonov, V.P., Alimarina, G.P., 1961. Stratigraphy and planktonic foraminifera of the Cretaceous–Paleogene “Transition”. Beds of the central part of the North Caucasus: Collected Papers Geological Faculty, University of Moscow, to XXI International Geological Congress. University of Moscow, Moscow, pp. 29–60.
- Li, L., Keller, G., 1998a. Maastrichtian climate, productivity and faunal turnovers in planktonic foraminifera in South Atlantic DSDP Sites 525 and 21. *Mar. Micropaleontol.* 33, 55–86.
- Li, L., Keller, G., 1998b. Maastrichtian diversification of planktonic foraminifera at El Kef and Elles, Tunisia. *Eclogae Geologicae Helvetiae* 91, 75–102.
- Lipps, J.H., 1997. The Cretaceous-Tertiary boundary: the El Kef blind test. *Mar. Micropaleontol.* 29, 65–66.
- Liu, C., Olsson, R.K., 1992. Evolutionary radiation of microperforate planktonic foraminifera following the K/T mass extinction event. *J. Foramin. Res.* 22, 328–346.
- Luterbacher, H.P., Premoli Silva, I., 1964. Biostratigraphia del limite cretaceo-terziario nello Appennino centrale. *Riv. It. Paleont. Strat.* 70, 67–128.
- Macleod, N., Rawson, P.F., Forey, P.L., Banner, F.T., Boudagher-Fadel, M.K., Bown, P.R., Burnett, J.A., Chambers, P., Culver, S., Evans, S.E., Jeffery, C., Kaminski, M.A., Milner, A.C., Milner, A.R., Morris, N., Owen, E., Rosen, B.R., Smith, A.B., Taylor, P.D., Urquhart, E., Young, J.R., 1997. The Cretaceous–Tertiary biotic transition. *J. Geol. Soc.* 154, 265–292.
- MacLeod, K.G., Whitney, D.L., Huber, B.T., Koeberl, C., 2007. Impact and extinction in remarkably complete K/T boundary sections from Demerara Rise, tropical western North Atlantic. *GSA Bull.* 119, 101–115.
- Mao, S., Mohr, B.A.R., 1992. Late Cretaceous dinoflagellate cysts (?Santonian–Maastrichtian) from the southern Indian Ocean (Hole 748C). In: Wise, S.W., Jr., Schlich, R., et al. *Proc. ODP, Sci. Results* 120, 307–341 (College Station, TX [Ocean Drilling Program]).
- Masters, B.A., 1997. El Kef blind test II results. *Mar. Micropaleontol.* 29, 77–79.
- Masure, E., Rauscher, R., Dejax, J., Schuler, M., Ferre, B., 1998. Cretaceous–Paleocene palynology from the Côte d’Ivoire–Ghana Transform Margin. In: Mascle, J., Lohmann, G.P., Moullade, M. (Eds.), *Proc. Ocean Drill. Prog. Sci. Results* 159, 253–276.
- McLean, D.M., 1991. Impact winter in the global K/T extinctions: no definitive evidences. In: Levine, J.S. (Ed.), *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*. MIT Press, Cambridge, pp. 493–503.
- Mohamed, O., Piller, W.E., Egger, H., 2012. The dinocyst record across the Cretaceous/Paleogene boundary of a bathyal midlatitude Tethyan setting: Gosau Group, Gams Basin, Austria. *Cretaceous Res.* 35, 143–168.
- Molina, E., Arenillas, I., Arz, A., 1996. The Cretaceous/Tertiary boundary mass extinction in planktonic foraminifera at Agost, Spain. *Rev. Micropaleontol.* 22, 225–243.
- Molina, E., Arenillas, I., Pardo, A., 1998. Planktonic foraminiferal biostratigraphy across the Paleocene/Eocene boundary and correlations. *Strata* 1 (9), 93–96.
- Molina, E., Alegret, L., Arenillas, I., Arz, J.A., Gallala, N., Hardenbol, J., Von Salis, K., Steurbaut, E., Vandenberge, N., Zaghbib-Turki, D., 2006. The



- Global Boundary Stratotype Section and Point for the base of the Danian Stage (Paleocene, Paleogene, "Tertiary", Cenozoic) at El Kef, Tunisia: original definition and revision. *Episodes* 2, 263–278.
- Molina, E., Alegret, L., Arenillas, I., Arz, J.A., Gallala, N., Grajales-Nishimura, M., Murillo-Muneton, G., Zaghbib-Turki, D., 2009. The Global Boundary Stratotype Section and Point for the base of the Danian Stage (Paleocene, Paleogene, "Tertiary" Cenozoic): auxiliary sections and correlation. *Episodes* 32 (2), 84–95.
- Moshkovitz, S., Habib, D., 1993. Calcareous nannofossil and dinoflagellate stratigraphy of the Cretaceous-Tertiary boundary, Alabama and Georgia. *Micropaleontology* 39 (2), 167–191.
- Motiei, H., 2003. Stratigraphy of Zagros, Treatise on the Geology of Iran. Geological Survey Press, Tehran, Iran, pp. 1–583.
- Murris, R.J., 1980. The Middle East stratigraphic evaluation and oil habitat. *Am. Assoc. Petrol. Geol. Bull.* 64, 597–618.
- Nederbragt, A., 1991. Late Cretaceous biostratigraphy and development of Heterohelicidae (planktonic foraminifera). *Micropaleontology* 37, 329–372.
- Neumann, M., 1967. Manuel de micropaléontologie des foraminifères (systématique, stratigraphie). Gauthier-Villars, Paris, 1297 p.
- Obaidalla, N.A., 2005. Complete Cretaceous/Paleogene (K/P) boundary section at Wadi Nukhul, southwestern Sinai, Egypt: inference from planktic foraminiferal biostratigraphy. *Rev. Paleobiol. Geneve* 24 (1), 201–224.
- Oboh-Ikuenobe, F.E., Yepes, O., Gregg, J.M., 1998. Palynostratigraphy, palynofacies, and thermal maturation of Cretaceous–Paleogene sediments from the Côte D'Ivoire–Ghana Transform margin. *Proc. Ocean Drill. Prog. Sci. Results* 159, 277–318.
- Olotu, I.N., 1989. Maastrichtian dinoflagellate cyst assemblage from the Nkporo Shale on the Benin Flank of the Niger Delta. *Rev. Palaeobot. Palynol.* 57 (3–4), 173–186.
- Olsson, R.K., 1997. El Kef blind test III results. *Mar. Micropaleontol.* 29, 80–84.
- Olsson, R.K., Hemleben, C., Berggren, W.A., Huber, B.T., 1999. Atlas of Paleocene planktonic foraminifera. *Smithsonian Contrib. Paleobiol.* 85, 252 (71 Pl).
- Orue-Etxebarria, X., 1997. El Kef blind test IV results. *Mar. Micropaleontol.* 29, 85–88.
- Pardo, A., Ortiz, N., Keller, G., 1996. Latest Maastrichtian foraminiferal turnover and its environmental implications at Agost, Spain. In: MacLeod, N., Keller, G. (Eds.), *Cretaceous-Tertiary Boundary Mass Extinction: Biotic and Environmental Changes*. W.W. Norton & Co., New York, London, pp. 139–172.
- Preisinger, A., Aslanian, S., Stoykova, K., Grass, F., Mauritsch, H.J., Scholger, R., 1993. Cretaceous/Tertiary boundary sections on the coast of the Black Sea near Bjala (Bulgaria). *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 104, 219–228.
- Powell, A.J., 1992. Dinoflagellate cysts of the Cretaceous system. In: Powell, A.J. (Ed.), *A Stratigraphic Index of Dinoflagellate Cysts*. Chapman & Hall, London, pp. 99–131.
- Rauscher, R., Doubringer, J., 1982. Les dinokystes du Maestrichtien Phosphaté au Maroc. *Sci. Geol.* 35 (3), 97–116.
- Ryder, G., Fastovsky, D., Gartner, S., 1996. The Cretaceous-Tertiary event and other catastrophes in Earth history. *Geol. Soc. Am. Boulder Spec. Pap.* 307, 1–580.
- Sampo, M., 1969. Microfacies and microfossils of the Zagros Area, southwestern Iran (from pre-Permian to Miocene). *Int. Sediment. Petrograph. Ser.* 12, 1840–1874.
- Sarkis, M.F., Arai, M., Koutsoukos, E.A.M., 2002. Dinoflagellates of the Cretaceous-Tertiary (K-T) boundary, Poty Quarry, Pernambuco-Paraíba Basin, Northeast Brazil. In: Boletim do VI Simpósio sobre o Cretáceo do Brasil, São Pedro, SP, 28–31 July 2002, pp. 271–277 (UNESP-Rio Claro).
- Schiøler, P., Brinkhuis, H., Roncaglia, L., Wilson, G.J., 1997. Dinoflagellate biostratigraphy and sequence stratigraphy of the Type Maastrichtian (Upper Cretaceous), ENCI quarry, The Netherlands. *Mar. Micropaleontol.* 31, 65–95.
- Schrank, E., 1987. Palaeozoic and Mesozoic Palynomorphs from Northeast Africa (Egypt and Sudan) with special reference to Late Cretaceous pollen and dinoflagellates. *Berliner Geowissenschaftliche Abhandlungen* 75, 249–310.
- Schulte, P., Alegret, L., Arenillas, I., Arz, J.A., Barton, P.J., Bown, P.R., Bralower, T.J., Christeson, G.L., Claeys, P., Cockell, C.S., Collins, G.S., Deutsch, A., Goldin, T.J., Goto, K., Grajales-Nishimura, J.M., Grieve, R.A., Gulick, S.P., Johnson, K.R., Kiessling, W., Koeberl, C., Kring, D.A., MacLeod, K.G., Matsui, T., Melosh, J., Montanari, A., Morgan, J.V., Neal, C.R., Nichols, D.J., Norris, R.D., Pierazzo, E., Ravizza, G., Rebolledo-Vieyra, M., Reimold, W.U., Robin, E., Salge, T., Speijer, R.P., Sweet, A.R., Urrutia-Fucugauchi, J., Vajda, V., Whalen, M.T., Willumsen, P.S., 2010. The Chicxulub asteroid impact and mass extinction at the Cretaceous–Paleogene boundary. *Science* 327, 1214–1218.
- Scotese, C.R., 2001. Atlas of Earth History. Paleomap project. Arlington, Texas, pp. 1–52, <http://www.scotese.com/paleocen.htm>
- Setudehnia, A., 1972. Stratigraphic Lexicon of Iran. *Union Int. Sci. Geol.* 3 (ASIE, South-West Iran).
- Setudehnia, A., 1978. The Mesozoic sequence in Southwest Iran and adjacent areas. *J. Petrol. Geol.* 1, 3–42.
- Sharpton, V.L., Ward, P.D., 1990. Global catastrophes in Earth history; an interdisciplinary conference on impacts, volcanism, and mass mortality. *Geol. Soc. Am. Boulder Spec. Pap.* 247, 1–631.
- Smit, J., 1977. Discovery of a planktonic foraminiferal association between the *Abathomphalus mayaroensis* Zone and the *Globigerina eugubina* Zone at the Cretaceous/Tertiary boundary in the Barranco del Gredero (Caravaca, SE Spain). A preliminary report. *Koninklijke Nederlandse Akademie Wetenschappen Proc. B* (4), 280–301.
- Smit, J., 1979. The Cretaceous/Tertiary transition in the Barranco del Gredero, Spain: In: Christensen, W. K., Birkelund, T. (Eds.), *Proc. C-T Boundary Events Symp. II*, 156–163.
- Smit, J., 1982. Extinction and evolution of planktonic foraminifera after a major impact at the Cretaceous/Tertiary boundary. *Earth Planet. Sci. Lett.* 74, 155–170.
- Smit, J., 1990. Meteorite impact, extinctions and the Cretaceous-Tertiary boundary. *Geol. Mijnbouw* 69, 187–204.
- Smit, J., 1994. Blind tests and muddy waters. *Nature* 368, 809–810.
- Smit, J., 1997. Predictive elements of large-body impacts in geologic history. *Geol. Rundsch.* 86, 464–470.
- Smit, J., Romein, A.J.T., 1985. A sequence of events across the Cretaceous-Tertiary boundary. *Earth Planet. Sci. Lett.* 74, 155–170.
- Sung, Z., He, C., Qian, Z., Pan, Z., Zheng, G., Zheng, Y., 1978. On the Paleogene dinoflagellates and acritarchs from the coastal region of Bohai. *Nanking Inst. Geol. Paleontol. Acad. Sin.*, 1–190.
- Tantawy, A.A., Keller, G., Adatte, T., Stinnesbeck, W., Kassab, A., Schulte, P., 2001. Maastrichtian to Paleocene (Dakhla Formation) depositional environment of the Western Desert in Egypt: sedimentology, mineralogy and integrated micro- and macrofossil biostratigraphies. *Cretaceous Res.* 22, 795–827.
- Toumarkine, M., Luterbacher, H.P., 1985. Palaeocene and Eocene planktonic Foraminifera. In: Bolli, H.M., Saunders, J.B., Perch-Nielsen, K. (Eds.), *Plankton Stratigraphy*. Cambridge University Press, Cambridge, pp. 87–154.
- Westerhold, T., Röhl, U., Raffi, I., Fornaciari, E., Monechi, S., Reale, V., Bowles, J., Evans, H., 2008. Astronomical calibration of the Paleocene time. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 257, 377–403.
- Williams, G.L., Bujak, J.P., 1985. Mesozoic and Cenozoic dinoflagellates. In: Bolli, H.M., Saunders, J., Perch-Nielsen, K. (Eds.), *Plankton Stratigraphy*. Cambridge University Press, Cambridge, pp. 847–964.
- Williams, G.L., Brinkhuis, H., Pearce, M.A., Fensome, R.A., Weegink, J.W., 2004. Southern Ocean and global dinoflagellate cyst events compared: index events for the Late Cretaceous-Neogene. In: Exon, N.F., Kennett, J.P., Malone, M.J. (Eds.), *Proc. Ocean Drill. Prog. Sci. Results* 189, 1–98.
- Williams, G.L., Ascoli, P., Barss, M.S., Bujak, J.P., Davies, E.H., Fensome, R.A., Williamson, M.A., 1990. Biostratigraphy and related studies: offshore eastern Canada. In: Keen, M.J., Williams, G.L. (Eds.), *Geology of the Continental Margin Off Eastern Canada*. *Geol. Surv. Canada* 2, 89–137.
- Wood, G.D., Gabriel, A.M., Lawson, J.C., 1996. Palynological techniques - processing and Microscopy. In: Jansonius, J., McGregor, D.C. (Eds.), *Palynology: Principles and Applications*. Am. Assoc. Stratigr. Palynol. Foundation, Dallas, TX 1, 29–50.
- Wynd, J.G., 1965. Biofacies of the Iranian oil consortium agreement area: Iranian oil operating companies, geological and exploration division. Unpublished Rep. 1082, 1–89.
- Yepes, O., 2001. Maastrichtian–Danian dinoflagellate cyst biostratigraphy and biogeography from two equatorial sections in Colombia and Venezuela. *Palynology* 25, 217–249.
- Zaghbib-Turki, D., Karoui-Yaakoub, N., Belayouni, H., Rocchia, R., Robin, E., 2000. Enregistrement des événements remarquables de la limite Crétacé-Tertiaire dans la coupe d'Ellès (Tunisie). *C.R. Acad. Sci. Paris Ser. IIa* 331, 141–149.
- Zaghbib-Turki, D., Karoui-Yaakoub, N., Benzarti-Said, R., Rocchia, R., Robin, E., 2001. Révision de la limite Crétacé-Tertiaire de la coupe d'Elles (Tunisie centro-septentrionale). *Proposition d'un nouveau stratotype*. *Geobios* 34 (1), 25–37.
- Ziegler, M.A., 2001. Late Permian to Holocene paleofacies. Evolution of the Arabian Plate and its Hydrocarbon Geochemical anomaly. *GeoArabia* 6 (3), 445–505.