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 km³ (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.

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 km², 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,
Current ideas on the K/Pg boundary event in Cuba began with several seminal presentations at 2000 Vienna meeting on “Catastrophic 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

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 deposits and their relationships has not been fully questioned. 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.
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 and the Northern edge of the Cuban fold and thrust belt

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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 prinssii (Tada et al., 2003); in the Cacarajícara Formation Omphalocyclus macroporus, Globotruncana stuarti, 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). Abanthomphalus 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, Contusotruncanana 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 Via Blanca Formation, whose younger beds contain taxa from the uppermost Maastrichtian Plummerita hantkeninoides subzone, together with bentic forms from the Bolovinoides draco zone (Gil-González et al., 2007; Menéndez-Peñate and Sánchez-Arango, 2007). Near Havana city, the oldest post-Peñaiver 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 foraminifers, together with nannoplanktonic upper Maastrichtian taxa as Micula prinssii 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...
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...
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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 Carmita Formation. This deep water unit is also present 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).

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

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 Cararajícara Formation, Loma Miracielo, Sierra del Rosario, Artemisa province; e) breccia from the Cararajícara 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 Junction, Sierra de los Órganos, Pinar del Río.
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 oozes (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 Via Blanca Formation) in western Cuba and carbonate-terragenous sediments and reworked tephas 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 Via 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-Arago, 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).

Bromimann 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 Via Blanca Formation. This fact clearly points to the development of abundant rudist reefs in the source area of this formation at the end Maastrichtian.

Bromimann and Rigassi (1963) suggested that in the Havana city area, the Via 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 Via 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 basin 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 bentic fossil assemblages are present in this area (Figure 8) below the K/Pg boundary deposits (Table 2). Therefore, a batal 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 Via 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 Via 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).

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
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 Via 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 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: Guanahaya (Escambray) massif: Mesozoic metamorphic complex (it was below the Earth’s surface until Middle Eocene). Discontinuous line: inferred contour of the late Maastrichtian-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).
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 Via 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 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: Camajuani zone; P: Placetas zone, VB: Vía Blanca basin, SC: Santa Clara basin. See explanation in text.
The **Peñalver Formation**

The Peñalver Formation (Brommimann 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 Via 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.

<table>
<thead>
<tr>
<th><strong>Peñalver Formation</strong></th>
<th><strong>Cacarajícara Formation</strong></th>
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<tbody>
<tr>
<td><strong>Upper Unit</strong></td>
<td><strong>Lime mudstone Member</strong></td>
</tr>
<tr>
<td><strong>Subunit B</strong></td>
<td>Massive homogeneous fine calcarenite to calcilutite. Some foraminifera and black carbon. Faint parallel bedding. Thickness: from some meters up to 100 meters.</td>
</tr>
<tr>
<td>Massive calcilutites. Cocobiella and micrite grains, clay minerals. Thickness: 0-60 meters.</td>
<td><strong>Gravity flow Unit</strong></td>
</tr>
<tr>
<td><strong>Subunit A</strong></td>
<td>Massive breccia overlaid by grainstone. Grains mainly derived from shallow and deep water carbonate rocks and clasts. Thickness: 15-400 meters.</td>
</tr>
<tr>
<td>Calcarenite, normal grading. Grains of micritic limestone, crystalline carbonates and foraminifera. Also serpentinous and volcanic grains. Pressure release structures. Thickness: 8-95 meters</td>
<td><strong>Homogenite</strong></td>
</tr>
<tr>
<td><strong>Lower Unit</strong></td>
<td>Coarse to medium calcarenite. Abundant grains of micritic limestone and skeletons of foraminifera. Grains of quartz and feldspar. Fluid-escape structures. Thickness: from some meters up to 200 meters.</td>
</tr>
<tr>
<td>One to several debris flow deposits. Shallow water carbonate and shale lithoclasts. Thickness: 18-45 meters.</td>
<td><strong>Gravity flow deposits</strong></td>
</tr>
<tr>
<td><strong>Upper Maastrichtian</strong></td>
<td><strong>Basement</strong></td>
</tr>
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<td><strong>Albian-Cenomanian</strong></td>
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**Figure 11.** General features of the Type 1 deposits in the Peñalver and Cacarajícara formations.

**Figure 12.** Olistolith (VB) of fine-grained siliciclastic rock (partly outlined by the discontinuous white line), probably derived from the Via 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 escape 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 Pizarrales 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 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 (Pszczołkowski, 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 Alban-Cenomanian limestones with black cherts (the Carmita Formation), together with clasts from Alban-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 Alban-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 (Pszczołkowski, 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 (Pszczołkowski, 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 Kanchtev 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.]
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 km², a rough estimate of about 2500 km³ 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 km², yields 1750 km³ 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, “accretionary lapilli”, and irregular carbonated vitreous splinters (similar to “cored melt fragments”, recorded in unit 2 of Yax-1 well in Chixculub by Goto et al., 2004; fig. 4c) lie on the breccia. The beds probably correspond to the upper
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 planctonic 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 thinning. 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 scarp, 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,
clasts are mainly derived from the Pan de Guajíbón (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 tsunami waves (Matsui et al., 2002) and the preceeding 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 Via Blanca Formation are subordinate (Figures 11 and 12), whereas upper Cretaceous shallow-water carbonate bioclasts 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 Via 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 denuded (Figure 10). Siliciclastic beds are dominant, even in the uppermost Via 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 Via Blanca basin during the first hours after the impact, previous to the arrival of the hyperdense 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 Yucatan 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 megaeathquake 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 Via 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 Via 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,
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 Ithurralde-Vincent, 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 km³ for Peñalver Formation rocks (see section on deposit types above) and about 1200 km³ 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 sequence.

Regional data, including the Geological Map of Cuba (Pushcharovski, 1988), clearly shows outcrops of Mesozoic serpentine 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 biotidetral 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
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 circm Gulf of Mexico region after the asteroid impact. Our study does not support 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 Micara Formation (Urrutia-Fucugauchi et al., 1998) on the cover of the Cretaceous volcanic terrane of easternmost Cuba.

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