Cretaceous-Paleogene boundary deposits and paleogeography in western and central Cuba

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ABSTRACT

Three types of Cretaceous/Paleogene (K/Pg) boundary deposits are widely distributed in western and central Cuba. Most deposits belong to type 1, with an original volume of circa 4000 km^3 (Peñalver, Cacarajícara and Amaro formations), and contain in its lower part thick gravity flow deposits. Above the coarse clastics rests a monotonous, mainly massive calcarenite to calcilutite section (homogenite), settled from a hyperdense suspension. The Cacarajícara and Amaro formations accumulated in the southern border of the North American Mesozoic paleomargin, whereas the Peñalver Formation deposited in a southern basin, developed on the extinct Cuban Cretaceous volcanic arc. Type 1 deposits are similar to the "clastic carbonate unit" of Yucatán. Type 2 deposits (Deep Sea Drilling Project, DSDP, leg 77 sites 536, 540 and the "chaotic clastic complex" interbedded in the middle part of the Santa Clara Formation), are local, have thinner basal gravity flow accumulations, and, instead of homogenite, contain ejecta rich deposits. Type 3 deposits (Moncada Formation) are mainly built by reworked ejecta, accumulated during the pass of megatsunami waves, which also affected the upper levels of Type 1 and 2 deposits. We carefully searched for data on the sedimentology and geological setting of each deposit, in order to obtain a detailed picture of its paleogeographic framework. Our research shows that, in an area proximal to Chicxulub crater, the regional relief was a main factor controlling sediment features and distribution of the Mesozoic-Cenozoic boundary sections.

Key words: Cretaceous-Paleogene boundary, sedimentology, paleogeography, tsunami, Cuba.

RESUMEN

Tres tipos de capas del límite Cretácico-Paleógeno (K/Pg) están ampliamente distribuidas en Cuba occidental y central. El grueso pertenece a los depósitos del tipo 1 (originalmente unos 4000 km^3; formaciones Peñalver, Cacarajícara y Amaro), que contienen en su porción inferior potentes depósitos de flujos gravitacionales. Encima descansa una sección mayormente masiva, calcarenítica a calcilutítica (homogenita), depositada a partir de suspensiones hiperdensas. Las formaciones Cacarajícara y Amaro se acumularon en el borde meridional del margen continental mesozoico norteamericano, mientras que la Formación Peñalver se depositó en una cuenca meridional, desarrollada sobre el extinto arco volcánico cretácico cubano. Los depósitos del tipo 1 son muy similares a la "unidad clástica carbonatada" de Yucatán. Los depósitos del tipo 2 (DSDP 536, 540 y el "complejo clástico caótico" intercalado en la Formación Santa Clara) son locales, con flujos gravitacionales basales menos potentes y, en lugar de la homogenita, sedimentos ricos en eyecta. Los depósitos del tipo 3 (Formación Moncada) están en gran parte constituidos de eyecta redepositada por olas de megatsunamis, las cuales afectaron también los niveles superiores de los tipos 1 y 2. Los autores revisamos cuidadosamente la información sedimentológica y el entorno geológico de cada depósito para lograr una imagen detallada de la paleogeografía regional. Nuestra investigación muestra que, en un área no lejana al cráter de Chicxulub, el relieve fue un factor fundamental en el control de los rasgos y distribución de los depósitos de la catástrofe en el tránsito Mesozoico/Cenozoico.

Palabras clave: límite Cretácico-Paleógeno, sedimentología, paleogeografía, tsunami, Cuba.

INTRODUCTION

Cretaceous-Paleogene (K/Pg) boundary sediments with sharp contrasts in composition and thickness are widely distributed in central and western Cuba, resting on different basements. As these sediments accumulated instantaneously, they give an excellent horizon to restore the paleorelief at about 66 Ma (International Commission on Stratigraphy, 2013), a subject almost unexplored in the geological literature on Cuba. The K/Pg boundary beds in western and central Cuba record the event chronology, related to the asteroid impact, in an original area of approximately 90,000 km^2, located 500 to 1200 km east to southeast of the Chicxulub impact crater. In such wide area, K/Pg boundary sediments accumulated (Figure 1). The Cacarajícara,

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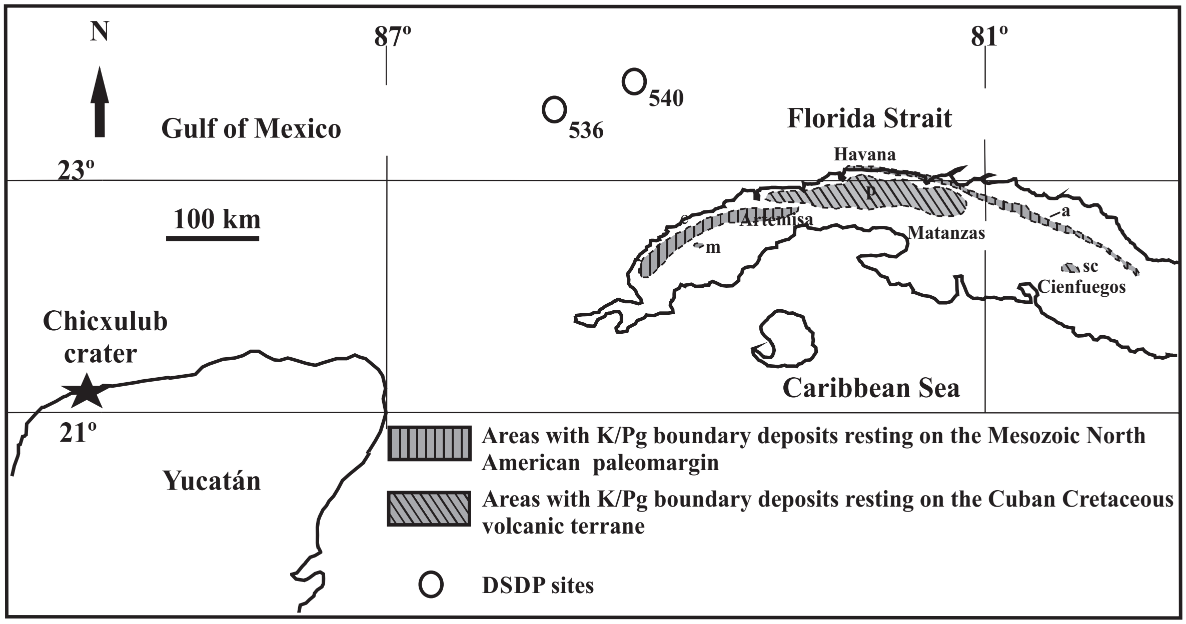

Figure 1. Areas with outcrops of K/Pg boundary deposits in western and central Cuba. a: Amaro Formation; c: Cacarajícara Formation; m: Moncada Formation; p: Peñalver Formation; sc: Santa Clara Formation, 536 and 540: Deep Sea Drilling Project Leg 77 sites. For the Cacarajícara and Amaro formations, the subsurface distributions are included.

Moncada and Amaro formations, together with the K/Pg beds in Deep Sea Drilling Project (DSDP) sites 536 and 540 in the southeastern Gulf of Mexico, rest on the North American Mesozoic paleomargin. The Peñalver and Santa Clara formations lie on the extinct Cuban Cretaceous volcanic arc (Pszczolkowski, 1986; Alvarez *et al*., 1992; Tada *et al*., 2003; Alegret *et al*., 2005; Blanco-Bustamante *et al*., 2007; Goto *et al*., 2008). Compared with other areas (Schulte *et al.* 2010), the Cuban K/Pg beds show extreme variation in thickness and composition in short distances.

Previous studies on K/Pg boundary event in Cuba

The ideas on the genesis of the extraordinary K/Pg boundary deposits in the western half of Cuba evolved with the geological sciences. In 1957, Hatten considered the Cacarajícara Formation a Middle or Upper Eocene talus deposit. Six years later, Brönnimann and Rigassi (1963) considered the thick Peñalver Formation as a single event bed of a great turbidity current. The further step was done by Pszczolkowski (1986), who correlated the Peñalver Formation with the Cacarajícara and Amaro formations and considered all of them upper Maastrichtian megaturbidites. Pszczolkowski (1986), for the first time, also speculated with the possibility of a K/Pg boundary age for these units, but finally concluded that evidence was not conclusive. New proposals developed at end of the 20th century. Cobiella-Reguera *et al.* (2000) considered the Cacarajícara Formation basal breccia (the Los Cayos Member) a debris flow deposit, in contrast with the overlying graded part, whose turbidity current origin remained unquestioned. Current ideas on the K/Pg boundary beds in Cuba began with several seminal presentations at 2000 Vienna meeting on "Catastrophic Events and Mass Extinctions: Impacts and Beyond", that reported the preliminary results of a Cuban-Japanese research project. Results from intensive and detailed study in several localities included (1) ejecta grains (spherules, shocked quartz) recorded in different deposits in western Cuba; (2) the firmly supported K/Pg boundary age of these deposits; and (3) distinct compositions, sedimentary processes and origin established for different parts of the Peñalver and Cacarajícara formations.

In the next years, several papers appeared by Takayama *et al.,* 2000; Tada *et al*., 2002; 2003; Kiyokawa *et al*., 2002; Matsui *et al*., 2002, among others. Later, a group of Cuban and foreign geologists worked on the almost unknown chaotic deposits of the Santa Clara Formation, in the frame of the Cuban-Spanish research project. A new K/Pg boundary deposit was reported by Alegret *et al.* (2005) and Rojas-Consuegra *et al.* (2005) in central Cuba.

Despite the remarkable results derived from the study of K/Pg boundary beds in Cuba during the first decade of the current century (Takayama *et al*., 2000; Tada *et al*., 2003; Alegret *et al*., 2005, Goto *et al*., 2008, among others), an integrated model dealing with the distinct deposits and their relationships has not been fully attained (with the exception of the model presented by Tada *et al.* (2003)). Our paper will focus on three targets: 1) To restore the paleogeography (centered on paleorelief) of the western half of Cuba at the end of the Maastrichtian; 2) to develop a genetic classification of K/Pg boundary deposits in the western half of Cuba, related to the paleogeography in an area proximal to Chicxulub crater; 3) to obtain a dynamic model of the events related to the K/Pg boundary in western and central Cuba and its surroundings.

Methods

Our paper proposes a new approach to some items of the K/Pg boundary event. We present a critical review of contributions dealing on K/Pg boundary deposits in Cuba and surroundings. A major handicap in these publications is the insufficient data from the geological literature on Cuba. Therefore, their authors arrived to some questionable conclusions on the origin of such beds. In order to offer a clear geological setting, we discuss articles from Cuban journals and publications poorly known by foreign geologists containing important data for the study of K/Pg boundary event in Cuba. We insist on brief discussions about regional geology that are essential to understand the depositional frame and origin of the K/Pg boundary deposits. The coeval geography was an essential element in the characteristics and location of K/Pg boundary beds and this aspect, together with the paleoenvironment where each deposit accumulated, is analyzed. We also include a palinspastic reconstruction eliminating early Paleogene tectonic translations and develop an integrated geodynamic model.

Our research was complemented with sedimentological and biostratigraphic work in several outcrops, specially in the Santa Clara city area, central Cuba. These studies include not only the K/Pg boundary beds but also the overlying and underlying strata. We focus our attention on the contacts and sedimentary structures. Thin sections (mainly from limestone and tuffaceous turbidites) were studied; biostratigraphic results come mainly from the study of foraminifera in thin sections and soft rocks.

REGIONAL GEOLOGICAL SETTING

The K/Pg boundary deposits settled on the existing relief, related to the impact of an 10 km diameter asteroid on the Yucatán platform (Hildebrand *et al*., 1991, Goto *et al.,* 2004). The dense and poisonous cloud generated by the impact surrounded the Earth for several months and severely reduced the solar radiation at the planet surface, with catastrophic effects on the biosphere (Urrutia-Fucugauchi *et al.*, 1997; Fastovsky, 1997, Cevallos-Ferriz, 1997, Grajales-Nishimura *et al.,* 2003, 2009; Schulte *et al.* 2010, Bralower *et al.*, 2010). The K/Pg boundary beds are a perfect key horizon, sealing the last Mesozoic deposits and relief in the basins. In western and central Cuba, this deposit has a broad distribution and settled on two different regional Mesozoic tectonic units: (1) the passive Mesozoic paleomargin of North America, (2) the Cuban Cretaceous volcanic terrane (Iturralde-Vinent, 1996; Cobiella-Reguera, 2000, 2005). The configuration of the major Mesozoic tectonic units was attained essentially during the early Paleogene Cuban orogeny (Hatten, 1967; Kantchev *et al*., 1978; Pszczolkowski and Flores, 1986; Bralower and Iturralde-Vinent, 1997; Cobiella-Reguera, 2005, 2009; Saura *et al.,* 2008; Pszczolkowski, 2009). To restore their paleopositions at the end of the Mesozoic, the effects of the Late Paleocene–Middle Eocene thrusting must be removed.

In western Cuba, a wide area of Mesozoic rocks outcrops along the Cordillera de Guaniguanico mountains, in the northern half of Pinar del Río and Artemisa mountains provinces (Figure 2; Puscharovsky, 1988). Four distinct sections (zones) represent the North American Mesozoic paleomargin: (1) Sierra de los Órganos (SO); (2) Alturas de Pizarras del Sur (APS); (3) Sierra del Rosario/Alturas de Pizarras del Norte (SR/APN); and (4) Cangre Belt (C).

In each zone, the Jurassic – Paleocene section has distinct stratigraphy and tectonic features. They belong to a fold and thrust belt resting, with tectonic contact, below the northern Cuban ophiolites and the Cretaceous volcanic terrane (KVT+O in Figure 2). Between the paleomargin and the northern oceanic sections, the Pan de Guajaibón nappe (G), with an Albian –Cenomanian carbonate bank, is located (Pszczolkowski, 1978). The tectonic units came from the S-SE (Rigassi-Studer, 1963; Hatten, 1967; Piotrowska, 1978). Table 1 summarizes recent estimates for their horizontal travel, supported on different approaches. Eastward, in Havana city, minimum estimates on the ophiolite belt displacement attain 15–25 km northward (Cobiella-Reguera, 2009). Data on the horizontal movements during the early Paleogene orogenesis in central Cuba are less well documented. For the southern border of the North American paleomargin (Placetas zone) Pszczolkowski (1983) calculated 50–70 km toward the northeast. Following this figure, the authors considered that the overlying ophiolitic belt and the Cretaceous volcanic arc terrane moved at least 60–80 km in the same direction during the early Paleogene event.

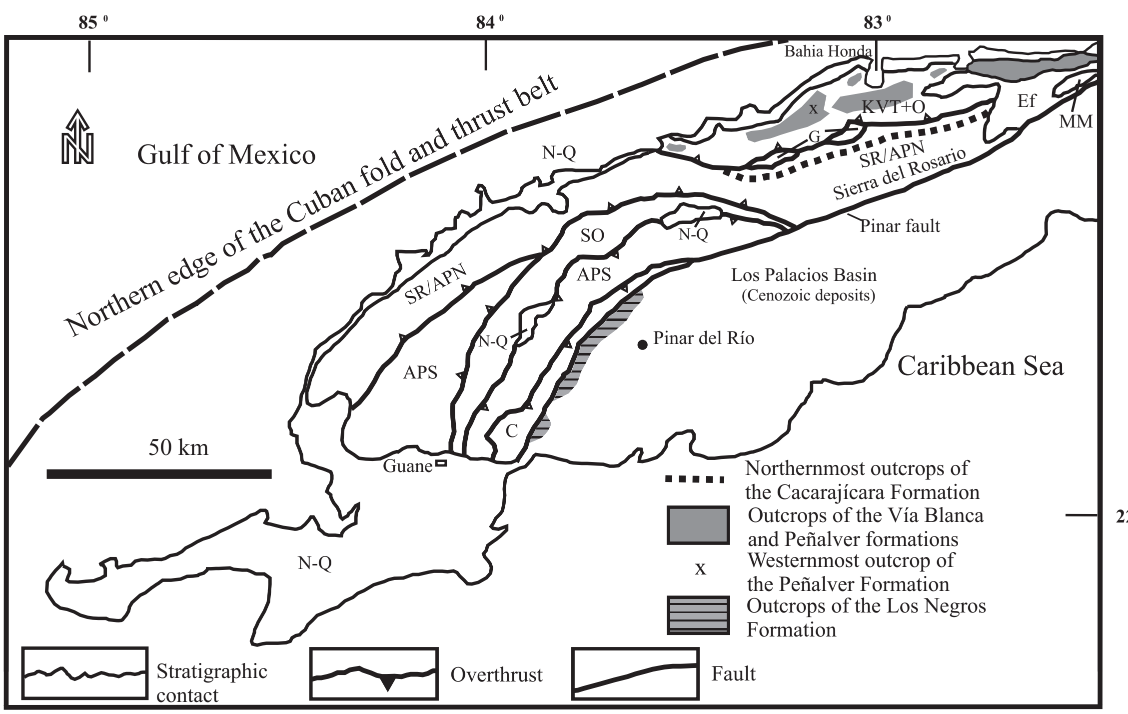

Figure 2. Schematic tectonic map of Pinar del Río and Artemisa provinces in western Cuba (modified after Cobiella-Reguera, 2008). The Guaniguanico Cordillera fold and thrust belt contains the following tectonic units (main nappes), APS: Alturas de Pizarras del Sur unit; C: Cangre belt; G: Pan de Guajaibón unit; SO: Sierra de los Órganos unit; SR/APN: Sierra del Rosario-Alturas de Pizarras del Norte-Esperanza unit. The ophiolitic belt and the Cretaceous volcanic arc terrane (KVT+O) overrode Cordillera de Guaniguanico units. The front of this complex structure is below the southeastern Gulf of Mexico waters. Ef: Lower Eocene flyschoid deposits. MM: Martin Mesa erosional window. N-Q: Neogene-Quaternary deposits. Los Palacios basin is a Cenozoic depression, and the Pinar fault is a regional structure active, at least, since the Early Eocene.

Table 1 Estimated horizontal displacement (in kilometers) of regional tectonic units in western Cuba.

Tectonic unit	**Pszczolkowski (1999)***	**Cobiella-Reguera (2008)**
Sierra de los Órganos	0–90**	12–25
Alturas de Pizarras del Sur		40–50
Cangre Belt		57(?)
Alturas de Pizarras del Norte		57–67
SIerra del Rosario	130–190***	92–111
Pan de Guajaibón		>92–111
Bahía Honda		122–141

* Interpretation of figure 13 in Pszczolkowski (1999). **Equivalent to Sierra de los Órganos + Alturas de Pizarras del Sur + Cangre Belt. *** Equivalent to Alturas de Pizarras del Norte + Sierra del Rosario + Pan de Guajaibón

EVIDENCE ON THE K/Pg AGE

Dealing with Cretaceous-Paleogene boundary sediments, a basic point is to be sure that they actually were deposited 66 Ma ago (International Commission on Stratigraphy, 2013), at the turnover of the eras. This subject was studied in some detail in previous papers (Takayama *et al*., 2000; Tada *et al*., 2003; Alegret *et al*., 2005; Goto *et al*., 2008; Sánchez-Arango, 2011, among others). The following four main criteria are considered in the current paper.

The fossil record

In all the lithostratigraphic units (Figure 1), the typical "K/T boundary cocktail" of Bralower *et al.* (1998), a mix of Maastrichtian and older Cretaceous fossils (without Paleocene and younger taxa), is present. In some cases, the youngest taxa detected in clasts are upper or uppermost Maastrichtian: In the Peñalver Formation *Micula prinsii* (Tada *et al*., 2003); in the Cacarajícara Formation *Omphalocyclus macroporus, Globotruncana stuar*ti, Globotruncanella havanensis, among others (Pszczolkowski, 1978; de la Torre, 1987). We visited the "chaotic clastic complex" (Alegret *et al.,* 2005), located in the middle part of the Santa Clara Formation, and found upper Maastrichtian forms (Table 2; see also fig. 2 in Alegret *et al*., 2005). *Abamthomphalus mayaroensis* (Pszczolkowski, 1986) and *Plummerita hantkeninoides* (Blanco-Bustamante *et al*., 2007) were found in the Amaro Formation. Díaz-Otero *et al.* (2001) report *Abanthomphalus mayaroensis, Globotruncanella petaloidea, Guembelitria cretacea, Racemiguembelina fructicosa, Contusotruncana contusa*, and *Rugoglobigerina macrocephala* in the Moncada Formation.

The age of underlying and overlying beds (Figure 3)

These criteria are very useful to constraint the age of the units in the cover of the Cretaceous volcanic arc. The Peñalver Formation rests upon Vía Blanca Formation, whose younger beds contain taxa from the uppermost Maastrichtian *Plummerita hantkeninoides* subzone, together with bentic forms from the *Bolivinoides draco* zone (Gil-González *et al*., 2007; Menéndez-Peñate and Sánchez-Arango, 2007). Near Havana city, the oldest post-Peñalver Formation deposits are lower Danian beds (Apolo Formation) with *Parvularugoglobigerina eugubina* and *Globoconusa fringa* (Goto *et al.,* 2008*).* According to Arz *et al.* (2001; see fig. 5 in Grajales-Nishimura *et al*., 2009), the first mentioned taxon has a small biozone, extending from 20 to 60 ka after the K/Pg boundary.

Alegret *et al* (2005) report the *Pseudoguembelina hariaensis* subzone in the beds just below the basal breccia of the K/Pg boundary beds in the Santa Clara Formation. Therefore, these authors believe that the last 0.3 Ma of the Maastrichtian stage are not represented in this section, according to the Arz and Molina (2002) zonation (see fig.5 in Grajales-Nishimura *et al*., 2009). However, in samples collected by the authors in the Santa Clara Formation, *Plummerita hantkeninoides, Pseudoguembelina hariaensis* and other foraminifera*,* together with nannoplanktonic upper Maastrichtian taxa as *Micula prinssi* and *M. murus* (Table 2) were found in the last 10 m of Cretaceous strata below the K/Pg beds. The preceding facts demonstrated that the uppermost Maastrichtian *Plummerita hantkeninoides* subzone is represented in the Santa Clara Formation strata (Pedraza-Rozón, 2010). Lowermost Danian beds, including the *Guembelitria cretacea* zone, were found in

Table 2. Distyribution of fossil taxa in Dos Hermanas section, Santa Clara, Cuba.

Taxon / *Sample*	*Parvularugoglobigerina eugubina*	*Woodringina hornerstownensis*	*Eoglobigerina eobulloides*	*Pseudotextularia elegans*	*Pseudotextularia petaloidea*	*H. globulosa*	*Globotruncana rosetta*	*Globotruncanita conica*	*Trinitella scotti*	*Rugoglobigerina macrocephala*	*R. rugosa*	*Globotruncanella petaloidea*	*Pseudoguembelina costulata*	*Globigerinelloides praeriehelinsis*	*Globotruncanita pettersi*	*Globigerinelloides ultramicus*	*Rugoglobigerina reicheli*	*Globotruncana falsostuarti*	*Heterohelix striata*	*Hedbergella holmdelensis*	*Globotruncanita stuarti*	*Globigerinelloides alvarezi*	*Globotruncanella havanensis*	*Globotruncana arca*	*Pseudoguembelina costulata*	*Radotruncana subspinosa*	*Plummerita hantkeninoides*	*Rugoglobigerina rotundata*	*Racemiguembellina powelli*	*Abamtophalus mayaroensis*	*Conicotruncana contusa*	*Plummerita hariaensis*	*Eoglobigerina edita*	*Globoanomalina planocompressa*	*Globoanomalina archeocompressa*	*Parasubbottina pseudobulloides*	
Y19			*cf*	x											x																			x	*aff*	x	*D*
Y18a							x																											x	x	x	*D*
Y18-11	x	x	x	x	x	x	x	x																									x				*D*
Y17								x	x	*cf*	x	x	x	x		x																					*bd*
Y16 b				x			x								x	x	x																				*M*
Y 16 a							x				x	x	x															x	x	x	x	x					*M*
Y15 c				x			x		x	x						x		*aff*	x	x																	*M*
Y15 b																					x	x	x	x	x	x	x										*M*

D: Danian; *bd*: K/Pg bonudary deposit; *M*: Maastrichtian.

the Santa Clara Formation strata resting on the chaotic clastic complex in the Dos Hermanas hill section (Table 2; Alegret *et al.,* 2005), tightly bracketing its age.

Due to the unconformable or tectonic lower contact of the Cacarajícara, Amaro (Pszczolkowski, 1986) and Moncada (Tada *et al.,* 2003) formations with the underlying Upper Cretaceous beds, this criteria is less definite in these cases. The same conclusion is valid for the DSDP K/Pg boundary sediments in the southeastern Gulf of Mexico (Alvarez *et al*., 1992).

In Sierra del Rosario, the Ancón Formation rests on the Cacarajícara Formation (Figure 3). The oldest known beds of Ancón Formation in Sierra del Rosario mountains belong to P2, *Praemurica uncinata* zone (Pszczolkowski, 1994). In Sierra de los Órganos this last unit rests on the Moncada Formation. A few poorly preserved small foraminifera skeletons, probably of lower Danian age, are scattered in the basal Ancón Formation (Tada *et al*., 2002, 2003). The *Parvularugoglobigerina eugubina* zone is reported in the beds overlying the boundary deposits found in DSDP leg 77 (Alvarez *et al.,* 1992). Paleocene deposits (Vega Alta Formation) rest on the Amaro Formation (Figure 4; Pszczolkowski, 1986). Recent data record a Danian age (P1, *Parasubbotina pseudobulloides-Praemurica uncinata* zone) for the Vega Alta Formation basal beds in northern central Cuba (García-Delgado *et al*., 2011) and near Havana (Blanco-Bustamante *et al.,* 2007).

Ejecta from asteroid impact

Collision produced particles have been recorded in many localities of western and central Cuba. In the Cacarajícara Formation, altered spherules are present in the lowest part of the basal breccia and shocked quartz (Figure 5d) is distributed over almost the whole formation, except for its top (Kiyokawa *et al.,* 2002; Tada *et al*., 2003). Spherules have been reported in the Amaro Formation (Fernández-Pérez *et al.,* 2011). Shocked quartz (Figure 5b), absent in the lower breccia, is present in the upper part of the Peñalver Formation, whereas altered vesicular glass presents a distribution similar to that recorded in the Cacarajícara Formation. Vitreous ejecta grains altered to chlorite or smectite are abundant in the Moncada and Cacarajícara formations (Figure 5f and 5g; Kiyokawa *et al.,* 2002; Tada *et al.,* 2002, 2003). In the Dos Hermanas hill section of the Santa Clara Formation (Figure 1), ejecta are reported only for its upper part and shocked quartz is scarce, but calcite spherules (from altered glass) and carbonate accretionary lapilli, are abundant (Figure 5c; Alegret *et al.,* 2005).

Iridium anomaly

This characteristic anomaly, reported at top of many Cretaceous-Paleogene boundary deposits in the world, is known only from the Moncada Formation (western Cuba; Tada *et al.,* 2003) and in DSDP sites 536 and 540 in the southeastern Gulf of Mexico (Alvarez *et al.,* 1992).

Therefore, all the units contain two main features of K/Pg boundary deposits in the NW Caribbean-Gulf of Mexico region: (a) the "K/T paleontological cocktail" of Bralower *et al.* (1997), and (b) impact ejecta grains. The biostratigraphic constraints for a K/Pg boundary age are tightly established for the Peñalver Formation, the "clastic complex" in the Santa Clara Formation and DSDP sites 536 and 540. Due to their current upper and lower tectonic contact, the stratigraphic position of the Cacarajícara and Amaro formations relative to K/Pg boundary is less constrained, but other data are not against a K/Pg boundary age.

An additional, but crucial fact, pointing to a K/Pg boundary age

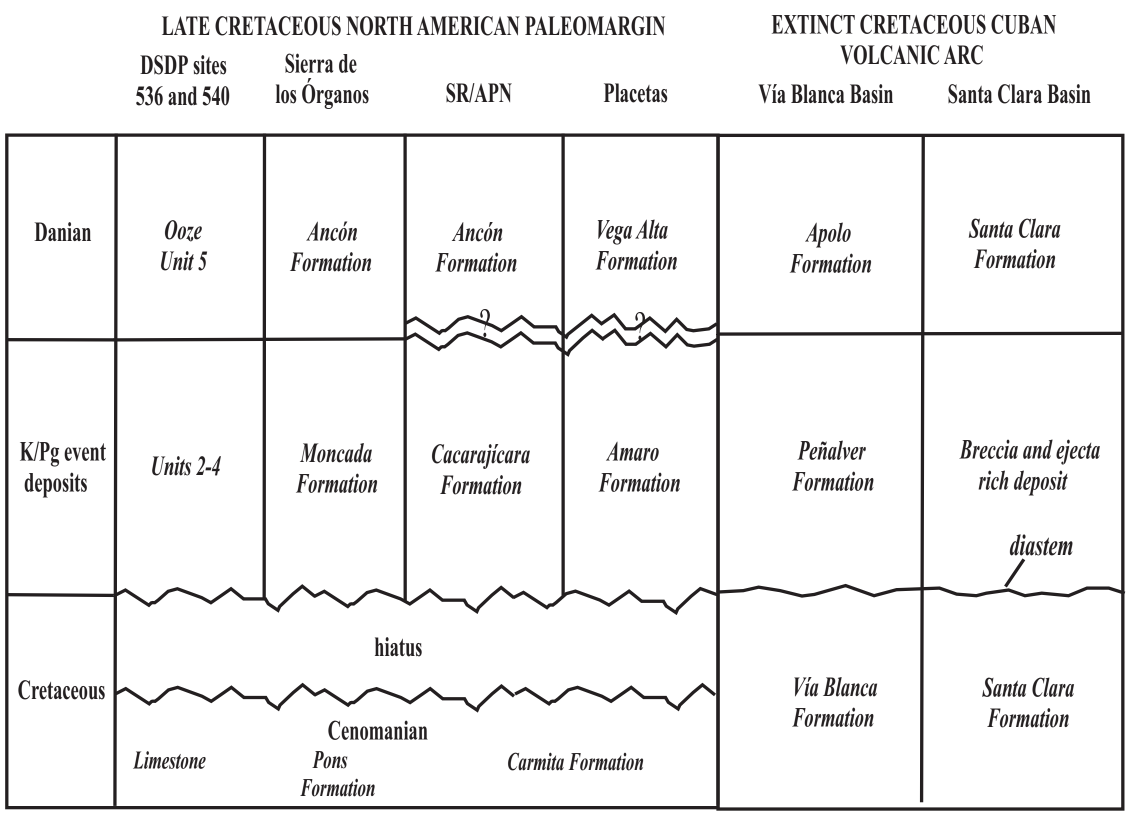

Figure 3. Correlation chart of Cretaceous/Paleogene boundary beds and related units in western and central Cuba and in Deep Sea Drilling Project leg 77 sites 536 and 540. See detailed explanation in text.

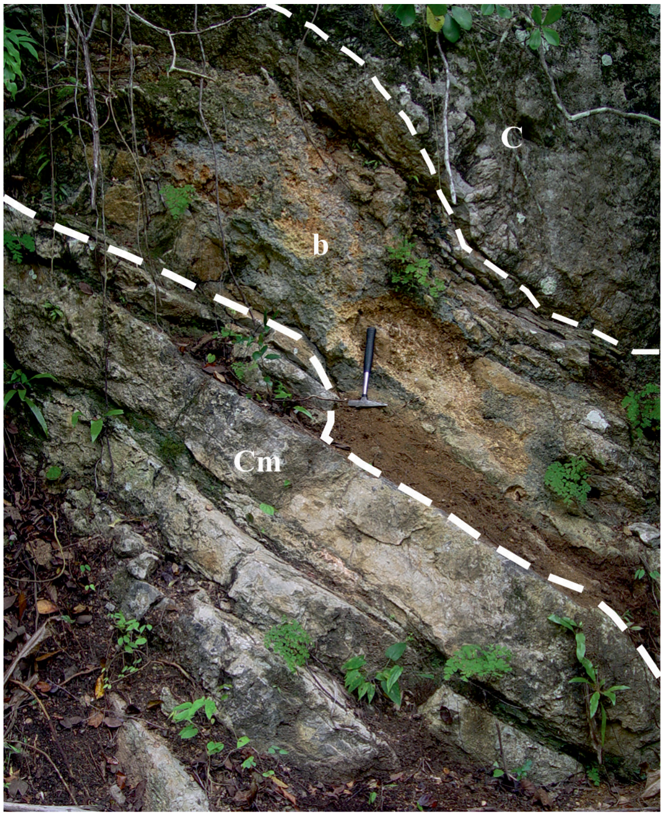

Figure 4. Outcrop of K/Pg boundary beds resting on the Mesozoic North American paleomargin. Massive Cacarajícara Formation (C) resting on the Albian-Cenomanian beds of the Carmita Formation (Cm). A tectonic breccia (b) separates both units. Such basal tectonic contact is characteristic of the Cacarajícara Formation. See position in Figure 14. Coordinates: 82°57'01" E; 22°51'21" N.

for all these units, is the abundant sedimentological evidence for a very fast deposition (Brönnimann and Rigassi, 1963; Pszczolkowski, 1986; Tada *et al.,* 2003, among others).

PALEOENVIRONMENTAL INTERPRETATION

As the K/Pg boundary sediments acted as an instantaneous mold of the underlying relief, in those places where they settled on active basins, the youngest Maastrichtian sediments were preserved below them. At the same time, the overlying sediments deposited just after the event, contain valuable paleoenvironmental information on the earliest Danian beds (Figure 3). These two data can be contrasted and used as mutual controls in the paleoenvironmental interpretation, clarifying some details. In the next paragraphs this straightforward procedure will be applied to the interpretation of K/Pg boundary strata in the western half of Cuba.

In the southern part of the North American paleomargin in Cuba, Turonian to Maastrichtian beds are very rare and K/Pg boundary strata rest disconformably mainly on Cenomanian rocks (Figure 3). This is the same hiatus of the Mid-Cretaceous disconformity in the southeastern Gulf of Mexico (Schlager and Buffler, 1984). In Sierra del Rosario zone, in western Cuba (Cobiella-Reguera *et al*., 2000; Cobiella-Reguera, 2008), and in Placetas zone, in central Cuba (Piotrowska *et al.,* 1981; Pszczolkowski, 1999), the lower contact of the K/Pg beds is always tectonic and generally rests on deep water Albian-Cenomanian strata of the Carmita Formation (Figure 4). In Sierra de los Órganos zone (Figures 2 and 3), the K/Pg boundary beds lie disconformably on Cenomanian deposits (Figure 6; the Pons Formation; Tada *et al*., 2003). In the southeastern Gulf of Mexico, K/Pg boundary beds in sites 536 and 540 rest on Cenomanian beds (Figure 1, Alvarez *et al*., 1992; Bralower *et al*., 1998).

In Sierra del Rosario, the Ancón Formation rest with tectonic contact upon Cacarajícara Formation. This deep water unit is also present

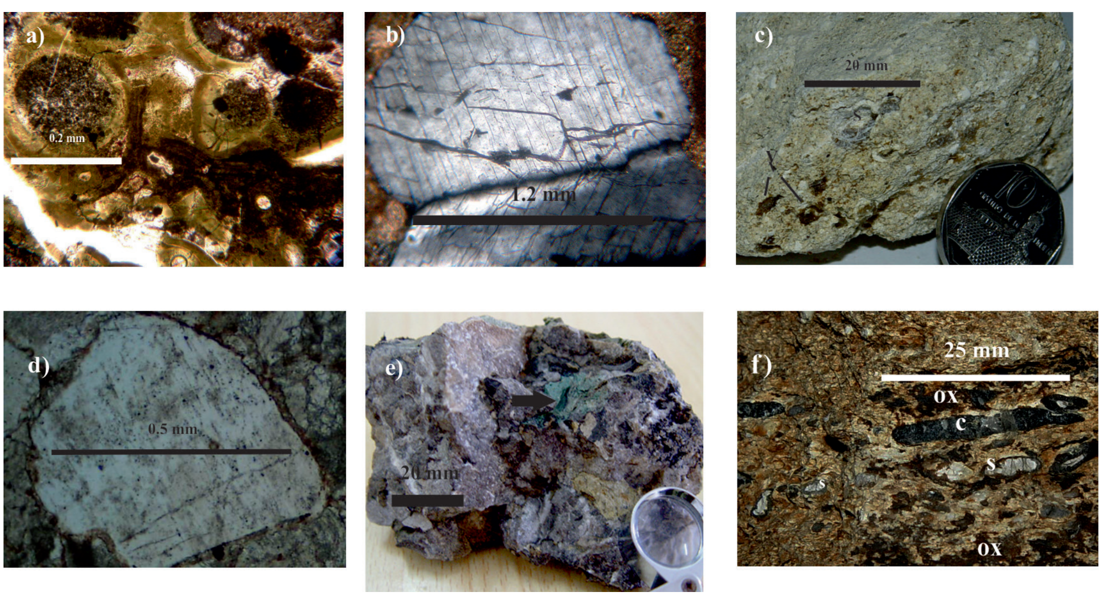

Figure 5. Ejecta in Cretaceous/Paleogene boundary beds. a) Spherules in the Peñalver Formation, La Victoria quarry, Havana; b) shocked quartz grain in the Peñalver Formation, La Victoria quarry; c) sample of carbonate "accretionary lapilli" from Santa Clara Formation (s: altered spherule, v: altered vitreous splinters), Dos Hermanas, Santa Clara city; d) shocked quartz grain from the Cacarajícara Formation, Loma Miracielo, Sierra del Rosario, Artemisa province; e) breccia from the Cacarajícara Formation, Las Terrazas, Sierra del Rosario. Arrow point to altered and deformed vitreous splinter; f) ejecta-rich fine-grained breccia from the lowest Moncada Formation (s: altered spherule, c: chert; see Figure 6), Moncada Juction, Sierra de los Órganos, Pinar del Río.

Figure 6. Outcrop view of the basal ejecta-rich bed of the Moncada Formation (M) (see Figure 5f (for details) resting on the Cenomanian strata of the upper part of the Pons Formation (P). The disconformity (white line) correlates with the Upper Cretaceous disconformity in the southeastern Gulf of Mexico (Schlager and Buffler, 1984). Coordinates: 83°50'43" E; 22°33'14" N.

in Sierra de los Órganos, concordant above the Moncada Formation (Figure 3; Tada *et al*., 2002, 2003). Lower Danian beds rest upon the Amaro Formation in Boca de Jaruco oil field, eastward from Havana city (Blanco-Bustamante *et al.*, 2007), and Middle Paleocene strata in northern central Cuba (García-Delgado *et al*., 2011). The K/Pg boundary strata in DSDP sites 536 and 540 are covered by basal Danian ooze (Alvarez *et al*., 1992). Therefore we conclude that the general absence of Coniacian-Maastrichtian beds, plus the rarity of Turonian strata suggest a starved basin condition in the North American margin from Cenomanian to Danian. Probably the margin was a deep basin, as suggested by the lower Danian beds in Sierra de los Órganos (Tada *et al*., 2002) and the huge thickness of some sections of the Cacarajícara (Tada *et al*. 2003) and Amaro formations.

On the upper Campanian-Maastrichtian cover of the volcanic arc terrane, the K/Pg boundary strata were deposited in basins filled with turbidites (the Vía Blanca Formation) in western Cuba and carbonate-terrigenous sediments and reworked tephras in central Cuba (the Santa Clara Formation, Kantchev *et al*., 1978; Pedraza-Rozón, 2010). In both depressions, the contact with the underlying uppermost Maastrichtian beds is erosional. The Vía Blanca Formation (Bronnimann and Rigassi, 1963; Piotrowska *et al*., 1981; Albear-Fránquiz and Iturralde-Vinent, 1985; Gil-González *et al.,* 2007; Menéndez-Peñate and Sánchez-Arango, 2007) is a volcanomictic turbiditic sequence several hundred meters thick, with intercalated limestone, resting unconformably upon a strongly deformed basement, composed by Cretaceous volcanic arc and ophiolitic rocks (Albear Fránquiz and Iturralde-Vinent, 1985; Pushcharovski, 1988; Cobiella-Reguera, 2005). Most of the clastics were derived from a source to the south, with outcrops of the extinct Cuban Cretaceous volcanic arcs (Figure 6; Piotrowska *et al*., 1981; Albear Fránquiz and Iturralde-Vinent, 1985; Cobiella-Reguera, 2005, 2009), whereas clasts derived from the ophiolitic suite are minor components (Albear and Iturralde-Vinent, 1985).

Brönnimann and Rigassi 1963), Piotrowska *et al.* (1981), and Pszczolkowski and Albear (1982) reported horizons with clastic limestone and rudist-rich olistostrome for several localities within the upper Vía Blanca Formation. This fact clearly points to the development of abundant rudist reefs in the source area of this formation at the end Maastrichtian.

Brönnimann and Rigassi (1963) suggested that in the Havana city area, the Vía Blanca Formation was deposited at water depths larger than 600 m. This interpretation has not been questioned in later publications and has been accepted for the whole distribution area (Pszczolkowski and Albear, 1982; Takayama *et al.,* 2000). A recent study by Pérez-Estrada *et al.* (2007), based on the bentic foraminifera record, considered deposition at depths between 200 and 1000 m in waters with low oxygen content for the samples from the Vía Blanca Formation they studied.

In central Cuba, the Santa Clara, Cocos, Vaquería and Fomento formations (Kantchev *et al*., 1978) record a Maastrichtian-Danian section (Figure 1 and 7). In the Santa Clara Formation strata, the K/Pg boundary event had been studied with some detail only in the Dos Hermanas hill section by Alegret *et al.* (2005). In the same locality, below the erosional contact of the K/Pg boundary deposit (Figure 3), we found a 100 m thick section of bioturbated marl, limestone and calcareous vitreous-crystalline tuff (reworked tephra) belonging to the Santa Clara Formation (Pedraza-Rozón, 2010). However, carbonate pelagic sediments representing the basinal background, attain only 25–30% of the total thickness, whereas the tuffs are interpreted as the result of instantaneous geological events, related to turbidity currents and submarine eruptions. Some uppermost Maastrichtian carbonate turbidites with shallow-water bentonic fossil assemblages are present in this area (Figure 8) below the K/Pg boundary deposits (Table 2). Therefore, a batial paleoenvironment can be envisaged for the Santa Clara Formation beds in its type locality (see also Kantchev *et al*., 1978 and Alegret *et al*., 2005), with shallow-water carbonate banks contributing to the sedimentary budget. Lithologically, other transitional Maastrichtian-Danian units in central Cuba resemble those of the Vía Blanca Formation, but they contain tuffs as minor components, and shallow carbonates (Pszczolkowski, 2002) and marls (Kantchev *et al*., 1978) are locally dominant. Except for the lower part of the Vaquería Formation, the remaining units are exposed in very limited areas. Obviously, these sections did not accumulate in small isolated depressions, but are the remains of a deeply eroded basin, located near the northern fringe of the extinct Upper Cretaceous volcanic arc (Figure 7).

The oldest beds resting on the Peñalver Formation belong to the Apolo Formation. (Figure 3, see below). Goto *et al.* (2008) remark the similarity of the Vía Blanca and Apolo formations, suggesting that the original environmental conditions were reestablished after the deposition of the Peñalver Formation. In central Cuba, lower Danian beds of the Santa Clara Formation, containing deep water fossils (Figure 8, Table 2; Alegret *et al*., 2005; Pedraza-Rozón, 2010) rest upon the chaotic clastic complex. Therefore, data from the underlying and overlying beds suggest the deposition of the Peñalver Formation and the K/Pg boundary section of the Santa Clara Formation in marine waters, at least several hundred meters deep. In the first case, this conclusion is reinforced by the great thickness of the unit (Goto *et al*., 2008).

END-MESOZOIC PALEOGEOGRAPHY OF WESTERN AND CENTRAL CUBA AND ITS SURROUNDINGS

Figure 9 shows the location of the North America paleomargin and the extinct Cretaceous arc in western and central Cuba in the latest Maastrichtian, according to preceding data. Two tectonic realms become evident. A northern one, related to the North America Cretaceous paleomargin, and a southern one, related to the extinct Late Cretaceous Cuban volcanic arc. This general palinspastic scenario will be essential to understand the distribution and composition of the K/Pg beds in central and western Cuba.

Figure 10 is a paleogeographic map of the northwestern Caribbean

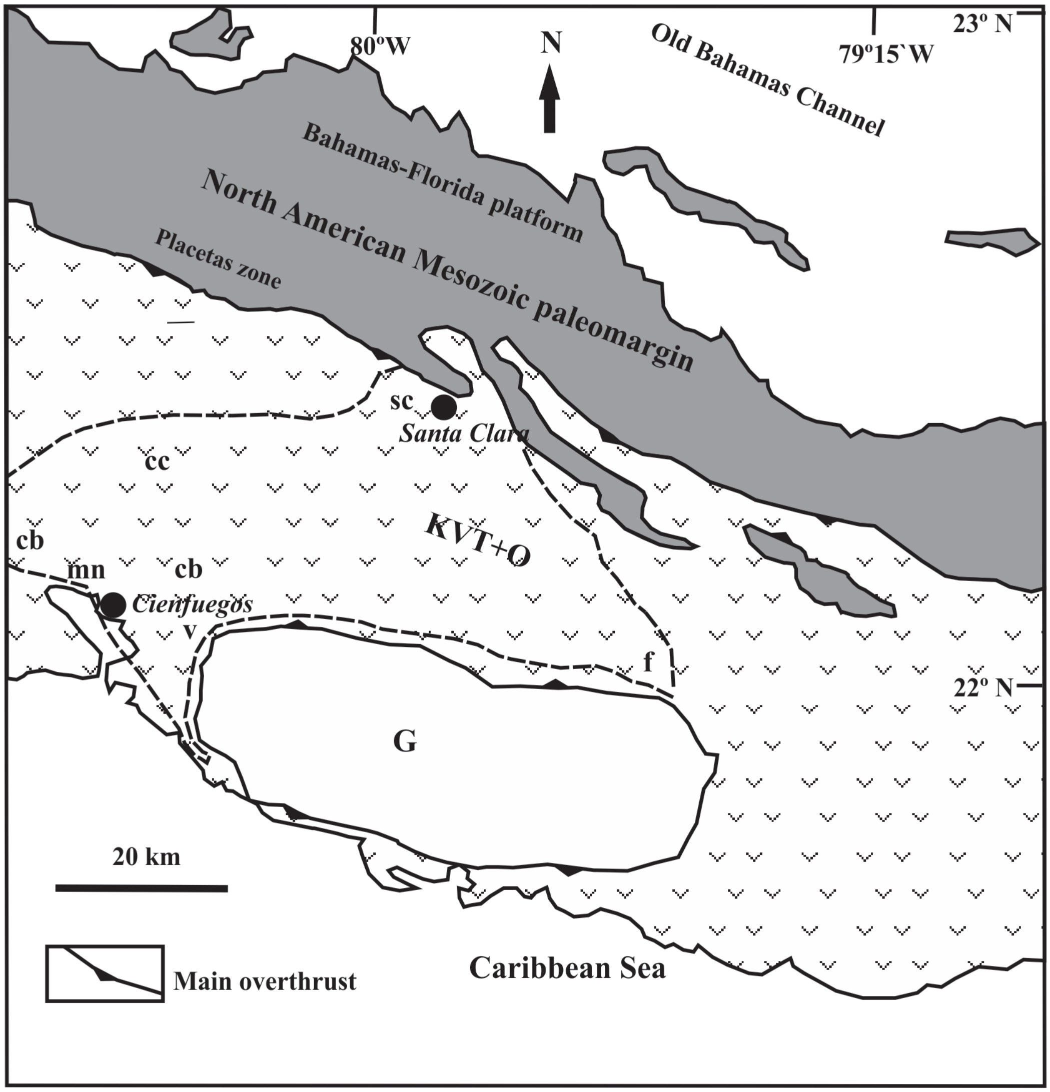

Figure 7. Simplified tectonic map of Cuba below the Cenozoic cover. The Placetas zone represents the southern fringe of the North American paleomargin. KVT+O: Cretaceous volcanic terrane plus the northern ophiolitic belt, G: Guamuhaya (Escambray) massif: Mesozoic metamorphic complex (it was below the Earth`s surface until Middle Eocene). Discontinuous line: inferred contour of the late Maaastrichtian-early Danian basin (sc: Santa Clara Formation, cc: Cocos Formation, f: Fomento Formation, v: Vaquería Formation, cb: Cantabria Formation, mn: Monos Formation). The tectonic contact between the Cretaceous volcanic terrane and the Mesozoic metamorphic complex is a Late Cretaceous structure, whereas the northern nappes developed during the Cuban orogeny (Paleocene-Middle Eocene in central Cuba).

area surrounding western and central Cuba at the end of Maastrichtian time, prepared with the information discussed in the preceding paragraphs and additional data from several sources (Pszczolkowski, 1982; Cobiella-Reguera, 2008, 2009; among others). Some brief comments are necessary.

1) Two basins developed on the extinct Cretaceous arc. A western SSW-NNE trending basin (Vía Blanca basin, VB), circa 300 km long and 100 km wide, collecting volcanoclastic turbidites derived from a southern source. Carbonate and terrigenous sediments, together with reworked tephra, accumulated in the eastern depression (Santa Clara Basin, SC; the Santa Clara, Cocos, Fomento and Vaquería formations; Figures 7 and 10). As no evidence exists for transitional sections between both basins, it seems very probable that some kind of geographic barrier interposed between them. In the map, a submarine high is assumed (Figure 10).

2) A submarine ridge, related to the North American paleomargin/ extinct Cretaceous arc collision belt, separated both domains (fig. 3 in Pszczolkowski, 1986; fig. 17 in Cobiella-Reguera, 2000). This ridge probably existed since the late Campanian and acted as a barrier, preventing the spillover of the turbidity currents travelling northward along the Vía Blanca basin into the North American paleomargin in western Cuba (Figure 10). This can explain why, despite the evidence of Cuban volcanic arc/North American paleomargin juxtaposition since the Campanian (Pszczolkowski, 1982, 1994; Cobiella-Reguera, 2000, 2005), the late Campanian-Maastrichtian volcanoclastic turbiditic currents did not arrive to the North American paleomargin. The turbidites originally accumulated at least circa 100 km southward of its present location, according to Cobiella-Reguera (2008) palinspastic reconstruction. The northern half of the ridge contained Mesozoic rocks of the North American paleomargin border, whereas its southern half

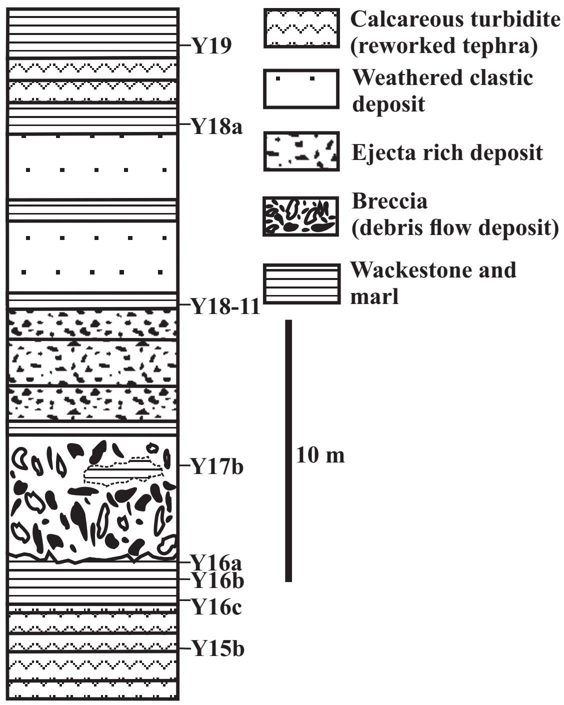

Figure 8. Stratigraphic log of K/Pg beds in the Santa Clara Formation at Dos Hermanas hill, Santa Clara City. Discontinous line: olistolith. The position of samples reported in Table 2 is also included.

was a tectonic mix of Cretaceous volcanic arc rocks and the Mesozoic ophiolite suite (Cobiella-Reguera, 2009).

3) Rudist banks were common along the coasts and on shallow marine floors. In late Maastrichtian time, they flourished on the coasts and shallow bottoms adjoining the southern sediment source of the Vía Blanca Formation (Figure 10) and also on the submarine ridge separating the northwestern Caribbean realms, as suggested by the vast amount of shallow-water Maastrichtian carbonate debris in the basal breccias of the Cretaceous/Paleogene boundary deposits (Kiyokawa *et al*., 2002; Tada *et al*., 2003; García-Lavín, 2009). However, nothing like the "Cuban Platform" carbonate bank (fig. 1 in Goto *et al*., 2008) probably existed. This subject will be treated later.

4) At least since Turonian time, the southern fringe of the North American paleomargin in Cuba (Cobiella-Reguera, 2000) and the southeastern Gulf of Mexico (Schlager and Buffler, 1984) were part of a starved basin, perhaps with bottoms below the carbonate compensation depth or with strong bottom currents preventing deposition of fine sediments (Figure 10).

TYPES AND DISTRIBUTION OF K/Pg BOUNDARY DEPOSITS

In the preceding section, the complex geographic scenario at the end of Maastrichtian time was shown. This fact, and the diverse nature and transportation mechanism (tsunamis, gravity flows, density currents, ballistic, etc.) of the huge mass of clastic particles generated by the asteroid impact and associated phenomena, ruled the sediment distribution and facies changes. According to its composition, internal architecture and thickness, we distinguish three types of K/Pg boundary deposits in Cuba: Type 1, with a thickness up to several hundred meters; basal chaotic breccia, followed by a thick massive fining upward sequence (calcarenite to calcilutite). Type 2, with a thickness of meters to tens of meters; basal chaotic breccias, followed by ejecta-rich deposits. Type 3, with a thickness in meters; ejecta-rich deposits.

The Cacarajícara, Amaro and Peñalver formations are Type 1 deposits, in which the impact ejecta are diluted in huge volumes of clastic particles. K/Pg boundary deposits in Santa Clara Formation and coeval rocks from ODP Leg 77 (Alvarez *et al*., 1992) are much thinner, type 2 beds. The Moncada Formation (Type 3) is a multiple graded sandy layer, less than 2 meters thick, with abundant ejecta.

Type 1 deposits

Very thick K/Pg beds extent over vast areas in western and central Cuba (Figure 1). They all present the same general architecture, pointing to a common depositional process (Figure 11). However some differences exist, particularly in the composition of basal breccias clasts.

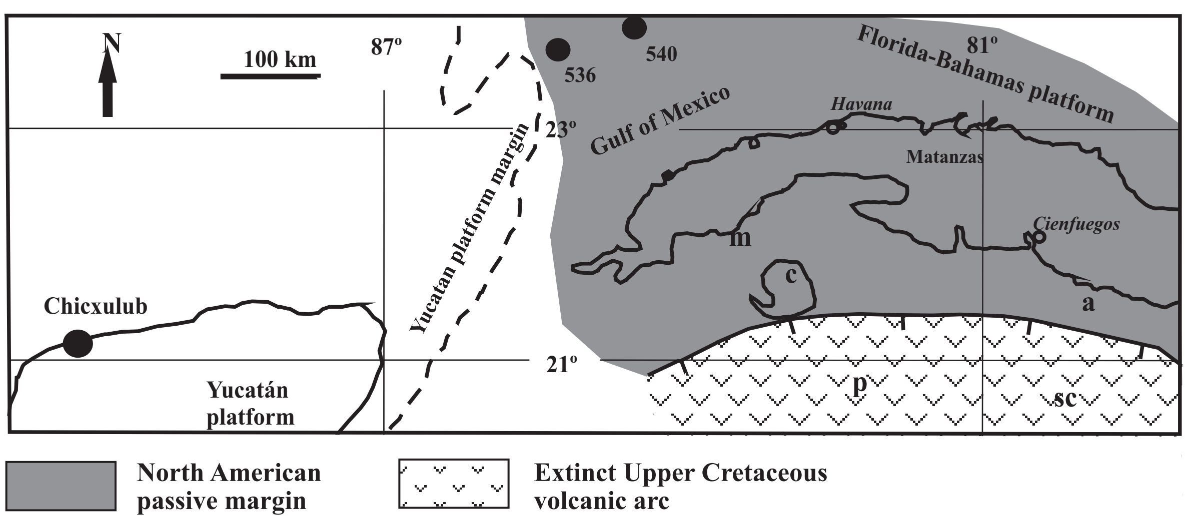

Figure 9. Paleopositions of the North American margin and the extinct Cretaceous volcanic arc at Maastrichtian end. The location of the K/Pg boundary deposits is shown. a: Amaro Formation; c: Cacarajícara Formation; m: Moncada Formation; p: Peñalver Formation; sc: Santa Clara Formation; 536 and 540: Deep Sea Drilling Project leg 77 sites.

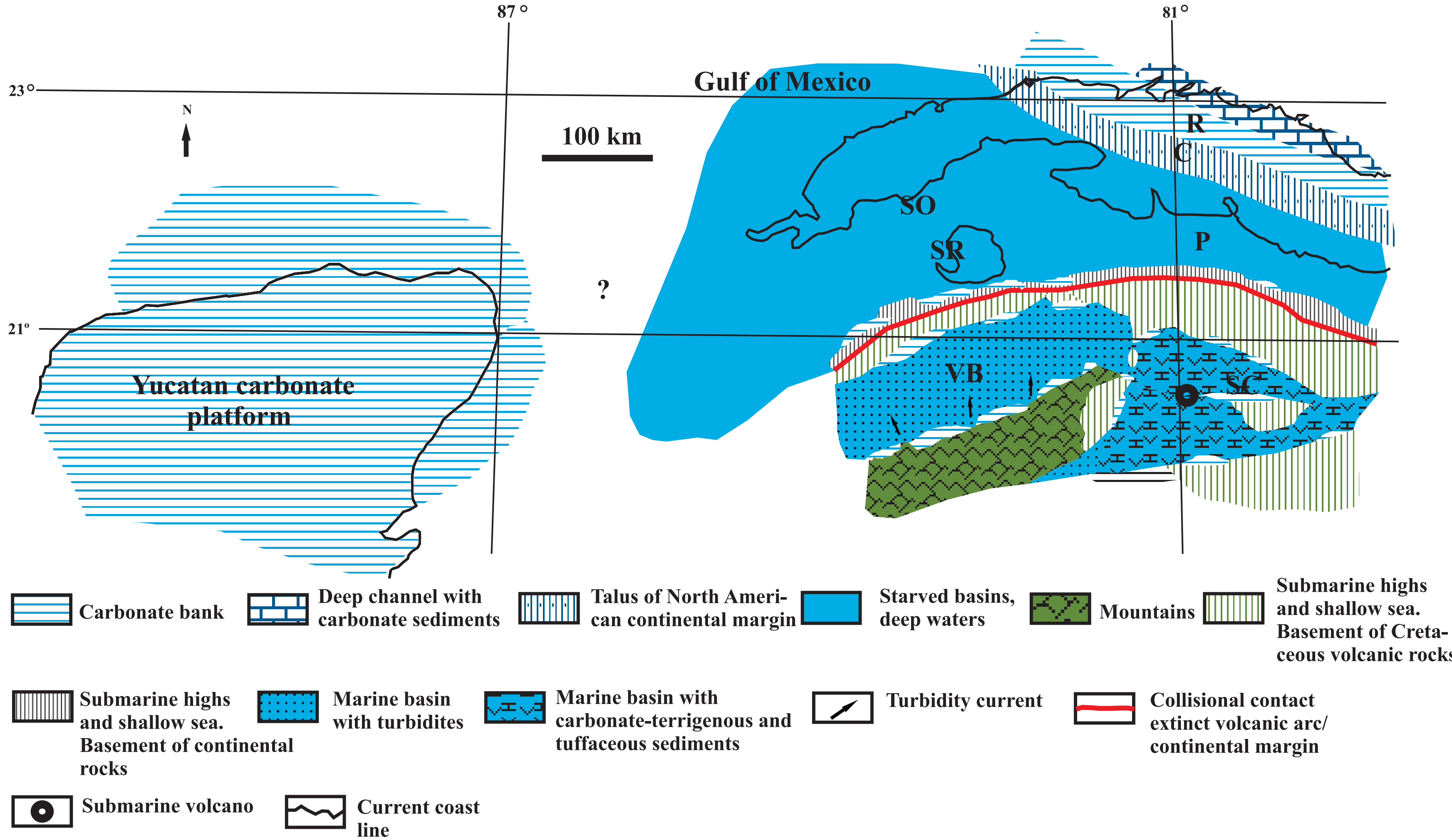

Figure 10. Paleogeographic map of western and central Cuba and its surroundings at Maastrichtian end. SR: Sierra del Rosario. Alturas de Pizarras del Norte-Esperanza unit; SO: Sierra de los Órganos unit; R: Remedios zone, C: Camajuaní zone; P: Placetas zone, VB: Vía Blanca basin, SC: Santa Clara basin. See explanation in text.

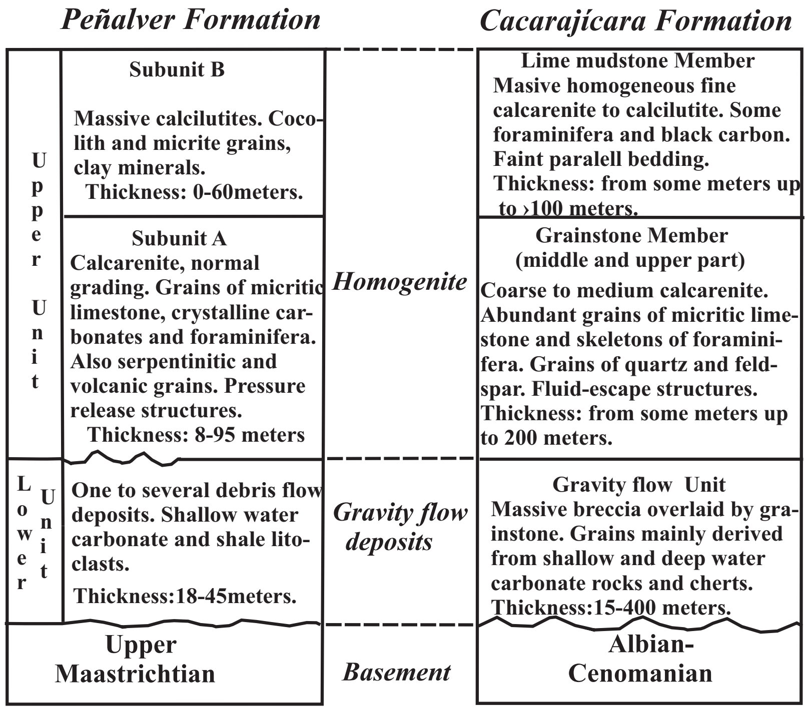

Figure 11. General features of the Type 1 deposits in the Peñalver and Cacarajícara formations.

The Peñalver Formation

The Peñalver Formation (Bronnimann and Rigassi, 1963) crops out in Cretaceous volcanic terrane of western Cuba. In the last years the formation was studied in detail by Takayama *et al.* (2000), Tada *et al.* (2003), and Goto *et al.* (2008). These authors distinguished two main genetic and compositional units in the Peñalver Formation, a lower and an upper unit; the last one is divided in subunits A and B (Figure 11). In the type locality, in Havana city, the formation is more than 180 meters thick. The lower unit is a massive, grain supported calcirudite, 30 meters thick, with large lutite olistoliths, derived from the Vía Blanca Formation (Figure 12). The clasts are mainly angular, shallow-water bioclasts with very subordinated matrix. Contact with the upper unit is a thin transitional zone (Goto *et al.,* 2008). The upper unit of the Peñalver Formation represents a huge massive deposit or homogenite (Takayama *et al*., 2000; Goto *et al.*, 2008), a term introduced by Kastens and Cita (1981) for graded homogeneous deposits, without current structures, accumulated from very dense suspensions in the Mediterranean Sea. The lower homogenite, subunit A, is a calcarenitic interval with a basal massive calcarenite, 55 m thick, with normal grading (Figure 11). Above rests a bedded calcarenite, 40 m thick, with micritic grains and some skeletal foraminifera. Serpentine and volcanic clasts are frequent in the whole subunit, with several peaks in serpentine grain contents. Subunit B is a massive calcilutite, several tens meters thick; serpentine grains are absent, except in the lowermost part (fig. 8 in Goto *et al.* 2008).

At Santa Isabel, westward from Havana (x in Figure 2), the lower unit (45 m thick) of the Peñalver Formation contains several debris flow deposits, with upward grading. Bioclast of shallow-water origin, biomicrites and crystalline carbonate are the main components, whereas non carbonate grains are less than 15%, and lutite clasts are abundant. The homogenite is 35 m thick. Subunit A is a massive calcarenite, similar to its equivalent in Havana, but lacks serpentine grains and contain abundant spinel. Subunit B is a calcilutite, which is stratified as result of fluctuations in clay content. A thin, slightly bioturbated bed, with a moderate Ir anomaly, rests at the top of the subunit. The easternmost outcrops are located in Matanzas province (Figure 1; Tada *et al*., 2003; Goto *et al*., 2008). Near Cidra, approximately 90 km to the east of Havana, the lower unit is 18 m thick and it is composed of two calcirudite to calcarenite beds. The rock contains abundant rounded fragments of shallow-water clasts and some shale fragments. The homogenite is only represented by subunit A, a fine to very fine graded grainstone bed, more than 67 m thick, with a basal erosional contact. The grain composition and size are similar to those in Havana. The amount of shallow marine fossils drastically decreases in its lower part, whereas serpentine grains first appear at the lower contact, with similar content fluctuations as recorded in Havana area.

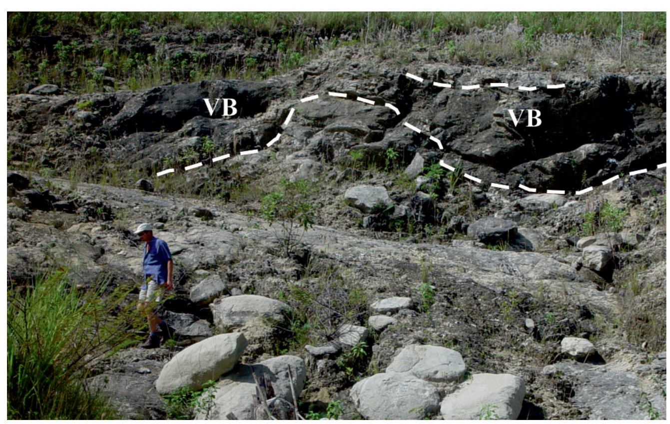

Figure 12. Olistolith (VB) of fine-grained siliciclastic rock (partly outlined by the discontinuous white line), probably derived from the Vía Blanca Formation, within the Peñalver Formation calcarenites (light-gray rocks weathering to big boulders). The man in the photo is 1.85 m high. Locality: Sepultura, near La Victoria quarry, southeastern Havana. Coordinates: 82°10’36”E; 23°03’41” N.

A faint bedding appears in its upper part. Pipe and pillar structures, related to water scape during sedimentation, are recorded in Havana and Cidra (Goto *et al.,* 2008). According to Piotrowska *et al.* (1981), the calcilutites (subunit B) outcrop in minor areas in the Matanzas province, probably as result of pre-Eocene erosion.

The Cacarajícara Formation

The Cacarajícara Formation (Hatten, 1957) rests on the Cretaceous beds of the North American paleomargin. The formation outcrops in Sierra del Rosario/Alturas de Pizarras del Norte tectonic unit, including its prolongation in the Martin Mesa window near Havana city area. This formation is also known in the deep wells of northwestern Cuba (Figures 1 and 2). In many places, tectonic slices of the formation are included in melanges, and the unit was strongly eroded during the early Paleogene tectonic events in western Cuba. Many olistoliths of the Cacarajícara Formation are included in the younger Manacas Formation (Cobiella-Reguera, 1998, 2008, 2009). Also, because of the complex geologic scenario in Sierra del Rosario, tectonic slices of other lithostatigraphic units were considered as part of the lower breccias of the Cacarajícara Formation (the Los Cayos Member; Cobiella-Reguera, 1998). Therefore, a correct interpretation of the Cacarajícara Formation original location must take account of all these facts. The unit is circa 800 m thick along the northern fringe of the mountains (Figure 2; Kiyokawa *et al.*, 2002; Tada *et al.* , 2003) but only tens of meters or less in others areas. As the beds originally deposited in the southernmost localities are located in the northern Sierra del Rosario (Pszczolkowski, 1999; Cobiella-Reguera, 2008), the maximum thickness of the unit was located in its southern depositional area. The lower section (Kiyokawa *et al.,* 2002; "Lower Breccia Member" of Tada *et al.,* 2003) is a massive grain-supported rudite, up to 400 m thick, almost without matrix (Figure 13). Detritus is derived from the Lower Cretaceous rocks of the underlying paleomargin: Aptian-Albian cherts with shaly interbeds (the Santa Teresa Formation) and Albian-Cenomanian limestones with black cherts (the Carmita Formation), together with clasts from Albian-Cenomanian and Campanian-Maastrichtian carbonate banks (Gil-González *et al.*, 1998; Kiyokawa *et al.,* 2002*;* Tada *et al.,* 2003*;* García-Lavín, 2009) and, more sporadically, from older units. The clasts are in tight contact, with olistoliths attaining up to 25 meters by the long axis. A decrease in grain size occurs in the upper part of the "Lower Breccia Member" (pebble breccias of Kiyokawa *et al*., 2002). Spherules and shocked quartz grains are present but the first ones are concentrated only in the basal part of the breccia (Kiyokawa *et al.,* 2002; Tada *et al.*, 2003). Upon the rudites rests a coarse conglomeratic grainstone section, with similar clast composition. Tada *et al.* (2003) consider this calcarenite section (lower part of their "Grainstone Member") genetically related to the lower breccia and together make "the lower gravity flow unit" (Figure 11). The middle and upper parts of the "Grainstone Member" and the "Mudstone Member" represent a massive well sorted fining upward, non stratified deposit almost 400 m of maximum thickness, equivalent to the Upper Unit (homogenite) of the Peñalver Formation. The sand grain composition includes micritic limestone and foraminiferal skeletons, circa 80% of them of Maastrichtian and 11% of Albian-Cenomanian age (García-Lavín 2009), with some larger bioclasts, detrital quartz and feldspars. Fluid-escape structures were recorded by Kiyokawa *et al.* (2002). A transition exists between the grainstone and the overlying "Mudstone Member". This last unit, composed of graded fine calcarenite to mudstone with disseminated foraminifera skeletons, bioclasts of shallow-water origin and black carbon clasts, can attain thicknesses over 100 m.

Several fluctuations in grain size and shocked quartz content are recorded in the Cacarajícara Formation homogenite. Shocked quartz and "carbonate pisoliths" (accretional carbonate tuff from impact-induced calcite vapor) were recorded by Kiyokawa *et al.* (2002) in the grainstones.

The general features of the Cacarajícara Formation described above correspond to the northern outcrops (Figure 2) in the Santiago river section. Southward, in the lower tectonic units with lesser horizontal movements (Cobiella-Reguera, 2008), the thickness is remarkably reduced (Pszczolkowski, 1986; 1994), and we detected some graded structures related to pulses of turbiditic currents in the upper part of the "gravity flow unit" (Figure 14). In these localities, the Cacarajícara Formation and other units are strongly dissected by numerous faults of different origins (Cobiella-Reguera *et al*., 2000).

The Amaro Formation

The Amaro Formation rests upon Cretaceous units of the North American paleomargin in northcentral Cuba (Figure 1). The deposit is a calcareous unit, 20 to 350 m thick, very similar to the Cacarajícara Formation (Pszczolkowski, 1986, Linares-Cala *et al*., 2011). A massive breccia, with Upper Jurassic to Lower Cretaceous clasts derived from the North American paleomargin, lies below a grainstone middle part, containing upper Maastrichtian taxa (Blanco-Bustamante *et al*., 2007, Fernández-Pérez *et al*., 2011). Mudstone, with poorly developed horizontal bedding, rests in the upper part (identified as the Rodrigo Formation in Kantchev *et al*., 1978). Frequently the formation lies with

Figure 13. The Cacarajícara Formation breccia in Loma Miracielo, Santiago river, Sierra del Rosario, Artemisa province. This is the same locality studied by Kiyokawa *et al.* (2002) and Tada *et al.* (2003). The clasts are tightly welded and some of them are broken. Matrix is almost absent. About 30–40% are chert fragments (darker clasts), probably derived from the Santa Teresa and Carmita formations. Scale: coin (13 mm in diameter) in the upper right corner. Coordinates: 83°02'40" E, 22°52'11" N.

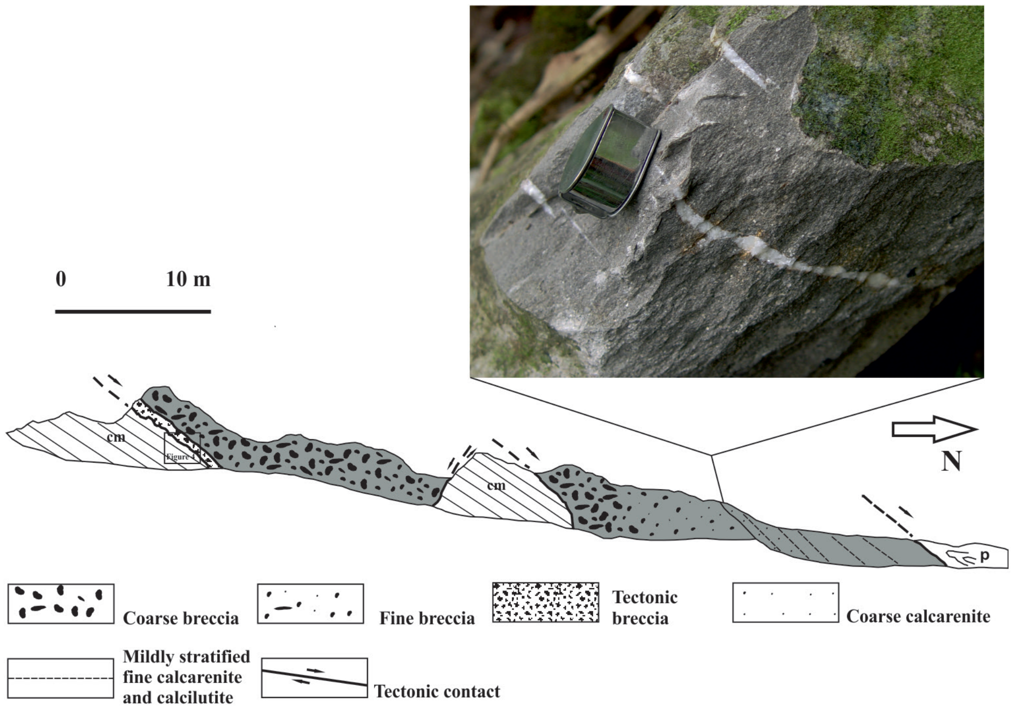

Figure 14. Profile through a section of the Polier (p, Berriasian-Aptian), Carmita (cm, Albian-Cenomanian) and Cacarajícara (light gray background; K/Pg strata) formations, near Las Terrazas, Sierra del Rosario. In this area, the Cacarajícara Formation is 20–25 meters thick. Inserted photo: graded calcarenite bed near the top of the lower unit of Type 1 deposits. Rectangle shows the position of Figure 4. Coordinates: 82° 57' 00" E; 22° 51' 21" N.

tectonic contact upon lower Upper Cretaceous beds (Piotrowska *et al.*, 1981). Fernández-Pérez *et al.* (2011) report spherules in two wells at Boca de Jaruco, near Havana City. The Amaro Formation is known from the subsurface in an area extending from Havana eastward to Matanzas province (Figure 1, Blanco-Bustamante *et al.*, 2007), and from outcrops in northern central Cuba (Pushcharovski, 1988). As the eastern outcrops of the Cacarajícara Formation are located in the Martín Mesa erosional window, 20 km west of Havana (Figure 2), probably both units represent a single deposit. The Amaro Formation is a reservoir in northern Cuba hydrocarbon fields (Blanco-Bustamante *et al.*, 2007).

By far, Type 1 deposits constitute the bulk of K/Pg boundary strata in Cuba western half. On the basis of Figure 10, some rough volume estimations are possible. Considering a moderate average thickness of 100 m for the Cacarajícara and Amaro formations and a common original depositional area of circa 25,000 km^2, a rough estimate of about 2500 km^3 of sediments seems possible for Type 1 beds deposited on the North American Mesozoic paleomargin in western and central Cuba. The same method, applied for the Peñalver Formation with an average thickness of 100 m and a depositional area (Vía Blanca basin) of 17,500 km^2), yields 1750 km^3 of original sediments. These values are at least one order of magnitude higher than those calculated by Pszczolkowski (1986).

Type 2 deposits

K/Pg boundary beds in the Santa Clara Formation

The Santa Clara Formation is a deep-water volcano-sedimentary section, with the K/Pg section resting in its middle part (Figure 8). Our team specially studied two sections of this unit, 0.5 km apart from each other, in Santa Clara city: Loma Capiro Monument and Dos Hermanas hill. A basal chaotic breccia is present in both places. In Loma Capiro Monument, the basal rudite is several meters thick, resting with erosional contact on Maastrichtian calcarenite and marl (Figure 15). Its composition changes abruptly in short distances (carbonate to igneous clasts ratio and shallow water carbonate to marl + limolite clasts ratio). Some limolitic and marly clasts preserve irregular shapes, suggesting erosion and transport while they were unconsolidated fragments. A clast with an upper Maastrichtian association (*Orbitoides villasensis*, *Asterorbis* sp., *Hedbergella monmonthensis* and *H. holmdelensis*) was identified. The poor quality of the outcrops above the breccia do not allow documenting a complete section (Figure 15).

Dos Hermanas hill section was studied by Alegret *et al.* (2005) and Rojas-Consuegra *et al.* (2005). We visited it in December 2009 and returned briefly in October 2010. The outcrop is severely weathered and eroded (Figure 16), and some differences were detected with respect to descriptions in previous papers. The Dos Hermanas hill section (Figure 8, circa 9.5 m thick) has two peculiar features:

1) The basal unit (breccia, b in Figure 16) rests on carbonate and tuffaceous beds of uppermost Maastrichtian age (Table 2) not reported in the Alegret *et al.* (2005) study. The breccia contains abundant clasts from the ophiolitic suite (diabase and basalt) mixed with tuff, marl (sometimes deformed and with Maastrichtian fossils) and limestone. Fabrics ranges from grain supported in the lower part, to matrix supported upward, where the grains become finer. The breccia is overlain by circa one meter thick, graded, clastic, stratified deposits (perhaps an olistolith), with a marl bed on top (arrow in Figure 16) containing Maastrichtian fossils (Table 2).

2) Three calcareous fining upward layers with crude bedding, synsedimentary deformation, "acrettionary lapilli", and irregular carbonated vitreous splinters (similar to "cored melt fragments", recorded in unit 2 of Yax-1 well in Chicxulub by Goto *et al.*, (2004; fig. 4c) lie on the breccia. The beds probably correspond to the upper

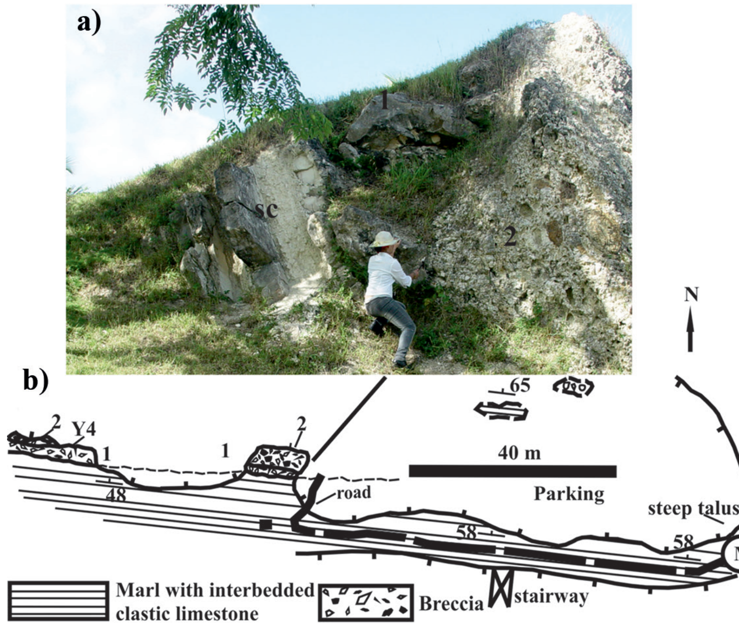

Figure 15. (a) Bedded Santa Clara Formation (sc) resting, with erosional contact, below the breccias of the K/Pg boundary deposits at Loma Capiro Monument. Two breccia lithosome (1 and 2) are present. Lithosome 1 is mainly composed of shallow-water limestone boulders, whereas in lithosome 2, the grains are smaller and volcanic (dark) clasts are abundant. Coordinates: 79°57'02" E; 22°24'31" N. (b) Plant view of the locality (M: monument). A clast in Y4 contains an upper Maastrichtian association.

subunit of Alegret *et al.* (2005), for which these authors reported shocked quartz, terrestrial chondrules, abundant accretionary lapilli (spherules) and calcitized dark olive-green glass (Figure 5c and 16).

About 40 km southeast of Santa Clara city, a probable K/Pg boundary bed, deposited in the same basin (Figure 7) as the Santa Clara Formation, was recently discovered in the Fomento Formation (Figure 7; Pérez-Estrada *et al.,* 2009). However, information on its composition and internal architecture is still insufficient.

K/Pg boundary strata at DSDP sites 536 and 540

Alvarez *et al.* (1992) divided sequence detected at DSDP sites 536 and 540 of the southeastern Gulf of Mexico (Figure 1 and 3) in five units, and considered units 3 and 4 as the K/Pg boundary deposits. Unit 1 is the Cenomanian basement of the section. Unit 2 is a 45 meters thick pebbly mudstone interpreted, at least in part, as a mudflow deposit. Alvarez *et al.* (1992) suspected a K/Pg boundary age for this part of the section, and this was later established by Bralower *et al.* (1998). Unit 3 is a grainstone interval 0.6–2.6 m thick. The rock contains smectite grains, derived from spherules, and impact-related ejecta glass. Abundant shocked minerals (28% of grains showing shock features) were recovered from site 540 (quartz, quartzite and feldspar). Cross bedding (locally bidirectional) is conspicuous in some intervals. Iridium contents values are high in unit 3, supporting the idea that this unit accumulated simultaneously with the Chicxulub impact event. Unit 4 is a 50 cm thick section in which the planktic foraminifera are only tiny Cretaceous species. Unit 5 is a Danian ooze with small basal Paleocene taxa (not including the planctic foraminifera P0 zone). Near the top of unit 4, Ir content peaks at 650±15 ng/g; high iridium contents continue at the base of unit 5, decreasing upward (Alvarez *et al.,* 1992).

Type 3 deposit

The Moncada Formation

The unit is a calcareous sandstone complex, circa two meters thick, with calcareous shales and fine sandstone intercalations near the top. The strata disconformably rest on Cenomanian beds of the Pons formation (Figure 6; Tada *et al.*, 2003). Moncada Formation is characterized by repetition of sandstone units with overall upward fining and thining. Ripple cross-laminations at several horizons indicate north-south trending paleocurrent directions with reversals. The unit contains abundant altered vesicular impact-related melt fragments, shocked quartz and altered and deformed greenish grains (Tada *et al.,* 2002) and also chert and limestone clasts derived from underlying Cretaceous beds (Figure 5f). Changes in detrital composition corresponding to paleocurrent reversals are also present. At top, a 3–5 cm thick bed (uppermost unit) of light colored shale and dark colored fine sandstone rests on unit 5. A strong Ir anomaly is related to the uppermost unit and the basal first centimeter of the overlying Ancón Formation (Tada *et al.*, 2002).

DISCUSSION. ORIGIN OF K/Pg BOUNDARY DEPOSITS IN WESTERN AND CENTRAL CUBA

The papers of the Cuban-Japanese project (Takayama *et al.,* 2000; Goto *et al.,* 2008; among others), Alegret *et al.* (2005), and Rojas-Consuegra *et al.* (2005), which appeared in the first years of the current century, reported that a remarkable and varied group of K/Pg boundary deposits are present in western and central Cuba. However, their geological setting, specially the paleogeography at Maastrichtian decline, was not fully understood. The following lines contain a brief discussion on the genesis and original distribution of the K/Pg boundary deposits in western and central Cuba, and on the role of latest Maastrichtian regional paleorelief in this event.

The coarse rudite in the Cacarajícara, Peñalver (Takayama *et al.,* 2000; Tada *et al.,* 2003; Goto *et al.,* 2008), Amaro (Pszczolkowski, 1986) and Santa Clara (Rojas-Consuegra *et al.,* 2005*)* formations, and probably in DSDP sites in the southeastern Gulf of Mexico (Alvarez *et al.,* 1992), are mainly debris flow deposits (Tada *et al.*, 2003) derived from local sources. The origin of breccia in Type 1 and 2 deposits is tightly related to the coeval regional relief. They were generated along steep island talus and submarine scarps, frequently with Maastrichtian rudist banks flourishing on top. The clast composition in the beds resting on the North American paleomargin (the Cacarajícara and Amaro formations) is related to the Cretaceous substrat in the southern paleomargin border (Figures 9 and 10). In the Cacarajícara Formation,

Figure 16. Outcrop at Dos Hermanas hill, Santa Clara, central Cuba. The basal breccia (b) in the background is covered by stratified deposits (olistolith?) with marl on top (arrow). Crudely stratified accretionary lapilli (al) with glass splinters rest above. This is the same locality studied by Alegret *et al.* (2005) and Rojas-Consuegra *et al.* (2005). Length of the hammers: 33 cm. Coordinates: 79°56'41" E; 22°24'34" N.

clasts are mainly derived from the Pan de Guajaibón (Cenomanian; Gil-González *et al.,* 1998), Santa Teresa (Aptian-Albian) and Carmita (Albian-Cenomanian) formations. The abundant Maastrichtian clasts (Gil-González *et al*., 1998) probably come from the combined erosion of the Maastrichtian carbonate banks growing on top of the collision zone submarine high (Figure 9 and 10) by giant tsunamis waves (Matsui *et al*., 2002) and the preceding seismic waves. Clast composition invalidates Kiyokawa *et al.* (2002) hypothesis, considering Yucatán platform as the source of the Cacarajícara Formation gravity flow unit. In the Amaro Formation (at least near Havana city), the coarse clasts were derived mainly from Upper Jurassic-Lower Cretaceous deposits of Placetas zone, whereas clasts from Maastrichtian carbonate banks have a subordinate role (Blanco-Bustamante *et al.,* 2007).

Kiyokawa *et al.* (2002) assumed an origin under "laminar flow conditions in a very high speed dilatant situation" for the basal unit of Cacarajícara Formation. We consider the beds of the lower unit (breccia plus coarse calcarenite) of the Cacarajícara and Amaro formations as originated mainly from huge and violent debris flows with contributions from massive slumps, avalanches, and sporadic turbidity currents, along the northern flank of the submarine ridge (Figure 10).

In the lower unit of the Peñalver Formation, Cretaceous volcanic clasts and detritus derived from the underlying Vía Blanca Formation are subordinate (Figures 11 and 12), whereas upper Cretaceous shallow-water carbonate biodetritus is very frequent. In the paleogeographic reconstructions by the Cuban-Japanese team, a great carbonate bank is located southward of the depositional site of the Peñalver Formation (Tada *et al*., 2003; Goto *et al*., 2008). A fact, previously described in the current paper but not considered in previous studies, is the abundant content of coarse bioclastic beds in the uppermost strata of Vía Blanca Formation in all localities. In our opinion, this scenario suggests an episode of intense erosion of the carbonate banks flanking the coast during the late Maastrichtian (probably related to the coeval global regressive event), whereas highlands with volcanic outcrops, located toward the interior, were denudated (Figure 10). Siliciclastic beds are dominant, even in the uppermost Vía Blanca strata, and little remains of that supposed platform could be invoked in western and central Cuba, except for the Cantabria Formation, in northern Cienfuegos basin (Figure 7; Pszczolkowski, 2002) and small bioherms in the carbonate-terrigenous Los Negros (San Juan y Martínez) Formation in westernmost Cuba (Figure 2; Piotrowski, 1987; Gil-González *et al*., 2007).

Following Goto *et al.* (2008), Tada *et al.* (2003) and others, we assume that the "lower unit" of the Peñalver Formation are huge debris flow deposits. These coarse sediments chaotically accumulated in the Vía Blanca basin during the first hours after the impact, previous to the arrival of the hiperdense carbonate suspension (Takayama *et al.,* 2000).

In Type 2 deposits, the breccia composition in the Santa Clara Formation is tightly related to the substrate in nearby areas, where ophiolitic and volcanic arc rocks crop out (Pushcharovski, 1988; Rojas-Consuegra *et al.,* 2005). Besides, close areas with Maastrichtian shallow carbonates are evident from grain composition of the Santa Clara Formation carbonate turbidites (Pedraza-Rozón, 2010) and from reports for the nearby Cienfuegos basin (Figure 7; Pszczolkowski, 2002). These Type 2 beds deposited at batial depths, more than 500–700 meters below sea level (Alegret *et al.,* 2005). On the other hand, in the southeastern Gulf of Mexico DSDP sites, the breccia was derived from Yucatán or Florida-Bahamas platform talus (Alvarez *et al.*, 1992).

Homogenite clastic composition records a distinct source, unrelated to that of the underlying coarse clastics (Figure 11; Takayama *et al*., 2000; Tada *et al*., 2003; Goto *et al*., 2008). Sedimentary structures as well as ejecta grain contents show that, in each case, the homogenite unit accumulated very fast from hyperdense suspensions (Tada *et al*., 2003). In their seminal paper, Kastens and Cita (1981) considered that the liquefaction of sediments originating the Mediterranean homogenite was due to tsunami erosion, whereas the impact of seismic waves was minor. Probably this was not the situation with the K/Pg boundary homogenite in Cuba, because the seismic waves of the megaearthquake generated by the Chicxulub impact (Matsui *et al*., 2002; Schulte *et al.* 2010), liberated an energy thousands times greater than the energy released in the major tectonic earthquakes so far recorded (Schulte *et al.*, 2010). The liquefied carbonate sediments created dense suspensions that quickly moved along the deepest parts of the complex sea floor relief, flowing towards the basins, where they finally settled. Data from different sources show that some extraordinary tsunamis, several hours apart, traveled the Gulf of Mexico and the ancient Caribbean basin after the Chicxulub impact (Smit *et al.,* 1992; Matsui *et al.,* 2002). The fluctuations in grain composition and diameter, particularly in the Peñalver Formation homogenite, also suggest the travel of successive tsunami waves during sedimentation (Tada *et al.,* 2003). Therefore, suspensions generating the homogenite of the Cacarajícara, Amaro and Peñalver formations formed before the late tsunamis, and were affected by them when settling was in progress in the deep basins (Tada *et al.,* 2003; Goto *et al.,* 2008). Additionally, the effect of oscillating currents, of the seiche type, described by Smit *et al.* (1992) in the northern Gulf of Mexico must be considered.

In the clastic complex of the Santa Clara Formation the homogenite is absent, probably because the Santa Clara and Vía Blanca deep basins were separated by a narrow shallow-water area (Figures 10 and 17). Alvarez *et al.* (1992) reported cross bedding (in part bidirectional) in some parts of unit 3 in the DSDP sites, whereas cut and fill structures have been reported for the Dos Hermanas section (middle subunit of Alegret *et al.,* 2005). Therefore, in both localities strong evidence for tsunami activity are present.

Type 3 deposits (Moncada Formation) are deprived of coarse chaotic sediments. This fact, together with the Upper Cretaceous unconformity below the Moncada Formation (Figure 6), point to accumulation above an elevated seafloor area, contrary to Types 1 and 2. Clear evidences of tsunami waves during deposition are recorded in the paleocurrent inversions and reiterated changes in sedimentary structures in the ejecta-rich deposits of the Moncada Formation (Tada *et al.*, 2002, 2003).

Geodynamic model

Figure 17 resume our ideas to explain the genesis and original distribution of K/Pg boundary deposits in Cuba and its surroundings. The model assumes extraordinary slumps along the Yucatán and Florida-Bahamas carbonate platform margins just after the asteroid impact. At the Chicxulub event, the long submarine ridge of the extinct Cuban volcanic arc/North American paleomargin collision zone (Figure 10) was a remarkable sea floor feature where great slumps and debris flows developed, triggered by the seismic waves and tsunamis traveling from the Chicxulub crater. These gravity flows originated the very thick "lower gravity flow unit" of the Cacarajícara and Amaro formations (Figure 17). Its equivalent in the Peñalver Formation probably resulted from the destruction of the rudist banks and the youngest siliciclastic Maastrichtian deposits along the steep southern shore of Vía Blanca basin (Figures 10 and 17). A great mass of detritus, chaotically mingled with sea water, descended as one (in Havana city area) or several giant debris flows (in Bahía Honda and Cidra areas), finally resting at considerable depths on the basin floor. At the same time, the coarse ejecta particles created during the asteroid impact settled through the atmosphere and hydrosphere, resting within the chaotic deposits.

Tada *et al.* (2003) proposed a 50 km wide and hundreds meters deep channel was excavated in the northern Sierra del Rosario Cretaceous deposits by flows carrying the clasts of Cacarajícara Formation breccia. However, the fact that, in most localities, the rocks below the Cacarajícara Formation breccia are Albian-Cenomanian strata (the Carmita Formation; Pszczolkowski, 1978, 1994, 1999) and that Turonian-Santonian clasts are almost absent in Cacarajícara calcirudite (García-Lavín, 2009) suggests that debris flow erosion was not very intensive (Figure 3). Probably the same applies for the deposition of the Amaro Formation. At least for the Peñalver Formation (Goto *et al.*, 2008) and for the breccia of the Santa Clara Formation (Figures 15 and 16; Rojas-Consuegra *et al.*; 2005; Pedraza-Rozón, 2010), there is no clear evidence of a remarkable erosional event acting upon the underlying beds, because upper Maastrichtian strata rest below the coarse K/Pg boundary sediments (Figures 3 and 15).

Meanwhile, in the great carbonate platforms talus near Cuba (Yucatán, Florida-Bahamas), giant, very fast moving avalanches and debris flows entrained many cubic kilometers of unconsolidated and poorly consolidated carbonate sediments from the ocean floor,

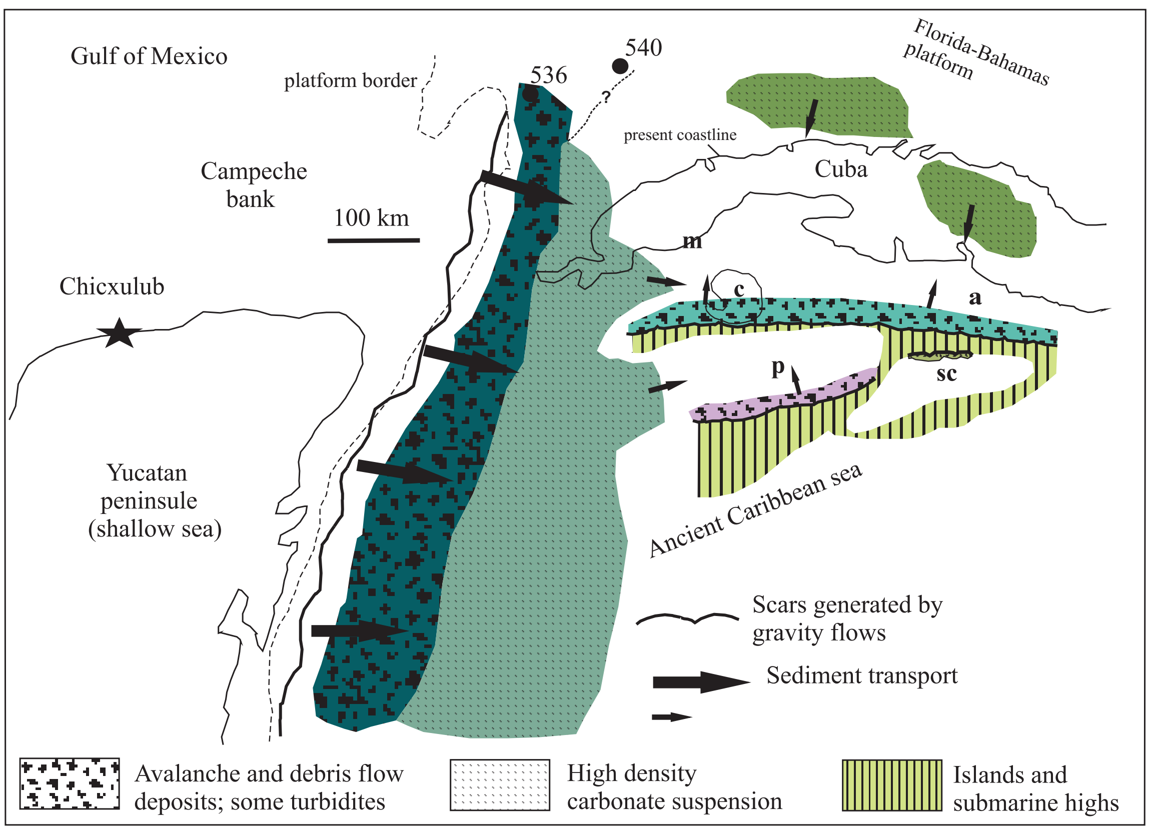

Figure 17. Geodynamic model (see explanation in text). a: Depositional area of the Amaro Formation; c: depositional area of the Cacarajícara Formation; m: depositional area of the Moncada Formation; p: depositional area of the Peñalver Formation (Vía Blanca basin); sc: depositional area of K/Pg boundary deposits of the Santa Clara Formation; 536 and 540: DSDP leg 77 sites.

previously shocked and liquefied by seismic waves (Figure 17). This process was followed by the first extraordinary receding and rushing tsunami waves (Matsui *et al.*, 2002). The huge volumes of psamitic and pelitic grains of Maastrichtian age in the homogenite source point to intense erosion of the youngest sea-floor deposits. A very dense suspension, at least several hundreds of meters thick, began to move, following the sea-floor relief and flowing toward the deepest basins. After the arrival of the suspension to the basins, the hyperdense current was braked and trapped**,** quickly dropping its contents in waters still affected by reflected tsunami waves (Smit *et al*., 1992; Matsui *et al.*, 2002). Takayama *et al.* (2000) estimated that settling of the Peñalver Formation calcarenite lasted between 3 and 12 days after the generation of the suspension, with an original concentration of 100–300 g/L. According to numerical models by Matsui *et al.* (2002), tsunami reflected waves traveled through the Gulf of Mexico during more than 30 hours after the impact. Although the figures are not strictly coincident, they indicate a high probability of tsunami waves influencing lower homogenite deposition. No evidence exists for an exceptional erosional event affecting the rocks below the homogenite of the Peñalver or Cacarajícara formations.

The bulk homogenite composition and its stratigraphic position in the Peñalver and Cacarajícara formations deposits are similar, pointing to a common main source (with relative minor amounts of coeval fine ejecta). However, the noncarbonate grain composition in the Peñalver and Cacarajícara formations homogenite are remarkably different. Whereas serpentine and volcanic rocks are the main siliciclastic detritus in the Peñalver Formation, frequently attaining more than 50% of the noncarbonated grains (Takayama *et al.*, 2000), in the Cacarajícara Formation homogenite, the main siliciclastic grains are feldspars and detrital quartz (Tada *et al.,* 2003). In both cases, this composition is in general agreement with the respective basin substrate.

Goto *et al.* (2008) proposed that, in the case of the Peñalver Formation, the homogenite was derived from erosion and redeposition of the Vía Blanca Formation. However, Vía Blanca Formation is a mainly terrigenous unit (Brönnimann and Rigassi, 1963; Albear-Fránquiz and Iturralde-Vinent, 1985), whereas the homogenite is a carbonate deposit and the erosional evidence below the Peñalver Formation breccia is modest (Figure 3).

In the small semi-closed Vía Blanca basin (Figure 10 and 17) the effects of the sudden injection of a hyperdense fast moving sediment suspension, gliding on the bottom can be assumed. Considering a bulk estimate of 1750 km^3 for Peñalver Formation rocks (see section on deposit types above) and about 1200 km^3 for its homogenite (circa 2/3 of the formation volume), the suspension had, at least, more than 1000 cubic kilometers. We suppose that the fast moving suspension wedge triggered the displacement of a similar volume of the overlying clear waters, generating exceptional waves and the abrupt drowning of the basin flanks by new tsunamis. The violent and repeated backwashs entrained and transported huge volumes of shallow and terrestrial deposits to the deep basin. In our opinion this mechanism explains the repeated changes in abundance of serpentine and volcanic grains in the Peñalver Formation homogenite section.

Regional data, including the Geological Map of Cuba (Pushcharovski, 1988), clearly shows outcrops of Mesozoic serpentinite next to the Peñalver Formation. Therefore, it is not necessary to invoke a provenance from central or eastern Cuba, 300–1000 km eastward, to explain the presence of serpentine grains in the Peñalver Formation, as Goto *et al*. (2008) proposed.

Figure 18 shows a correlation chart for the K/Pg boundary strata of the western half of Cuba, embracing the first 100 years of the Cenozoic erathem, in which the chronological relationships among the different K/Pg boundary deposits discussed in this paper become more explicit. Obviously, the gravity flow sediments in Types 1 and 2 deposits accumulated in the first hours after the impact (Takayama *et al.,* 2000; Tada *et al.,* 2003). If variations in grain composition in the Peñalver Formation subunit A (lower homogenite) was due to its deposition during the "tsunamic storm", the subunit was probably settled between several hours and several days after the impact, if Takayama *et al.* (2000), Matsui *et al.* (2002) and Tada *et al.* (2003) calculations are correct. A similar time span for the deposition of the equivalents in the Cacarajícara and Amaro formations can be assumed.

The Moncada Formation (Tada *et al*., 2002, 2003), the clastic complex in the Santa Clara Formation and unit 3 in the southeastern Gulf of Mexico DSDP sites (Álvarez *et al.* 1992) also contain clear evidence of several tsunami waves acting during their accumulation. In Matsui *et al.* (2002) model, the location of DSDP sites 536 and 540 suffered tsunami waves mainly in the first 25 hours after the impact.

The upper, fine grained homogenite in the Cacarajícara, Amaro and Peñalver formations were deposited after the tsunamis, when water movement became normal. The bed with very high Ir content is only found in the Moncada Formation (Tada *et al*., 2002, 2003) and in the DSDP sites 536 and 540 (Álvarez *et al*., 1992), but a moderate Ir anomaly was found at top of the Peñalver Formation at Santa Isabel (Goto *et al.*, 2008) and we speculate that a similar bed was originally deposited also on top of all Type 1 deposits. Probably the time recorded in Type 1, Ir-rich bed is lesser than in their equivalents in types 2 and 3 deposits (Figure 18), but this matter is only of theoretical interest.

Comparison with other K/Pg boundary deposits in the Gulf of Mexico–northwestern Caribbean area

Unquestionably related to Type 1 Cuban deposits are the sections at Bochil, Chilil and Guayal in southeastern Mexico, and the offshore Campeche Sound. Grajales-Nishimura *et al.* (2003, 2009) named these detrital carbonate deposits "Clastic Complex Unit" (CCU), and divided them in three subunits. The CCU rests on pelagic carbonate beds with black cherts. The lower subunit (1) is a gravity flow breccia with abundant pelagic carbonate blocks, attaining two meters in diameter, and black chert nodules. The lower subunit attains thicknesses between 40 and 300 m. As in Cuba, clast ages varies from Albian to Maastrichtian (Grajales-Nishimura *et al.,* 2003). Upward, the breccia becomes fine grained and, in subunit 2 (10–30 m in thickness), the clasts are fragments of shallow-water biodetrital limestone. Scarce matrix, with pelagic microfossils, is present between the grains. Finally, the breccia grades into coarse-grained sandstone. Toward the top of unit 2, a 0.8 m thick ejecta-rich layer, with accretionary lapilli and quartz with planar deformation features (PDF), is recorded. Subunit 3 (3–15 m in thickness) rests with gradational contact and is a graded ejecta-rich deposit beginning with calcarenite and ending with siltstone and claystone. This last subunit seems similar to the homogenite unit in Cuban Type 1 deposits.

Most of the Actela Formation in the southern Peten basin, Guatemala, is a K/Pg boundary carbonate breccia, up to 50 m thick, but lacks the overlying fine carbonate beds present in Cuban and Mexican equivalents (Fourcade *et al.,* 1999).

In the northern Gulf of Mexico, K/Pg boundary deposits are different from those in the south that accumulated under the influence of the huge Yucatán Bank. The terrigenous beds show a distinct scenario from those we studied in western and central Cuba or southeastern Mexico (Smit *et al.* 1992; Alegret *et al.,* 2002 and others). One of the first cases studied was in El Mimbral, near the Gulf of Mexico coast (Smit *et al.* 1992), where a 3 m thick sequence records the depositional event of a megatsunami at the Mesozoic/Cenozoic boundary. The lower part is the "spherule bed", containing altered spherules and quartz grains, with planar deformation features. The rocks above this horizon are

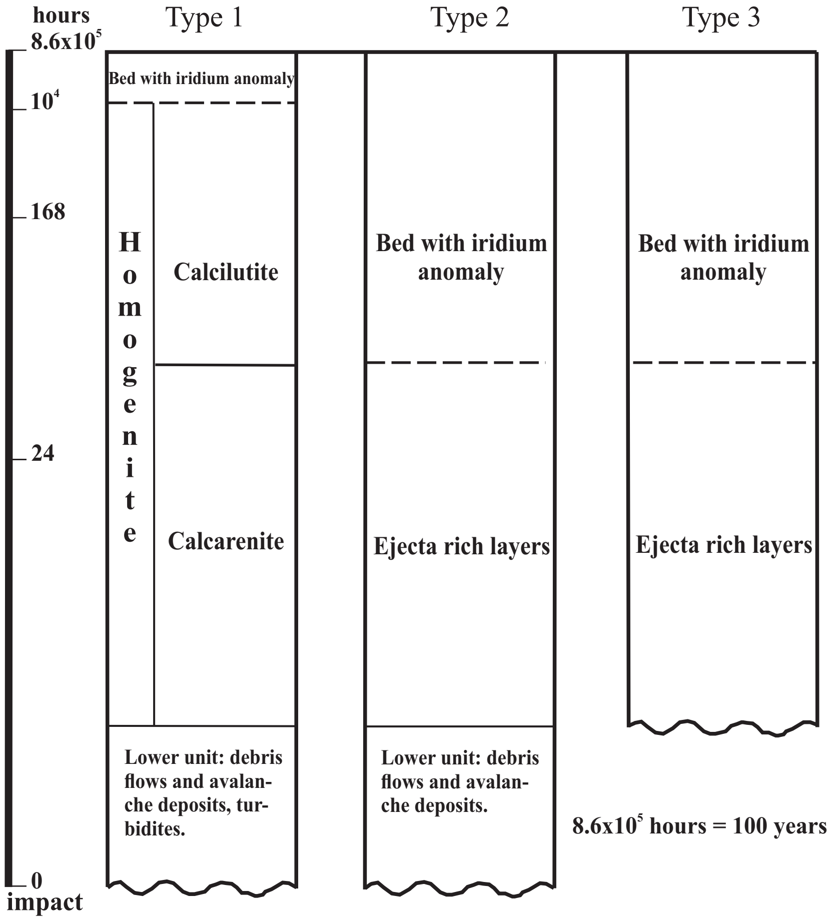

Figure 18. Correlation chart for the first 100 years of the Paleogene system, recorded in the Cuban Cretaceous/Paleogene deposits. The lower erosional contact corresponds to an unconformity in the Cacarajícara, Amaro, Moncada formations and DSDP sites 536 and 540; whereas it is related to a diastem below the Peñalver Formation and the K/Pg bed in the Santa Clara Formation (see Figure 3). The chart is mainly based on data from Fastovsky (1997), Cevallos-Ferriz (1997), Takayama *et al.* (2000), Kiyokawa *et al.* (2002), Matsui *et al.* (2002), Tada *et al.* (2003), Goto *et al.* (2008) and Schulte *et al.* (2010). Detailed explanation in text.

fine-bedded strata with intraclasts, and plant debris, interpreted as the result of the backwash of megatsunamis that carried coarse debris from shallow parts of the continental margin into deeper water. The third unit is represented by fine-bedded ripple beds alternating with clay drapes, with an Ir anomaly at the top of the ripple beds interval, interpreted as deposits of oscillating currents (seiches).

CONCLUSIONS

1) K/Pg boundary deposits attain great volumes and geographic distribution in western and central Cuba. This is related to the complex tectono-geographic scenario in the ancient northwestern Caribbean–southeastern Gulf of Mexico area at the time of the Chicxulub impact.

2) Three types of K/Pg boundary beds were distinguished. Type 1 deposits include in its lower part thick gravity flow sediments, derived from nearby cliffs. Above rests a fining upward massive calcarenite to calcilutite section, settled from hyperdense calcareous suspensions, formed by fine calcareous grains and some siliciclastic and impact ejecta grains (homogenite). Deposits accumulated in two depressions; in the south, a basin located upon the extinct Cretaceous Cuban arc (the Peñalver Formation); in the north, the southern fringe of the starved North American Mesozoic margin (the Cacarajícara and Amaro formations).

3) Type 2 deposits also contain gravity flow deposits in their lower part but, instead the homogenite, ejecta-rich deposits are present. They accumulated in basins near cliffs, in areas protected from the influence of dense suspensions (the Santa Clara Formation and sediments in DSDP sites 536 and 540).

4) Type 3 deposits are built by reworked ejecta-rich thin beds, accumulated in submarine highs. They are only known from a small outcrop at Sierra de los Órganos (the Moncada Formation).

5) No evidence of a major erosional event in the basins, just preceding deposition, has been found. On the other hand, the clastic nature of all the sediments, especially in Type 1 deposits, point to huge erosional events in nearby more elevated source areas. In the basins developed on the extinct Cretaceous Cuban volcanic arc, the K/Pg boundary event was only a special moment in their long-term Campanian-Paleocene sediment accumulation. Also, in the North American late Mesozoic margin, the episode was an ephemeral interruption in its long submarine erosional history.

6) The fluctuations in siliciclastic grain composition in the homogenite of the Peñalver and Cacarajícara formations, the cut and fill structures in the clastic chaotic complex of the Santa Clara Formation, the opposite paleocurrent directions in the Moncada Formation and the cross bedding in DSDP sites 536 and 540 can be explained by the pass of several tsunami waves during the deposition of these sediments, a fact well documented in the northern circum-Gulf of Mexico area

and predicted in numerical models of tsunami generation by the fill of Chicxulub crater.

7) Deposits similar to Type 1 in Cuba, the "clastic carbonate unit", accumulated in the northern and southwestern fringes of Yucatán peninsula. The main difference is the limited development of fine carbonate deposits (calcarenite plus calcilutite) in the Yucatán area.

8) The original location of the reviewed Cuban K/Pg boundary deposits was between 800 and 1200 km from the Chicxulub crater (Figure 17). A general worldwide correlation between distance from the Chicxulub crater on one hand, and bed thickness and grain size on the other is evident (Schulte *et al.,* 2010). Our study shows that, in certain areas located proximal to the impact site, the regional relief at the Maastrichtian end was a main factor controlling sediment features and distribution, supporting Bralower *et al.* (2010) conclusion on the highly complex sequence of events in the circum Gulf of Mexico region after the asteroid impact. Our study does not supports a multiple impact hypothesis to explain the K/Pg event, as some authors have suggested (Stüben *et al.*, 2005).

9) Despite the richness in K/Pg boundary beds in the western half of Cuba, coeval deposits are unknown from its eastern part, where Maastrichtian–Danian units exist and, therefore, impact related accumulations are expected. At present, the best candidates for Cretaceous/Paleogene boundary deposits in the eastern half of Cuba are the Camaján Formation, resting on the North American Mesozoic paleomargin, in the Camagüey province (Kantchev *et al*., 1978; Pszczolkowski, 1986), and the Mícara Formation (Urrutia-Fucugauchi *et al.,* 1998) on the cover of the Cretaceous volcanic terrane of easternmost Cuba.

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