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K/T Boundary Deposits in the Paleo-western Caribbean Basin

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ABSTRACT

A thick, calcareous, clastic megabed of late Maastrichtian age has been known for sometime in western and central Cuba. This megabed was formed in association with the bolide impact at Chicxulub, Yucatán, at the K/T boundary, and is composed of a lower gravity-flow unit and an upper homogenite unit. The lower gravity-flow unit is dominantly composed of calcirudite that was

formed because of collapses of the Yucatán, Cuban, and Bahamian platform margins and subsequent accumulation in the lower slope to basin margin environment. The gravity flow probably was triggered by a seismic wave induced by the impact, although a ballistic flow may have triggered collapse in the case of proximal sites (Yucatán margin). The upper homogenite unit is composed of massive and normally graded calcarenite to calcilutite that was formed as a result of large tsunamis associated with the impact and deposited in wider areas in the deeper part of Paleo-western Caribbean basin. Slight grain-size oscillations in this unit probably reflect the influence of repeated tsunamis. The large tsunamis were generated either by the movement of water into and out of the crater cavity or by the large-scale slope failure on the eastern margin of the Yucatán platform. In upper slope to shelf environments, gravity-flow deposits and homogenite are absent, and a thin sandstone complex influenced by repeating tsunami waves was deposited.

INTRODUCTION

The Cretaceous/Tertiary (K/T) boundary is one of the major boundaries of biotic turnover in Phanerozoic history (e.g., Raup and Sepkoski, 1984), and its origin is of great interest to the geoscience community. In their seminal paper, Alvarez et al. (1980) proposed that an asteroid or comet approximately 10 km in diameter collided with the earth and caused the K/T boundary mass extinction, based on their finding of high concentrations of iridium (Ir) and platinum group elements (PGEs) in the K/T boundary clay layer. Further evidence, such as the presence of shocked quartz, glass spherules, Ni-rich spinel, and diamond presented in subsequent studies, reinforce this hypothesis (Bohor et al., 1984; Sigurdsson et al., 1991; Kyte and Smit, 1986; Carlisle and Braman, 1991). Ten years later, Hildebrand et al. (1991) identified a circular subsurface structure approximately 180 km in diameter at Chicxulub in the northwestern part of the Yucatán Peninsula as the K/T boundary impact crater. Since then, the focus of K/T boundary studies has shifted toward the estimation of the mode, magnitude, and environmental consequences of the impact, and proximal K/T boundary sites have become the target of intensive studies (e.g., Ocampo et al., 1996; Smit et al., 1996; Smit, 1999; Grajales-Nishimura et al., 2000).

Sandstone complexes as much as 9-m thick are reported from many proximal K/T boundary sites surrounding the Gulf of Mexico (Figure 1). They are interpreted as having been formed in environments on the continental shelf to the upper slope under the influence of tsunamis (e.g., Bourgeois et al., 1988; Smit et al., 1996; Smit, 1999), although alternative views have been proposed by several authors (e.g., Bohor, 1996; Stinnesbeck and Keller, 1996). Information on the K/T boundary deposits from proximal deep-sea environment is sparse, however. The only example is the K/T boundary deposit from DSDP Sites 536, 537, 538, and 540 in the Gulf of Mexico, where

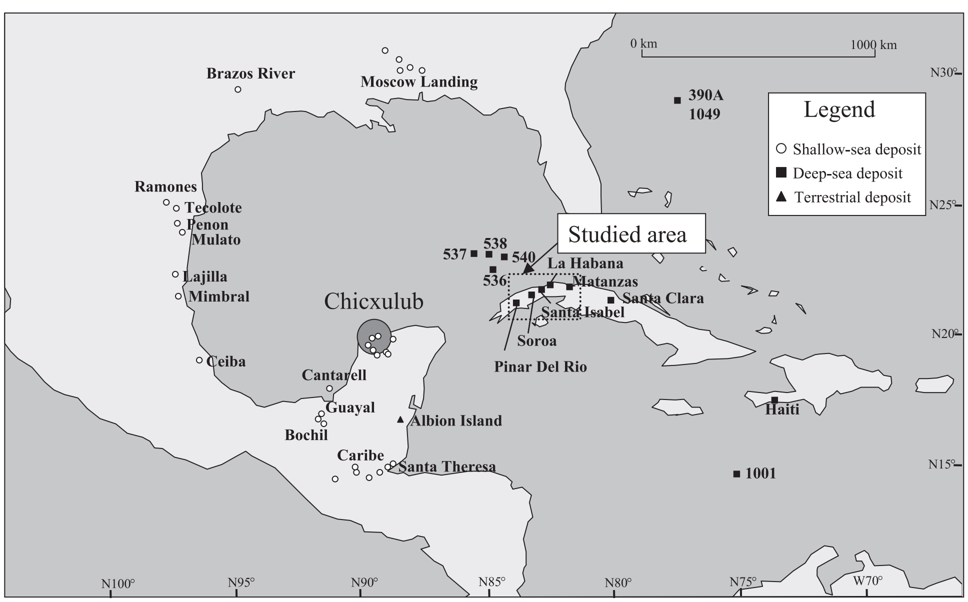

Figure 1. A map showing locations of Chicxulub crater and K/T boundary sites in areas surrounding the Gulf of Mexico.

the K/T boundary deposit was identified based on the presence of an Ir anomaly and shocked quartz grains (Alvarez et al., 1992; Bralower et al., 1998). The K/T boundary deposit at site 540 is composed of 45-m-thick pebbly mudstone of probable gravity-flow origin, 5-m-thick calcarenite with bidirectional cross-bedding, and 50-cm-thick calcilutite with small Cretaceous planktonic foraminifera. The calcarenite and calcilutite contain anomalous Ir, tektite glass, and shocked quartz with the Ir peak in the calcilutite (Alvarez et al., 1992).

A clastic megabed, which is extremely thick, generally homogeneous, and showing overall upward fining, has been known for some time in central and western Cuba close to the K/T boundary (Brönniman and Rigassi, 1963; Pszczólkowski, 1986; Iturralde-Vinent, 1992). Pszczólkowski (1986, 1999) suggested its possible relation to a seismic shock or a tsunami caused by the K/T boundary impact. However, its relation to the impact remained controversial because of lack of the latest Maastrichtian fossils and sufficient evidence of impact signatures, such as shocked quartz, impact glass spherules, and high concentration of Ir (Iturralde-Vinent, 1992), although Pszczólkowski (1999) reported glass fragments of possible impact origin from the Cacarajícara Formation.

In 1997, we started a Japanese-Cuban joint research project on the K/T boundary in Cuba in order to understand the nature and magnitude of environmental perturbations immediately following the impact at proximal deep-sea sites, with emphasis on the impact-generated tsunamis. The result of our preliminary study suggests that the thick, calcareous clastic megabed near Havana, called the Peñalver Formation, is the deep-sea K/T boundary deposit of probable tsunami origin (Takayama et al., 2000). Subsequent studies confirmed the presence of the K/T boundary deposit at multiple sites in western and central Cuba and revealed spatial variation in the thickness and facies of the deposits (Tada et al., 2002; Kiyokawa et al., 2002; Goto et al., 2001).

In this paper, we summarize the result of our research project on the K/T boundary deposits in western Cuba and document the present state of our understanding of their origin, nature, and distribution. It becomes increasingly evident that the breccia component of the proximal K/T boundary deposits in the northwestern part of the Caribbean Sea and the Gulf of Mexico serves as a major oil reservoir in these areas (Grajales-Nishimura et al., 2000). Consequently, the origin and depositional mechanism of the thick and coarse-grained K/T boundary deposits in the Caribbean basin should be of great interest.

GEOLOGICAL SETTING OF CUBA

The geology of Cuba can be subdivided into the Mesozoic-Cenozoic fold belt and the neoautochthonous, postorogenic sedimentary cover of latest Eocene to Holocene age (Figure 2). The Cuban fold belt is a complex, deformed structure that embraces five major tectonic units: (1) the Bahamian platform and borderland, (2) the allochthonous Cuban Southwest terranes (Guaniguanico, Escambray, and Pinos terranes), (3) the allochthonous Northern ophiolites–Placetas belts, (4) the allochthonous Cretaceous arc complex, and (5) the Paleocene–middle Eocene volcanic arc (Iturralde-Vinent, 1994; 1996; 1998; Kerr et al., 1999).

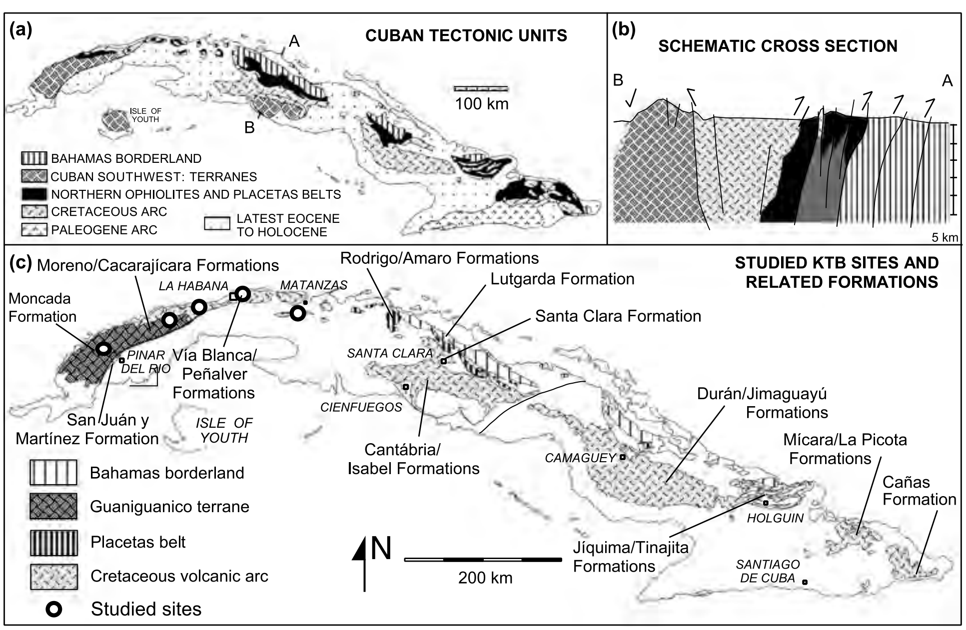

Figure 2. (a) Geologic structure and subdivision of tectonic units in western Cuba; (b) north-south cross section of central Cuba; and (c) localities of the studied K/T boundary sites and related formations.

The ***Bahamian platform and borderland*** tectonic unit is located in the northern margin of central to eastern Cuba and is characterized by shallow-marine to hemipelagic sediments of a Mesozoic passive-margin sequence and a Paleocene-Eocene foreland sequence (Iturralde-Vinent, 1994). The K/T boundary in this tectonic unit probably is represented by the latest Cretaceous Lutgarda Formation (Pushcharovsky, 1988), but its lithology is not well understood.

The ***Cuban Southwest terranes*** are distributed in western Cuba and are represented by the Guaniguanico, Escambray, and Pinos terranes that are characterized by a continental-margin metamorphic sequence and an oceanic crust section of Mesozoic age. In the Cuban Southwest terranes, only Guaniguanico terrane yields K/T boundary deposits, called the Moncada and Cacarajícara Formations (Tada et al., 2002; Kiyokawa et al., 2002). The Guaniguanico terrane outcrops in western Cuba as a stack of north-to-northwestward-dipping thrust sheets (Brönnimann and Rigassi, 1963; Pszczólkowski, 1978). According to Rosencrantz (1990), Iturralde-Vinent (1994, 1998) and Hutson et al., (1998), the Cuban Southwest terranes originally were located in the Yucatán platform borderland (Maya Block) and part of the western margin of the Caribbean basin. They were transported to their present position during the late Paleocene to middle Eocene (Bralower and Iturralde-Vinent, 1997).

The ***Northern ophiolites–Placetas belts*** are distributed throughout Cuba and are composed of Mesozoic oceanic volcano-sedimentary sequences that originally filled the Proto-Caribbean Sea. The Lower Tertiary sequences in these belts are olistostromic sedimentary rocks. They are strongly deformed to form a stack of thrust sheets tectonically emplaced above the Bahamas platform and borderland area (Iturralde-Vinent, 1998). Probable K/T boundary deposits have been reported in the Placetas belt as calcareous clastic rocks of the uppermost Cretaceous Amaro Formation, which lithologically resemble other K/T boundary deposits in western Cuba (Pszczólkowski, 1986; Iturralde-Vinent, 1992). However, more age and lithological data are needed to confirm their genetic relation to the K/T boundary impact.

The Cuban segment of the volcano-plutonic ***Cretaceous arc complex*** tectonically overlies the Bahamian platform, Cuban Southwest terranes, and Northern ophiolites–Placetas belts (Figure 2; Iturralde-Vinent, 1998). This unit is composed of the deformed and partially metamorphosed arc complex overlain by the latest Campanian through Eocene sedimentary sequence. The sequence encompasses the K/T boundary in the Peñalver Formation of western Cuba, the Santa Clara Formation of central Cuba, and the Mícara Formation of eastern Cuba (Iturralde-Vinent et al., 2000). The Peñalver Formation has been carefully studied, proving its genetic relation to the K/T boundary impact (Takayama et al., 1999, 2000), whereas more research is necessary to identify the relationships of the other formations with the K/T boundary impact.

PALEOGEOGRAPHY OF THE WESTERN CARIBBEAN DURING THE LATE CRETACEOUS

The K/T boundary deposits are reported from various proximal sites with different geological settings surrounding the Chicxulub crater, such as Belize, Yucatán, the Gulf of Mexico, Cuba, the Cayman rise, and Haiti (Figure 1). However, many of the K/T boundary deposits in Cuba are strongly deformed and located in allochthonous belts. The Cayman rise and Haiti sections also are in allochthonous terranes. Consequently, it is necessary to reconstruct the paleogeography of these areas at the time of the impact to identify the locations where sedimentation of these allochthonous K/T boundary deposits took place (Figure 3).

The southern borderland of the Bahamian platform on the north margin of central Cuba is represented by the hemipelagic carbonate sequence of the Lutgarda Formation of probable Maastrichtian age (Pushcharovsky, 1988), which is strongly deformed to form a stack of superimposed thrust sheets. The original width of this deformed belt (Camajuaní belt *sensu* Ducloz and Vuagnat, 1962) was on the order of several hundred kilometers (Meyerhoff and Hatten, 1968, 1974) that should have filled the basin between the Bahamian platform and the Cretaceous arc (Figure 3). The Placetas belt is located to the south-southeast of the Camajuaní belt (Figure 2); the strata in this belt, including the latest Cretaceous Amaro Formation, also are strongly deformed, with their original width being several hundreds of kilometers (Iturralde-Vinent, 1998). However, the Cretaceous-Tertiary sequences in the Bahamas borderland are not as well documented as those of the Yucatán borderland. Therefore, the paleogeographic reconstruction of the Bahamas borderland in Figure 3 is highly speculative.

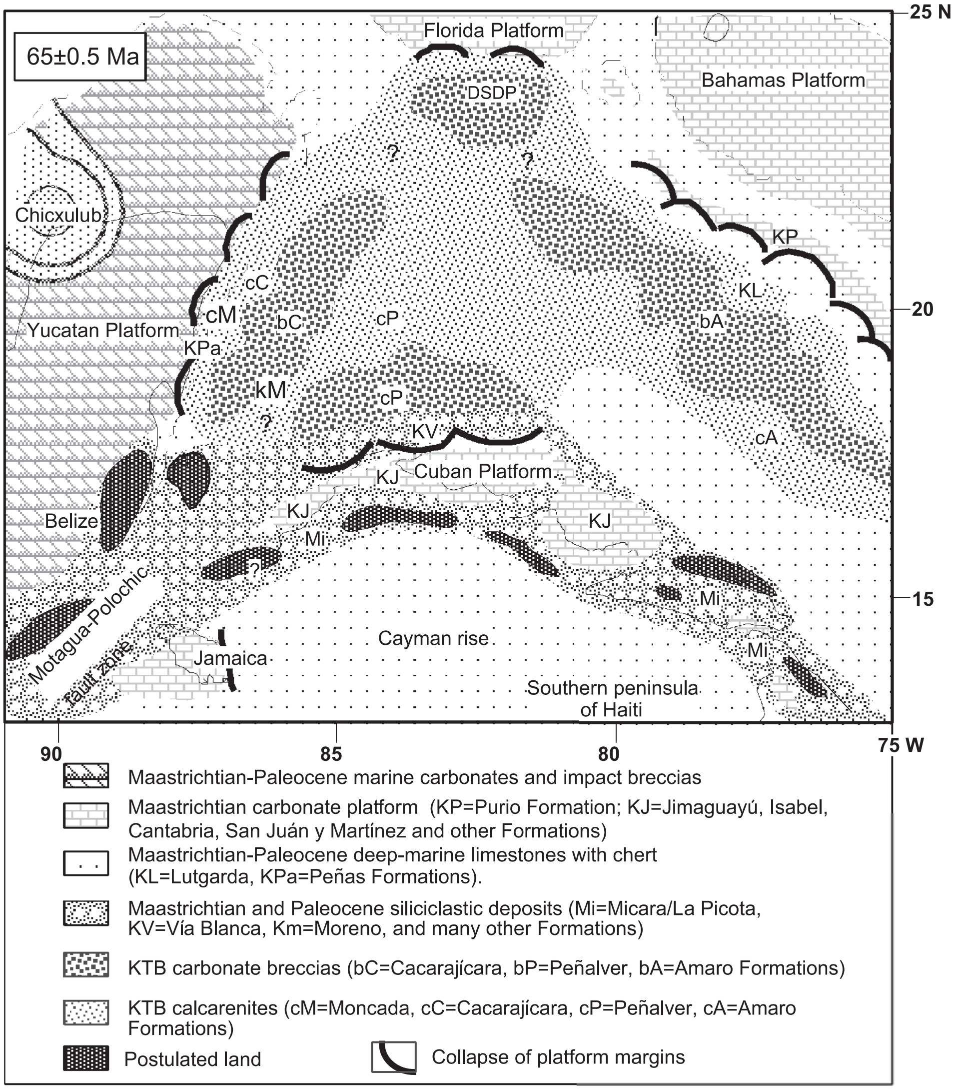

Figure 3. **Paleogeographic reconstruction of Cuba and surrounding areas at the time of K/T boundary impact and distribution of K/T boundary deposits discussed in this study.**

The Cuban segment of the Cretaceous arc complex (Cretaceous Cuban arc) was located to the south-southeast of its present position, between 500 and 700 km away from the Bahamas (Rosencrantz, 1990; Pindell, 1994). It was moving northward during the late Paleocene to middle Eocene and collided with the Bahamian platform during the middle Eocene in response to the opening of the rift basins in the western part of Yucatán Basin (Rosencrantz, 1990; Bralower and Iturralde-Vinent, 1997). The latest Campanian-Maastrichtian Cuban carbonate platform overlies the axial part of the Cretaceous arc complex (Iturralde-Vinent, 1992, 1994, 1998). This platform is characterized by siliciclastic sediments interbedded with shallow-marine carbonates represented by the San Juán y Martínez Formation in southwestern Cuba, the Cantabria/Isabel and Durán/Jimaguayú Formations in central Cuba, and the Jíquima/Tinajita and Cañas Formations in eastern Cuba (Figure 2; Nagy et al., 1983; Albear and Iturralde-Vinent, 1985; Pushcharovsky, 1988). The Vía Blanca/Peñalver Formations developed on the north-northwest slope of the Cuban carbonate platform (Figure 2; Pszczólkowski, 1987; Iturralde-Vinent, 1992). The Mícara/La Picota Formations were deposited on the northeastern slope of the Cuban carbonate platform (Figure 2).

According to the above interpretation, the Paleo-Caribbean Basin was bounded to the north by the Florida platform, to the northeast by the Bahamian carbonate platform, to the west by the Yucatán platform, to the south by the Cuban carbonate platform, and to the southeast by the Atlantic Ocean.

The original position of the allochthonous thrust belts of the Guaniguanico terrane has been discussed (Iturralde-Vinent 1994, 1996, 1998; Bralower and Iturralde-Vinent, 1997; Hutson et al., 1998; Pszczólkowski, 1999). Based on these studies, the Guaniguanico terrane was originally located to the southwest of its present position along the Yucatán platform borderland (Pszczólkowski, 1987, 1999; Rosencrantz, 1990; Iturralde-Vinent, 1994, 1998), probably on the slope near the latitude of Belize (Hutson et al., 1998). The reconstruction of this terrane suggests that the thrust sheets encompassing the Moncada Formation (Los Organos belt) were originally deposited closer to the Yucatán platform compared to the thrust sheets encompassing the Cacarajícara Formation (Rosario belt) that were originally located on the slope and deep-ocean floor of the Paleo-Caribbean Basin, off the Yucatán borderland.

The north-south width of the basin was more than 500 km at the time of impact (Figure 3). Between these shallow-submarine platforms, a deep-marine basin with oceanic crust, represented by the Northern ophiolites and Placetas belts, developed in the central part of the Paleo-Caribbean Sea.

The latest Cretaceous sediments deposited near the edge of the Yucatán and Bahamian platforms, such as the Peñas Formation (off the Yucatán platform) and the Lutgarda and Lindero Formations (off the Bahamian platform), are characterized by carbonate rocks with little or no clastic detritus (Pushcharovsky, 1988). However, the stratigraphic sequences developed on the north side of the Cuban platform, such as the uppermost Campanian and Maastrichtian San Juán y Martínez, Vía Blanca, Jíquima, and Mícara Formations, are characterized by siliciclastic sediments (Pushcharovsky, 1988), since the area surrounding the Cuban carbonate platform was an active tectonic unit with continuous uplift and subaereal erosion. A thin and fine-grained Campanian-Maastrichtian siliciclastic sequence (Moreno Formation) was deposited in the Guaniguanico terrane in the western tip of the Cuban platform very close to the Yucatán borderland (Figure 3; Pszczólkowski, 1999).

THE K/T BOUNDARY DEPOSIT OF THE CRETACEOUS ARC COMPLEX

The K/T boundary deposit, called the Peñalver Formation, is a thick, upward-fining, calcareous clastic megabed that previously was interpreted as megaturbidite (Pszczólkowski, 1986; Iturralde-Vinent, 1992). The Peñalver Formation has a 150-km east-west distribution in the northern part of western Cuba, but no evidence has been presented to support its K/T boundary-impact-induced turbidite origin.

The Peñalver Formation at the Type Locality

Our detailed research of the Peñalver Formation is described in Takayama et al. (1999, 2000) and Goto et al. (2001). We examined the Peñalver Formation in detail at the type locality near Havana (Takayama et al., 2000). The Peñalver Formation at the type locality near Havana is more than 180-m thick and overlies the Campanian–late Maastrichtian Vía Blanca Formation with erosional contact. Takayama et al. (2000) subdivided the Peñalver Formation into five members: the basal, lower, middle, upper, and uppermost members, in ascending order (Figure 4). The basal member is 25-m thick and is composed of massive calcirudite with large mudstone intraclasts derived from the underlying Vía Blanca Formation (Figure 5a). The calcirudite is grain-supported with only a small amount of matrix. The poorly sorted grains are dominantly composed of pebble to granule size, subangular to angular fragments of shallow-marine fossils, such as rudists and benthic foraminifera, and whitish bioclast-bearing limestone. The lower member is 20-m thick and is composed of coarse- to medium-grained calcarenite with frequent intercalations of thin, well-rounded pebble conglomerate. The pebbles are dominantly composed of well-rounded mudclasts with a subordinate amount of shallow-marine bioclasts. The abundance of shallow-marine fossil fragments decreases upward, whereas serpentine and micritic limestone lithics increase upward in the calcarenite of this member. The middle member is 40-m thick and composed of medium- to fine-grained, massive, homogeneous calcarenite with abundant water-escape structures, whereas the upper member is 40-m thick and is composed of fine-grained, decimeter-scale bedded calcarenite. The calcarenite of the middle and upper members shows upward fining and has a similar composition dominated by micritic limestone lithics and crystalline carbonate fragments with a subordinate amount of planktonic foraminiferal skeletons and noncarbonate grains. The noncarbonate grains are characterized by abundant fragments of serpentine and altered volcanic lithics. The uppermost member is at least 40-m thick and is composed of massive, homogeneous calcilutite. The calcilutite is composed of clayey micritic matrix with a subordinate amount of planktonic foraminiferal skeletons. Transitions between the basal and lower, lower and middle, middle and upper, and upper and uppermost members are gradual.

We demonstrated that the composition of the basal and lower members is characterized by grains derived from a shallow-water carbonate platform and is distinctly different from the grain composition of the middle through uppermost members (Takayama et al., 2000). Together with its massive and poorly sorted character, with rip-up intraclasts of the underlying Vía Blanca Formation, we considered the calcirudite in the basal to lower members as a gravity-flow deposit derived from the platform on the Cretaceous Cuban arc. We also demonstrated that the calcarenite and calcilutite in the middle to uppermost members are characterized by the occurrence of pelagic planktonic microfossils with different diagnostic ages, ranging from early Aptian

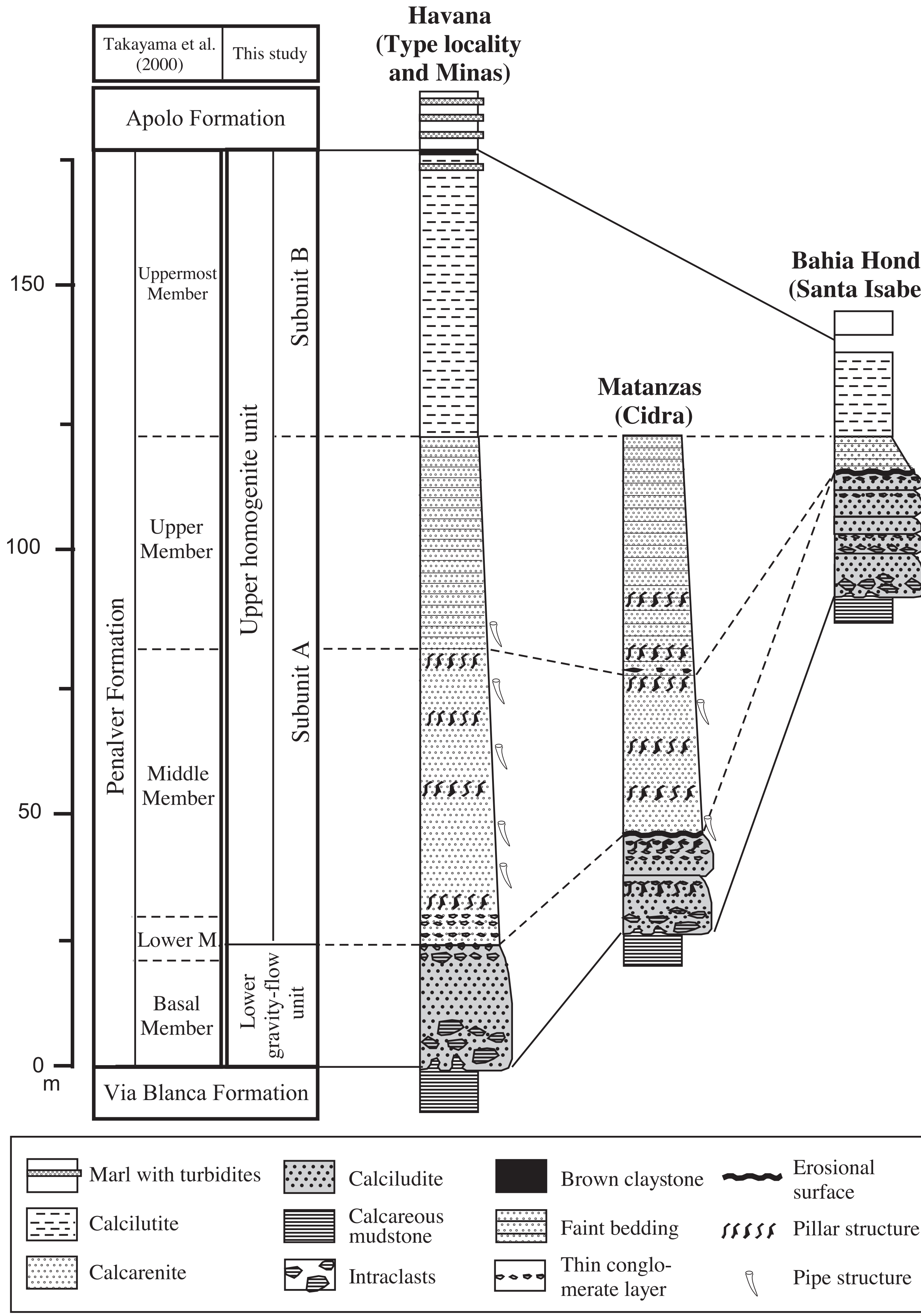

Figure 4. Columnar sections of the Peñalver Formation in the studied sites and their correlations based on stratigraphic subdivisions described in the text.

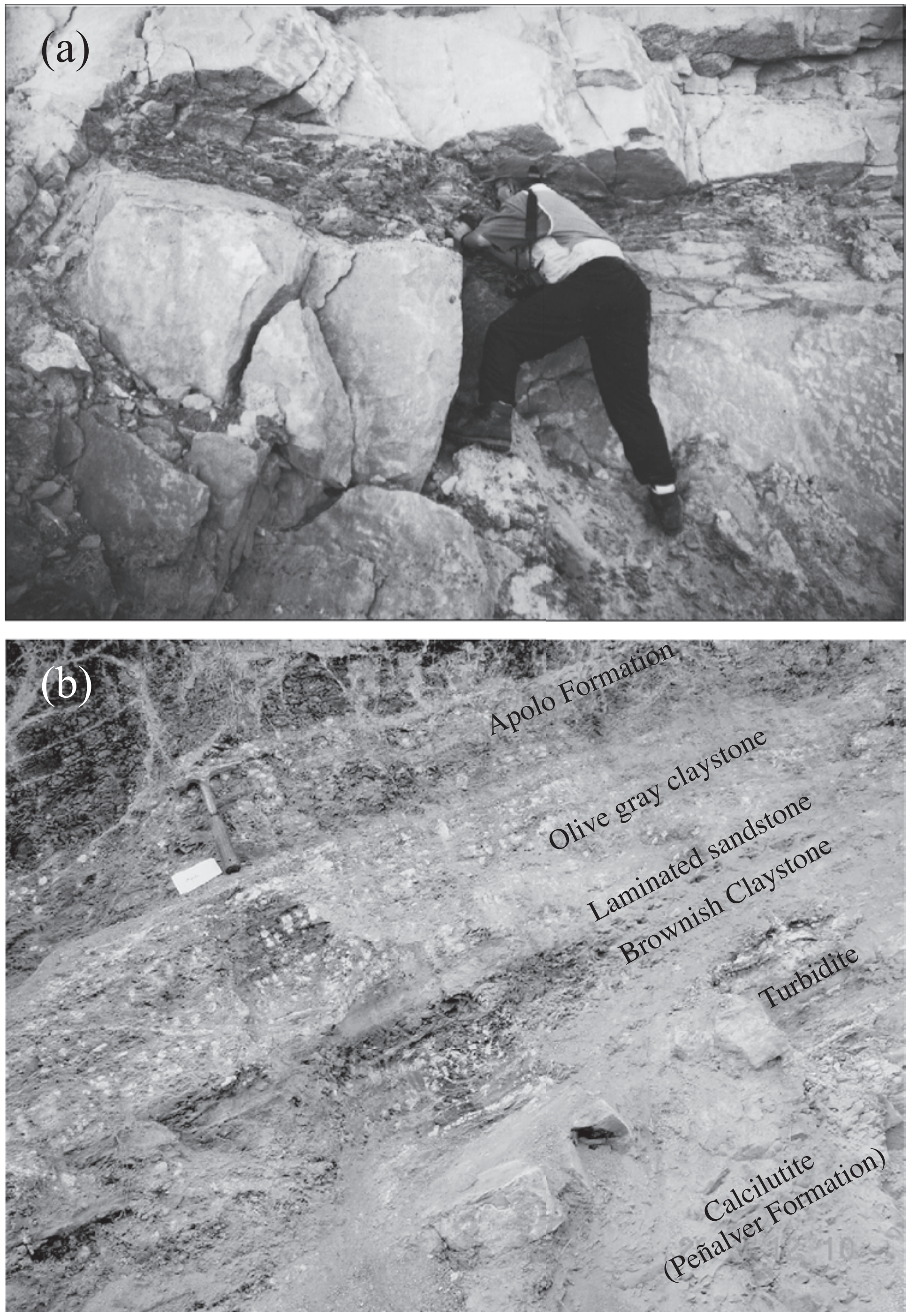

Figure 5. Field photographs of a large mudstone intraclast of the Via Blanca Formation in the upper part of the basal member of the Peñalver Formation; (a) at a quarry 2 km northeast of the type locality, from which *Micula prinsii* was found; (b) the contact between the Peñalver Formation and the overlying Apolo Formation at the quarry near Minas.

to late Maastrichtian, as well as serpentine lithics (Takayama et al., 2000). Such mixed assemblage with different diagnostic ages is similar to the ''K/T boundary cocktail'' of Bralower et al. (1998) and demonstrates their reworked origin (Díaz-Otero et al., 2000). The calcarenite to calcilutite of the middle through uppermost members is thought to be a homogenite based on their upward-fining character with homogeneous appearance, predominance of pelagic bioclastic grains over shallow-marine bioclastic grains, and lack of bioturbation (Takayama et al., 2000). Homogenite is a thick, homogeneous, fine sand to silt that shows monotonous upward fining without any sedimentary structures, and it is composed of pelagic grains derived from the surrounding basin. This lithology is interpreted as a deep-sea tsunami deposit that has settled from a resuspended sediment cloud (Kastens and Cita, 1981). The calcirudite to coarse calcarenite of the basal to lower member is referred to as the lower gravity-flow unit, and the upward-fining calcarenite to calcilutite of the middle to uppermost member is referred to as the upper homogenite unit.

We further examined microfossils in the Peñalver Formation and found *Micula prinsii* from a large, organic-rich mudstone intraclast in the lower gravity-flow unit (Takayama et al., 2000; Figure 5a). Since occurrence of *Micula prinsii* is restricted to the latest Maastrichtian between 65.4 and 65.0 Ma (Bralower et al., 1995), the Peñalver Formation is younger than 65.4 Ma. Díaz-Otero (unpublished data) also found latest Maastrichtian microfossils in the underlying Vía Blanca Formation. On the other hand, there are no Tertiary microfossils found from the Peñalver Formation in spite of abundant occurrence of well-preserved microfossils, especially in the upper

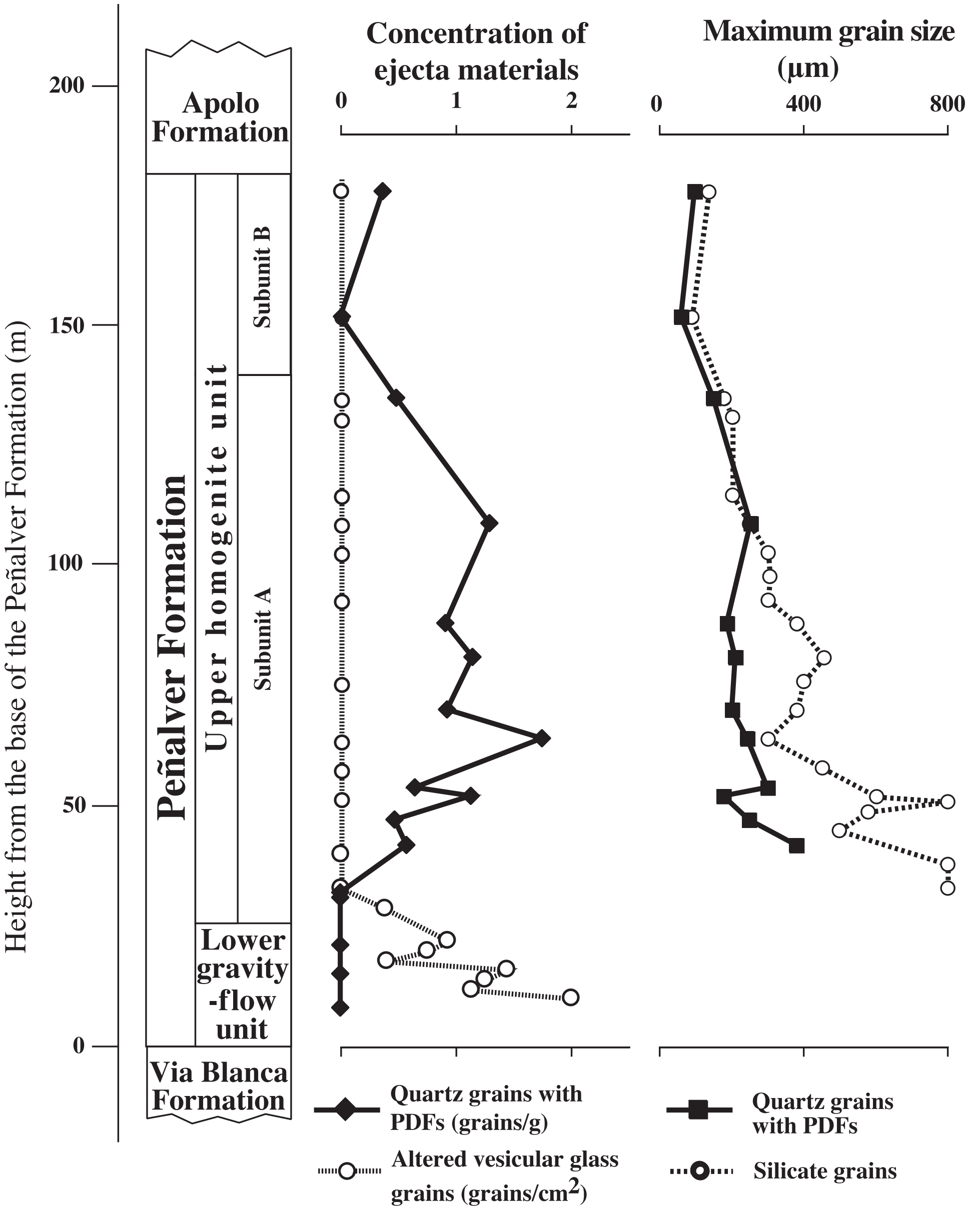

Figure 6. Vertical variations in abundance and grain size of shocked quartz and altered vesicular glass in the Peñalver Formation at the type locality.

homogenite unit (Takayama et al., 2000; Díaz-Otero et al., 2000). The basal age of the overlying Apolo Formation is estimated as late Paleocene (CP8; Takayama et al., 2000), and its equivalent part in the Vibora Group in Bahia Honda is lower Danian (NP1; Bralower and Iturralde-Vinent, 1997). Based on these constraints, the age of the Peñalver Formation is circa 65.0 Ma.

We also examined the Peñalver Formation in search of the ejecta, and discovered shocked quartz grains throughout the upper homogenite unit (Takayama et al., 2000; Figure 6). On the other hand, shocked quartz is absent, but altered vesicular glass grains are found from the lower gravity-flow unit. We also discovered altered vesicular glass grains of possible impact origin as large as 2 mm in diameter in the lower gravity-flow unit, whereas such grains are absent in the upper homogenite unit. Increased iridium concentration has not been detected in the formation. Based on the well-constrained age circa 65.0 Ma and the occurrence of shocked quartz can be concluded that the Peñalver Formation is a K/T boundary deposit.

Lateral Lithological Variation in the Peñalver Formation

In our subsequent study, we examined several other outcrops of the Peñalver Formation and found that it shows significant lateral variation in thickness, although its lithological character is more or less the same and the lithological subdivision of Takayama et al. (2000) is applicable (Goto et al., 2001). In the abandoned quarry near Matanzas, approximately 90 km to the east of Havana, calcirudite and calcarenite corresponding to the basal to upper member of the Peñalver Formation at the type locality is continuously exposed (Figure 4). The calcilutite of the uppermost member is not exposed except at its basal transition with the calcarenite of the upper member. In this quarry, the lower gravity-flow unit (basal plus lower member) is thicker than at the type locality and is composed of two gravity-flow beds with thin layers of mud pebble in the upper part of each bed. The thickness of the calcarenite part of the upper homogenite unit (the middle plus upper member) is approximately three-fourths that of the type locality, and the base of the upper homogenite unit is characterized by the erosional contact (Figure 4).

We also examined the outcrop at Santa Isabel, approximately 60 km west of Havana (Figure 4). At Santa Isabel, the Peñalver Formation is continuously exposed except at the contact between the uppermost part of the upper homogenite unit and the overlying Apolo Formation. However, the total thickness of the Peñalver Formation is only 55 m. The lower gravity-flow unit at Santa Isabel is slightly thicker and coarser-grained than at the type locality and is an amalgam of five gravity-flow beds (Goto et al., 2001). Thin layers of mud pebble are recognized in the upper part of many of the gravity-flow beds. The calcarenite part of the upper homogenite unit is only 8-m-thick, parallel laminated, and overlies the calcirudite of the lower gravity-flow unit with erosional contact. The calcilutite in the upper part of the upper homogenite unit is 25-m-thick; it is characterized by nine meter-scale alternations of thinner, lighter-colored, more calcareous layers and thicker, darker-colored, more argillaceous layers (Goto et al., 2001). Such compositional oscillations in the calcilutite are a unique feature at Santa Isabel.

The contact between the Peñalver Formation and the overlying Apolo Formation is observed only in the quarry near Minas, approximately 10 km east of the type locality. There, the calcilutite of the upper homogenite unit is conformably overlain by a 50-cm-thick brownish clay layer, a 20-cm-thick laminated fine-sandstone layer, and a 60-m-thick olive-green clay layer, which in turn is overlain by yellowish-gray marl of the Apolo Formation (Figure 5b). Decimeter-thick calcareous turbidite layers are intercalated in the uppermost part of the upper homogenite unit. These calcareous turbidite layers are fine- to very-fine-grained, normally graded, and generally characterized by cross-lamination in the lower part of the upper homogenite unit and the presence of burrows in its uppermost part. Intercalations of the turbidite layers in the calcilutite in the uppermost part of the upper homogenite unit suggest that turbidites occurred during the latest stage of deposition of the homogenite, possibly several days to a few weeks after the impact. The presence of burrows at the top of the turbidite layers suggests that benthic organisms survived in the deep-sea environment immediately after the impact, which occurred only 800 km away.

We found that mineral and grain composition of the calcirudite of the lower gravity-flow unit is different from that of the type locality, Matanzas, and Santa Isabel, whereas that of the calcarenite in the upper homogenite unit is similar (Goto et al., 2001). We also found that six oscillations in grain composition and size in the calcarenite of the upper homogenite unit at the type locality and Matanzas (Figure 7). Intervals with larger maximum sizes of carbonate lithics and silicate grains tend to correspond to the intervals with lower contents of serpentine (Figure 7). This relation suggests a two-component mixing system with a smaller grain size end-member characterized by serpentine lithics and a larger grain size end-member characterized by micritic limestone. Based on these results, we propose that the compositional oscillations are caused either by repeated agitation of the water column by tsunami waves or by repeated injection of coarser material into the water column by tsunami backwash.

K/T BOUNDARY DEPOSIT OF THE GUANIGUANICO TERRANE

The Cacarajícara Formation in the Rosario belt is known for its extreme thickness. It is correlated generally with the Peñalver Formation based on its lithology, and is considered as megaturbidite possibly triggered by the K/T boundary impact (Pszczólkowski, 1986, 1992, 1999). The Cacarajícara Formation is interpreted as being deposited on the eastern flank of the Yucatán platform borderland, probably close to the floor of the Paleo-Caribbean Basin (Figure 3). The relationship of this unit with the K/T boundary impact was first speculated by Pszczólkowski et al. (1992) and later confirmed by Kiyokawa et al. (2002). The Moncada Formation in the Los Organos belt, which is only 2-m thick, was related to the K/T boundary impact by Iturralde-Vinent (1995). The Moncada Formation also is considered as being deposited in the Yucatán platform borderland, probably closer to the platform. However, its lithological details and association with K/T boundary impact had not been studied until our study (Tada et al., 2002).

The Cacarajícara Formation

We conducted a detailed study of the Cacarajícara Formation along the San Diego River, approximately 10 km north of Soroa, western Cuba, where the Cacarajícara Formation is exposed almost continuously (Kiyokawa et al., 2002; Figures 8 and 9). Based on our detailed mapping, the Cacarajícara Formation is more than 700-m thick and disconformably overlies well-bedded limestone and chert of the Cenomanian-Turonian Carmita Formation. The Cacarajícara Formation is divided into the Lower Breccia, Middle

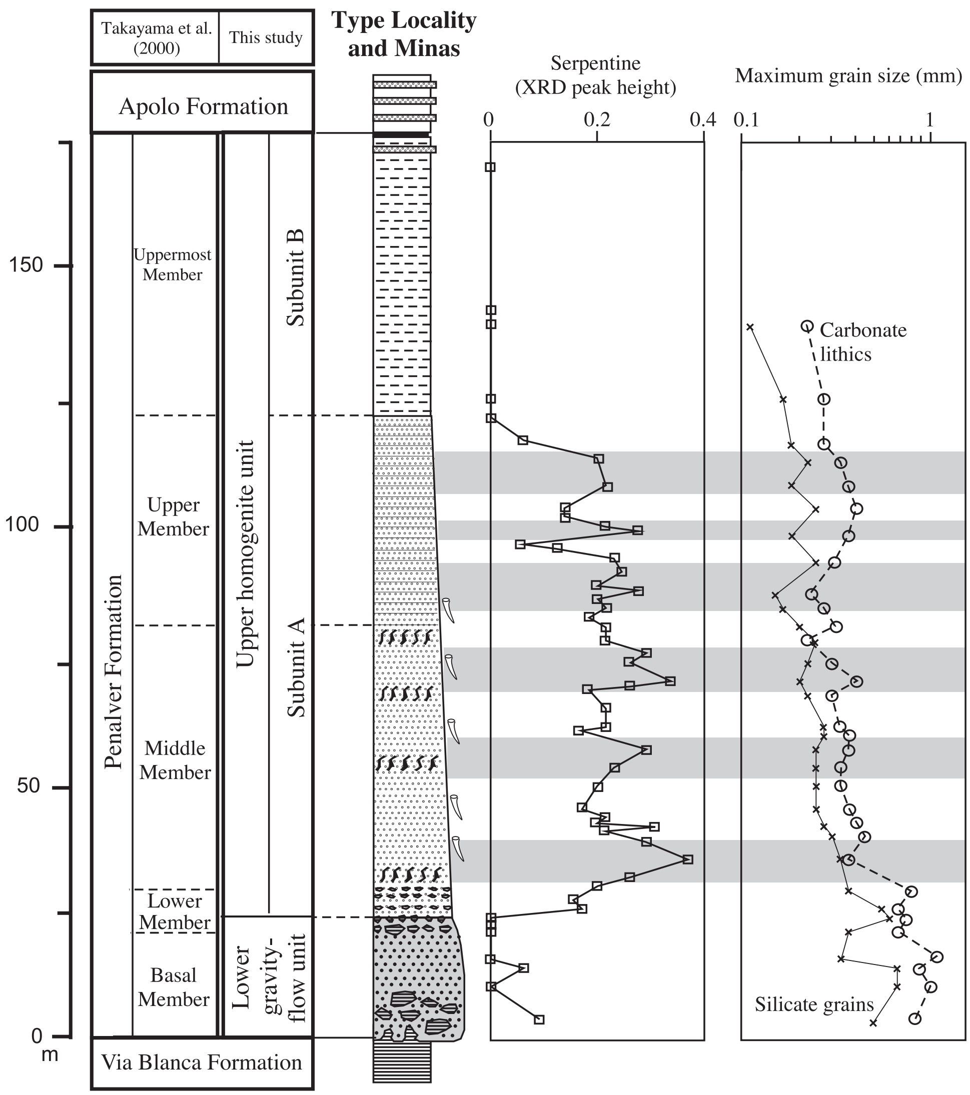

Figure 7. **Slight vertical variations in mineral composition and grain size in the upper homogenite unit of the Peñalver Formation at the type locality.**

Grainstone, and Upper Lime Mudstone members (Figure 8; Kiyokawa et al., 2002). It is in fault contact with the overlying Paleocene–lower Eocene Ancon Formation in the studied area.

The Lower Breccia member (= the Los Cayos member of Pszczólkowski [1994]) is more than 250-m thick and is composed of cobble- to pebble-sized clasts of shallow- and deep-water limestones, black chert, and reddish bedded chert, with small amounts of greenish shale and altered volcanic rocks (Figure 9). The breccia is well sorted and grain-supported with only a small amount of matrix. There is no obvious size grading throughout the member. The Lower Breccia member contains occasional large angular boulder clasts floating in the cobble-pebble clasts. The largest one is an approximately 25-m-thick block of Aptian-Albian well-bedded cherts exposed at the top of the member, which was improperly depicted as "Eocene sediments" in Figure 2 of Kiyokawa et al. (2002). The Middle Grainstone member is approximately 300-m thick and gradational with the Lower Breccia member. It is composed of massive calcirudite to calcarenite (grainstone), which fines upward. The lower part of the member consists of granule-size calcirudite to coarse calcarenite with pebble-size clasts. The calcarenite is mainly composed of fragments of rudist, algal mat, and foraminifer-bearing limestone derived from a shallow-marine environment, whereas pebble-size clasts are black chert with subordinate amount of greenish shale, volcanic rocks, and schist. The middle and upper part of the member is well-sorted, massive, coarse- to medium-grained calcarenite that is composed dominantly of micritic limestone fragments and foraminiferal skeletons with a subordinate amount of bioclasts, detrital quartz, and feldspars. Water-escape structures are common. The Middle Grainstone member grades into the Upper Lime Mudstone member. The Upper Lime Mudstone member is more than 100-m thick and is composed of massive to faintly bedded, muddy, fine calcarenite to calcilutite. The Upper Lime Mudstone member is in fault contact with the overlying Paleocene Ancon Formation in the studied area.

The thickness of the Cacarajícara Formation is highly variable in the Rosario belt, ranging from 5 to 700 m (Pszczólkowski, 1994; Kiyokawa et al., 2002) and tends to be thinner in the thrust sheets presently located in the southwest of the belt. It is interesting to note that the time gap caused by erosion of the underlying strata tends to be larger to the southwest. The age of the underlying strata is as old as Late Jurassic in the thrust sheets in the southwest

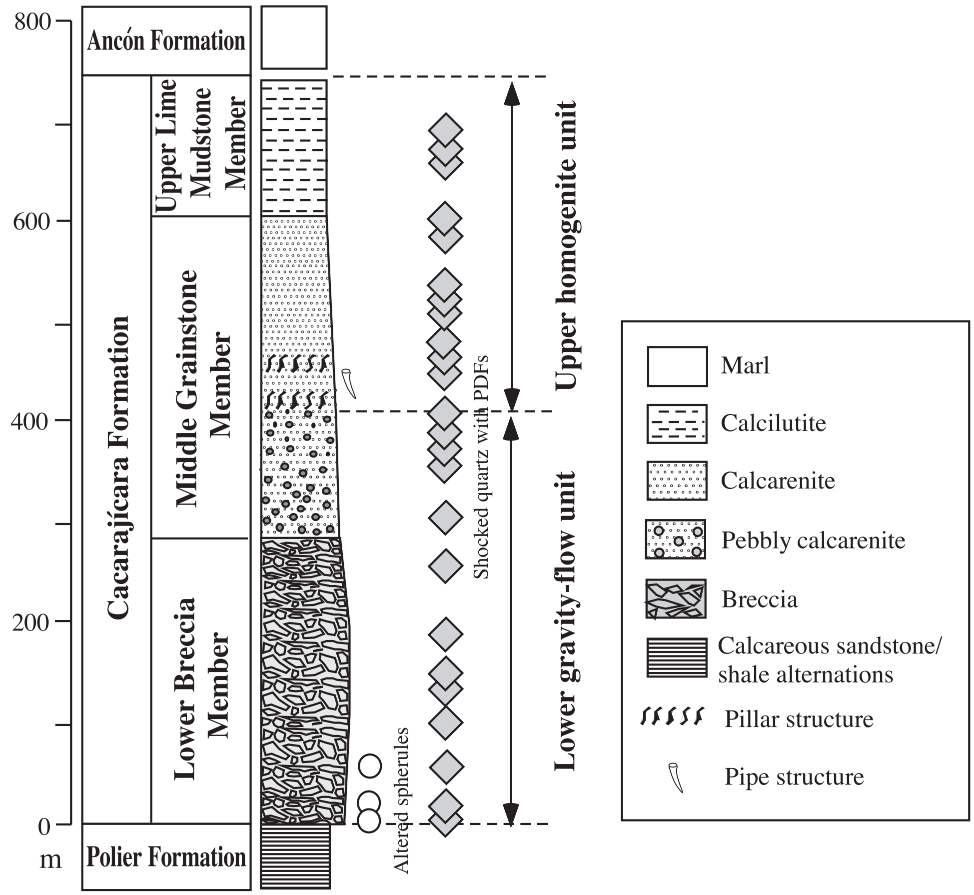

Figure 8. **A columnar section of the Cacarajícara Formation and its stratigraphic subdivision along the San Diego River. Also shown are the occurrence of shocked quartz and spherules. Modified from Kiyokawa et al. (2002).**

of the belt and as young as late Maastrichtian in the thrust sheets in the northeast (Pszczólkowski 1978, 1994, 1999; Pushcharovsky, 1988). The Early Cretaceous age of the underlying strata in the studied area, in spite of its location in the northeastern end of the belt, is explained by the site being situated in the middle of the more than 50-km-wide submarine channel that deeply cut the underlying formations. Since the thrust sheets presently located in the north are considered to have traveled farthest from the south, the breccia becomes thicker toward the south, and erosion of the underlying strata becomes more significant toward the north when the thrust sheets are restored to their original position (Iturralde-Vinent, 1994).

We explored the evidence for the association of the Cacarajícara Formation with the K/T boundary impact (Kiyokawa et al., 2002). We found shocked quartz grains throughout the formation, including the matrix of the Lower Breccia member. The orientation pattern of PDF (Planner Deformation Features) for the shocked quartz in the Cacarajícara Formation is similar to those for other K/T boundary sites (e.g., Sharpton et al., 1992), further supporting their K/T boundary origin. We also found spherules replaced either by smectite, quartz, or goethite from the basal part of the Lower Breccia member (Kiyokawa et al., 2002).

The lithology of the Cacarajícara Formation is similar to the Peñalver Formation, suggesting their common origin, as was previously pointed out by Pszczólkowski (1986) and Iturralde-Vinent (1992). Although the K/T boundary age of the Cacarajícara Formation is not as tightly constrained as the Peñalver Formation, the late Maastrichtian age of the underlying Moreno Formation, the absence of Paleocene microfossils in the Cacarajícara Formation, lithological similarity to the Peñalver Formation, and occurrence of impact ejecta throughout the formation strongly suggest its association with K/T boundary impact (Díaz-Otero et al., 2000; Kiyokawa et al., 2002).

Kiyokawa et al. (2002) interpreted that the Lower Breccia member was deposited from the laminar flow with high-speed dilatant condition based on (1) its grain-supported fabric with rare matrix suggesting high-dispersive pressure, (2) the reverse-graded and imbricated nature of the boulder clasts, and (3) presence of hydrofractured clasts suggesting high pore-pressure conditions. Moreover, pebble to cobble clasts of the Lower Breccia member consist of a mixture of shallow-water limestone clasts derived from the Yucatán platform and deep-water limestone and chert clasts derived from the underlying Polier, Santa Teresa, Carmita, and others. The matrix of the breccia contains abundant shocked quartz grains. Based on this evidence, Kiyokawa et al. (2002) considered that the laminar flow resulted from the slope failure of the Yucatán platform triggered either by the seismic wave caused by the impact or by the impact ballistic flows.

Figure 9. **(a) The continuous exposure of the Lower Breccia member of the Cacarajicara Formation along the San Diego River and (b) pebble- to cobble-sized clasts of the Lower Breccia member.**

Kiyokawa et al. (2002) also interpreted the Middle Grainstone member and Upper Lime Mudstone member as being a high-concentration turbidite and a low-density turbidite, respectively, that comprise parts of the hyperconcentrated flow deposit that was associated with the high-concentration laminar flow deposit of the Lower Breccia member. However, grain compositions in the middle and upper parts of the Middle Grainstone member are characterized by abundant micritic limestone fragments and foraminiferal skeletons of pelagic origin and the near absence of shallow-marine limestone and megafossil fragments and chert fragments. This grain composition is distinctly different from that of the Basal Breccia member and is rather similar to that of the upper homogenite unit of the Peñalver Formation. The occurrence of abundant water-escape structures in the middle part of the Middle Grainstone member and the homogeneous appearance with single upward fining in the Middle Grainstone and Upper Lime Mudstone members also resemble those in the upper homogenite unit of the Peñalver Formation. For these reasons, we prefer an alternative interpretation that the middle to upper part of the Middle Grainstone member plus the Upper Lime Mudstone member represent a homogenite unit formed by the deep-sea tsunami associated with the K/T boundary impact, in the same way as the upper homogenite unit of the Peñalver Formation.

The Moncada Formation

The Moncada Formation is exposed on the roadcut 18 km to the west of Viñales, western Cuba. It is an approximately 2-m-thick calcareous sandstone complex that disconformably overlies grayish-black, bedded micritic limestone of the Albian to Cenomanian Pons Formation (Díaz-Otero et al., 2000) and is conformably overlain by marly limestone of the Ancon Formation, which is early Paleocene (older than NP4) to earliest Eocene in age (P6a) (Bralower and Iturralde-Vinent, 1997). Díaz-Otero et al. (2000) reported a mixed microfossil assemblage from the Moncada Formation with ages ranging from Aptian to late

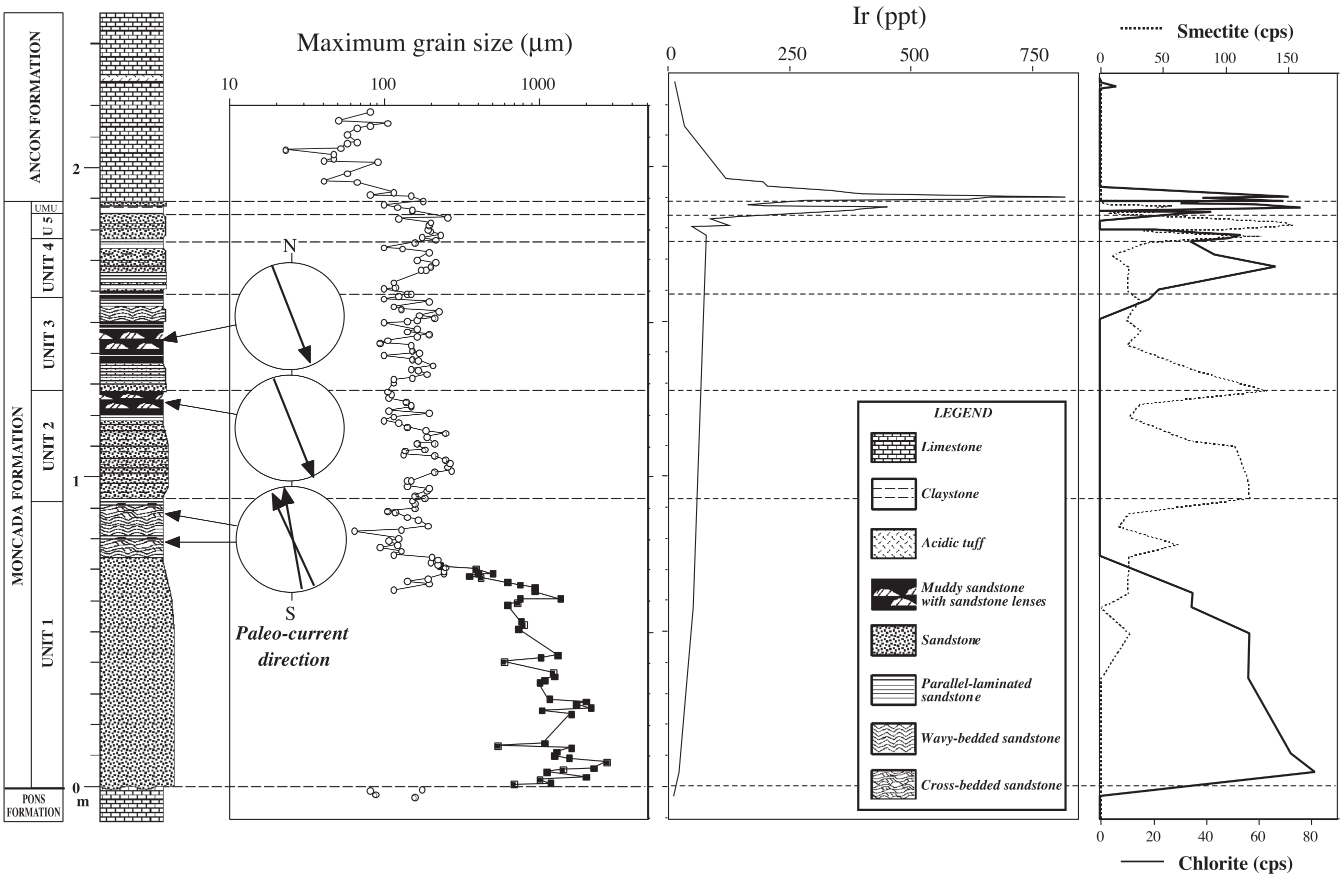

Figure 10. **A columnar section of the Moncada Formation at Moncada. Also shown are paleocurrent directions, vertical variations in grain size, the Ir concentration profile, and clay mineral abundance. Modified from Tada et al. (2002).**

Maastrichtian. Thus, the age of the Moncada Formation is biostratigraphically constrained between late Maastrichtian and early Paleocene. The Moncada Formation is weakly metamorphosed to pumpellyite facies, but the primary fabric, sedimentary structures, and fossils still are preserved (Tada et al., 2002).

We examined the Moncada Formation in detail and found that it is composed of a calcareous sandstone complex in the main part and alternations of thin calcareous claystone and very-fine sandstone in its uppermost part (Tada et al., 2002; Figure 10). The calcareous sandstone complex is characterized by repetition of five sandstone units with an upward decrease in unit thickness and maximum grain size. The lower two units show a distinct upward fining, whereas the upper three units do not show clear upward fining. Boundaries between the units are gradational, and no erosional contacts are observed. The lower part of each unit is composed of a thicker, coarser-grained, parallel-laminated, light-olive, calcareous sandstone, whereas the upper part is composed of alternations of thinner and finer–grained, parallel to ripple cross-laminated, light-gray calcareous sandstone and grayish-black mud drapes (Figure 11). Flat and rounded granules of light-gray micritic limestone and grayish-black chert, probably derived from the underlying Pons Formation, occur in the basal part of the lowest unit. Light-olive calcareous sandstone in the lower part of each unit is composed of flattened, olive-green grains and angular, whitish, vesicular fragments. The upper part of each unit is composed of light-gray calcareous sandstone with grayish-black mud drapes. Light-gray calcareous sandstone is composed of recrystallized calcite grains with a small amount of detrital plagioclase and quartz, whereas grayish-black mud drapes are composed of clayey micritic matrix, opaque wisps, and a small amount of fine-grained detrital quartz and plagioclase, micritic limestone fragments, and foraminiferal skeletons. A 3–5-cm-thick unit of light-colored, calcareous claystone and dark-colored, very-fine calcareous sandstone alternations overlies the sandstone complex. A 1-cm-thick, olive-gray, fine sandstone layer with a yellowish rim is present at the top of this

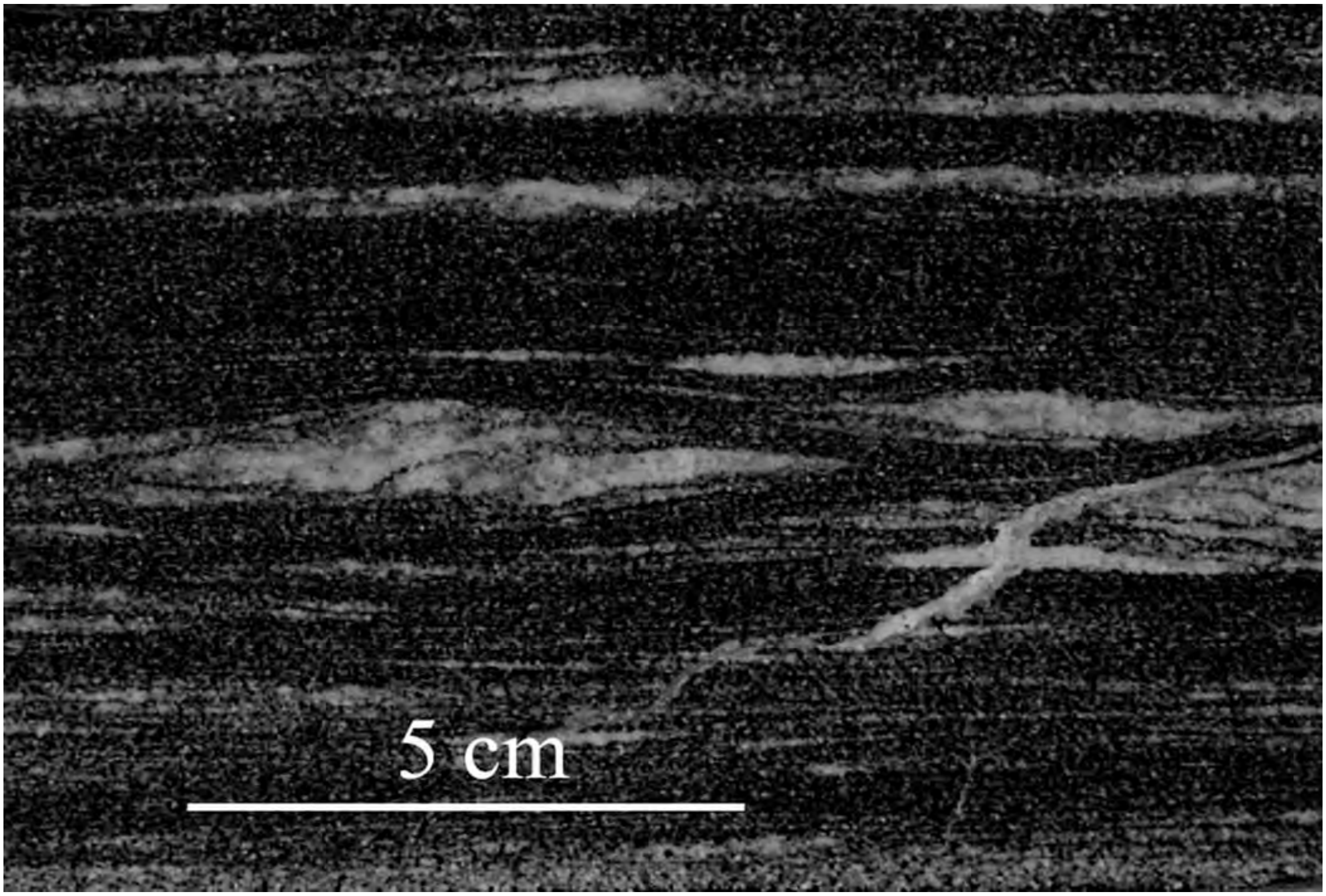

Figure 11. **Ripple cross-laminated calcarenite with mud drapes in the upper part of unit 1 in the Moncada Formation.**

unit. The upper boundary of this sandstone is bioturbated, and the sandstone grades upward into the marly limestone of the Ancon Formation.

We found that the mineral and major element compositions varied systematically in each unit, reflecting the dominance of ejecta materials in the lower part and reworked materials from the underlying substrates in the upper part (Tada et al., 2002). We further demonstrated that the relative abundance of smectite and illite versus chlorite are different between the basal, fourth, and fifth units versus second and third units, with the former three units being characterized by higher chlorite content, whereas the latter two units had higher smectite and illite contents (Tada et al., 2002; Figure 10). This pattern probably reflects difference in grain composition because flattened, olive-green grains are dominantly composed of chlorite, whereas whitish, altered, vesicular fragments are dominantly composed of smectite.

Paleocurrent directions are estimated from cross-laminations that are from S5°W± 10° for the lowest unit and from N7°E± 20° for the second and third units after correction for crustal rotation (Figure 10; Tada et al., 2002). The paleocurrent direction is unidirectional in individual units, reversed between the basal and second units, and unchanged between the second and third units. This paleocurrent reversal pattern in the lowest three units is concordant with the pattern of clay mineral assemblage (chlorite versus smectite and illite) variation described above. For this reason, we suggested that the variation in clay mineral assemblage, which is caused by variation in abundance of flattened, olive-green grains of possible impact glass versus whitish, vesicular fragments of probable impact melt fragments, reflects variation in provenance in response to changing bottom current directions (Tada et al., 2002). If correct, the fourth and fifth units are from the south, and, consequently, the paleocurrent direction in the sandstone complex reversed every two units. The paleocurrent directions corrected for crustal rotation are nearly parallel to the eastern margin of the Yucatán platform.

We found a high iridium concentration peak in the calcareous claystone in the uppermost part of the Moncada Formation and yellowish marly limestone at the base of the Ancon Formation (Tada et al., 2002). The petrographic observation revealed the occurrence of abundant shocked quartz grains throughout the Moncada Formation. We also demonstrated that whitish vesicular fragments preserve quench texture of clinopyroxene, suggesting their impact melt origin. Together with its biostratigraphically constrained age between late Maastrichtian and early Paleocene, the presence of Ir peak and occurrence of abundant ejecta strongly suggest that the Moncada Formation is a K/T boundary deposit associated with the bolide impact at Yucatán.

The sandstone complex of the Moncada Formation is characterized by the repetition of sandstone units with an overall upward decrease in grain size and unit thickness. Each unit shows upward fining with systematic changes in sedimentary structures, from thin parallel beds to parallel laminations to flaser and/or lenticular bedding with cross-laminations, suggesting deposition from flowing current with gradual decrease in flow speed in the units (Tada et al., 2002). Together with the reversal of current directions between the units, the lack of erosional contact at the base of each unit, and the high concentration of Ir at the top of the sandstone complex, these characteristics are similar to those of the K/T boundary sandstone complexes in the Gulf of Mexico region (Smit et al., 1996; Smit, 1999), suggesting a tsunami origin of the sandstone complex. The major difference between the sandstone complex of Moncada and those of Mexico is the pattern of current reversals. In Mexico, the pattern is simple alternations (a single beat) with the first wave from the crater (Smit et al., 1996), whereas in Moncada, the pattern is more complex and characterized by alternations of double beats with the first wave toward the crater (Tada et al., 2002). The north-south-trending paleocurrent directions subparallel to the eastern margin of the Yucatán platform can be explained by the deeper depth of the site that prevented the wave direction from becoming perpendicular to the shoreline direction (Tada et al., 2002).

Paleogeographic reconstruction in Figure 3 suggests deposition of the Moncada Formation on the slope near the latitude of Belize (Hutson et al., 1998). The lack of basal debris flow unit in the Moncada Formation and lack of Coniacian to Maastrichtian sequence underneath the formation suggests that the Coniacian to Maastrichtian sequence was eroded by the landslide before deposition of the Moncada Formation (Tada et al., 2002). The landslide and consequent gravity flow probably supplied chert and limestone breccia to the lower member of the Cacarajícara Formation. Thus, the depositional site of the Moncada Formation probably was located in the upper-slope environment.

K/T BOUNDARY DEPOSIT OF THE NORTHERN OPHIOLITES-PLACETAS BELTS

The Amaro Formation in the Northern ophiolites–Placetas belts is also known for its thickness. It is correlated to the Peñalver Formation in the Cretaceous arc complex and the Cacarajícara Formation in the Guaniguanico terrane (Pszczólkowski, 1986; Iturralde-Vinent, 1992) based on their similarity in lithology. Although its K/T boundary impact origin is speculative, no evidence has been presented to support its K/T boundary age and association with the impact. Because of the poor exposure, we have not yet conducted a field survey of the Amaro Formation.

The Amaro Formation is composed of a thick, upward-fining, calcareous clastic unit deposited in the Paleo-Caribbean Basin between the Camajuaní belt to the north and the Cretaceous arc complex to the south (Figure 3). The thickness of the Amaro Formation is in the range of 20 to 350 m (Pszczólkowski, 1986). Calcirudite in the basal part of the formation grades upward into calcarenite in the middle part and calcilutite in the upper part. The Amaro Formation is interpreted as deposited in the southern flank of the Bahamian platform close to the floor of the Paleo-Caribbean Basin (Figure 3) because the bulk of its carbonate-clastic materials are considered as having been derived from the Bahamian platform (Pszczólkowski, 1986; Iturralde-Vinent, 1992, 1998; Rojas et al., 1995). However, clastic grains probably derived from the volcanic arc also are reported from the Amaro Formation (Pszczólkowski, 1986; Iturralde-Vinent, 1992). Although it is not certain from which horizon in the Amaro Formation these redeposited "volcanic" lithics were found, it is possible that they derive from the middle calcarenite part. If so, it may suggest a different source for the lower calcirudite part than for the middle calcarenite part, which is a common feature of the K/T boundary calcareous clastic mega-beds of the Peñalver and Cacarajícara Formations.

DEPOSITIONAL MECHANISM(S) AND DISTRIBUTION OF THE K/T BOUNDARY DEPOSITS IN THE PALEO-CARIBBEAN BASIN

In summary, the thick calcareous clastic megabeds of the Peñalver Formation in the Cretaceous arc complex and the Cacarajícara Formation in the Guaniguanico terrane are at the K/T boundary associated with the bolide impact at Chicxulub. The calcareous clastic megabeds are composed of a lower gravity-flow unit and an upper homogenite unit. The Amaro Formation of the Northern ophiolites–Placetas belts probably is of the similar origin. The 2-m-thick sandstone complex of the Moncada Formation in the Guaniguanico terrane is also at the K/T boundary associated with the bolide impact.

The Lower Gravity-flow Unit

The gravity-flow deposit in the lower part of the Cacarajícara Formation was derived from the shelf edge or the upper slope of the Yucatán platform and was deposited in the lower slope to basin floor along the western margin of the Paleo-Caribbean Basin. The gravity-flow deposit is absent in the upper-slope setting, such as at Moncada where a significant section above the lower Cretaceous was eroded, probably by the slope failure that caused the gravity flow and resulted in the deposition of the lower unit of the Cacarajícara Formation (Tada et al., 2002). The basal erosion by the gravity flow does not seem significant in the lower slope to basinal setting except in large-scale channels such as the 50-km-wide and 250-m-deep feature observed in the northeastern part of the Rosario belt. Except in such large-scale submarine channels, the thickness of the gravity-flow deposits rarely exceeds 15 m (Pszczólkowski, 1986). The gravity-flow deposits, especially those in such channels, were composed of granule- to boulder-sized breccia with grain-supported fabric and rare matrix. A huge block of Aptian-Albian bedded cherts found in the lower part of the Cacarajicara Formation is interpreted as secondary slumps from the margins of the submarine channel. Similar blocks of the Via Blanca Formation found in the Peñalver Formation also are late slumps from the slope of the Cretaceous Cuban Arc. The gravity-flow deposit in the Peñalver Formation was derived from the shelf edge to the upper slope of the Cretaceous Cuban Arc and deposited on its northern flank along the southern margin of the Paleo-Caribbean Basin. The grain compositions of the gravity-flow deposits vary significantly from site to site, reflecting the local geology of the source area. Multiple gravity-flow beds in the lower gravity-flow unit in Matanzas and Santa Isabel probably reflect that gravity flows came from different drainages upstream. Large-scale channels observed for the Cacarajícara Formation are not obvious in the Peñalver Formation, possibly reflecting the smaller amplitude of the impact seismic wave because of larger distance from the impact site. The lower part of the Amaro Formation probably is a gravity-flow deposit derived from the Bahamian platform and deposited on its southern flank.

The gravity flow most likely was triggered by the seismic wave caused by the impact at Yucatán. However, possibility of the impact ballistic flow as a trigger of the gravity flow remains in the case of the Cacarajícara Formation (Kiyokawa et al., 2002). Presence of shocked quartz grains in the matrix of the gravity-flow unit of the Cacarajícara Formation (Kiyokawa et al., 2002) suggests that the gravity flow occurred during or after deposition of shocked quartz grains. Because the distance between the eastern margin of the Chicxulub crater and the depositional site of the Cacarajícara Formation was approximately 400 km, the time required for ejecta to reach the sea surface of the depositional site is approximately 4 to 7 min, assuming ballistic trajectory of ejecta launched at the elevation angle of 30 to 60° (e.g., Alvarez, 1996). Assuming a depositional depth of 2000 m for the Cacarajícara Formation and a nonturbulent water column, the time required for the shocked quartz grains of 400-μm diameter to reach the sea floor is estimated as 12 hr. In this scenario, the accumulation of the gravity-flow deposit of the Cacarajícara Formation should have taken place more than 12 hr after the impact. Kiyokawa et al. (2002) prefer an alternative explanation that shocked quartz grains were transported by an impact ballistic flow, which triggered the gravity flow, and the ejecta were incorporated into the gravity flow. Because deposition of ejecta carried by the ballistic flow could be as thick as 30 m at the eastern edge of the Yucatán platform (McGetchin et al., 1973), it could have been the trigger of the gravity flow. Assuming a 200-km distance between the eastern edge of the Yucatán platform and the depositional site of the Cacarajícara Formation and the speed of the high-density gravity flow as 100 km/hr, the deposition of the gravity-flow unit of the Cacarajícara Formation should have taken place approximately 2 hr after the impact.

Shocked quartz grains are absent, but altered vesicular glass grains of as much as 2 mm in diameter

are present in the gravity-flow unit, and shocked quartz grains of as much as 380 μm in diameter are present in the overlying homogenite unit of the Peñalver Formation (Takayama et al., 2000). This suggests that the gravity-flow unit was emplaced after the arrival of the vesicular glass grains but before arrival of the shocked quartz grains on the sea floor. Because the distance between the Chicxulub crater and the depositional site of the Peñalver Formation is approximately 800 km, the time required for ejecta to reach the sea surface of the depositional site is approximately 5 to 10 min, assuming ballistic trajectory of ejecta launched at the elevation angle of 30 to 60° (e.g., Alvarez, 1996). If the effect of atmospheric drag for small ejecta are taken into account, the time required for 2-mm vesicular glass grains (density is estimated as 2.0 g/cm^3) and 380-μm shocked quartz grains to reach the sea surface could be as long as 0.5 and 1.2 hr, respectively. Assuming depositional depth of 600 to 2000 m for the Peñalver Formation and a nonturbulent water column, the time required for the vesicular glass and shocked quartz grains to reach the sea floor is 0.8 to 2.8 and 3.9 to 13 hr, respectively. Consequently, the total time required for the vesicular glass and shocked quartz grains to reach the sea floor is estimated as 1 to 3 and 4 to 14 hr, respectively, and deposition of the gravity-flow unit of the Peñalver Formation should have taken place between 1 and 14 hr after the impact. Taking into account the distance on the order of 100 km from the source area to the depositional site and the gravity flow speed of 50 to 100 km/hr (e.g., Hsü, 1989), the onset of gravity flow should have been within 13 hr of the impact.

In the case of the Peñalver Formation, the impact ballistic flow is unlikely to have been a trigger of the gravity flow because the thickness of ejecta deposited in the site is estimated as less than 5 m (McGetchin et al., 1973). The remaining possible mechanisms to trigger the gravity flow at the northern margin of the Cretaceous Cuban arc are the impact seismic wave and impact-related tsunamis. The impact seismic wave is a highly plausible trigger because it should have arrived at the studied site within 2 min of the impact, and its peak amplitude should have reached several meters, enough to cause slope failures (Figure 12a, b; Boslough et al., 1996). However, Matsui et al. (2002) suggested, based on their numerical simulation of tsunamis, that the large-scale slope failure along the Yucatán platform margin could generate large-scale tsunamis. Since it is now evident that large-scale slope failure occurred along the eastern margin of the Yucatán platform and resulted in deposition of the lower unit of the Cacarajícara Formation, it is also possible that the large tsunami generated by the slope failure hit the northern coast of the Cretaceous Cuban Arc within a few hours of the bolide impact and triggered the gravity flow. Further research is necessary to specify the triggering mechanism of the gravity flows in the Cretaceous arc complex and Placetas belt.

The Upper Homogenite Unit

We suggest, based on the lithological similarities between the upper homogenite unit and the homogenite described in the Mediterranean (Takayama et al., 2000; Kastens and Cita, 1981), that deposition of the upper homogenite unit of the Peñalver Formation resulted from large tsunamis associated with the bolide impact. We further demonstrate, based on the distinct compositional difference between the units (Takayama et al., 2000), that the upper homogenite unit is genetically unrelated to the lower gravity-flow unit. We therefore assert that the tsunami that caused deposition of the homogenite did not result from the gravity flows that deposited the lower gravity-flow unit of the Peñalver Formation. The occurrence of an erosional surface at the base of the upper homogenite unit in Matanzas and Santa Isabel reinforces this interpretation, and suggests that the erosional power of the first tsunami wave reached the sea floor at these two sites. The lack of erosional surface at the type locality probably reflects its depth beyond the reach of the tsunami wave. Lack of erosional surfaces in other horizons of the upper homogenite unit in Santa Isabel and Matanzas suggests that subsequent tsunami waves had much less erosional power than the first wave and did not reach the sea floor. Brönnimann and Rigassi (1963) estimated the paleodepth of the underlying Vía Blanca Formation near Havana as between 600 and 2000 m, based on its planktonic/benthic foraminifera ratio. Although we do not have any paleodepth information for the Matanzas and Santa Isabel areas, presence of erosional surface at the base of the upper homogenite unit and larger thickness and coarser grain size of the lower gravity-flow unit in these two areas suggests that paleodepths in these two areas were shallower than in the type locality.

Slight compositional oscillations observed in the lower to middle part of the upper homogenite unit suggest that as many as six large tsunami waves were involved in deposition of the upper homogenite

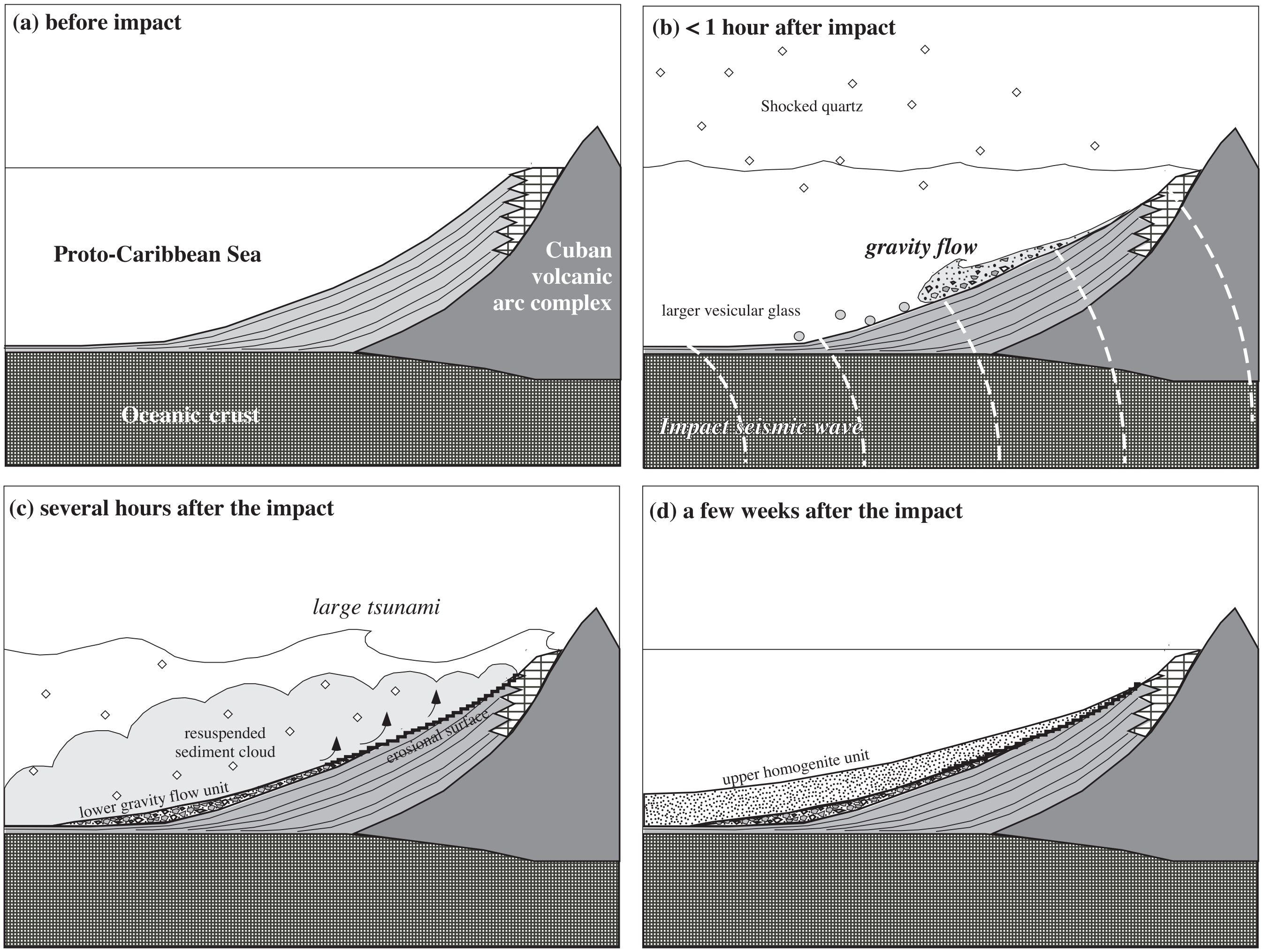

Figure 12. A cartoon showing the depositional processes of the deep-sea K/T boundary deposit (the Peñalver Formation as an example). (a) The situation immediately before the impact. (b) The impact seismic wave triggered the gravity flow. (c) Large tsunami waves associated with the impact eroded the deep sea floor and formed a resuspended sediment cloud. (d) Resuspended sediment particles settled down to form homogenite.

unit (Goto et al., 2001). Occurrence and distribution of shocked quartz grains throughout the upper homogenite unit at the type locality and the similarity in their size to other silicate grains (Figure 6) suggest that the first tsunami that formed the resuspended sediment cloud reached the site while shocked quartz grains were still in the water column (Figure 12c). Based on the calculation described previously, shocked quartz grains should have reached the sea surface in approximately 1 hr and the sea floor in 4 to 14 hours after the impact. Consequently, the first tsunami wave should have hit the type locality between 1 and 14 hours after the impact. In a similar manner, assuming a 600- to 2000-m thickness of the resuspended sediment cloud and gravitational settling of the sediment particles with 100-μm diameter (the maximum grain size at the top of the calcarenite part of the upper homogenite unit), deposition of the calcarenite portion of the upper homogenite unit should have taken 3 to 12 days, and the periodicity of the tsunami waves is estimated at 0.5 to 2 days.

Matsui et al. (2002) suggested that large tsunami waves could be created by the water movements that fill and flow out of the crater cavity after crater formation, and it requires approximately 10 hr to fill up an impact crater 200 km in diameter, 3 km in central depth, and 200 m in marginal depth. They also demonstrated that the tsunami waves created by this mechanism are characterized by long periodicity, on the order of 10 hr. This simulation result is consistent with our estimation of arrival time of the first tsunami wave and periodicity of the tsunami waves. For this reason, we consider that fill

and flow out of the crater cavity is the most likely mechanism to have caused the tsunamis, although further research is necessary.

In any event, it is evident that the large tsunami waves hit the coast to upper slope area of the continents and islands surrounding the Paleo-Caribbean Basin and eroded hemipelagic sediments from the upper to middle slope environment (Figure 12c). The eroded hemipelagic sediments formed a resuspended sediment cloud from which the upper homogenite unit was deposited (Figure 12d). Contrary to the lower gravity-flow unit, the composition of the upper homogenite unit is similar throughout the distribution area of the Peñalver Formation. The composition of the upper homogenite unit of the Cacarajícara Formation also is similar to that of the Peñalver Formation. Previous literature also suggests similarity in composition of the Amaro Formation with the Peñalver and Cacarajícara Formations (Iturralde-Vinent, 1992). This point should be confirmed because, if it is correct, it means that a resuspended sediment cloud of more or less the same composition was formed, spread basinwide, and resulted in deposition of thick homogenite throughout the deeper part of the Paleo-Caribbean Basin. The upper homogenite unit becomes thinner with decreasing depositional depth and changes to a thin calcareous sandstone complex in the upper slope to shelf environment, suggesting the continuous influence of the repetitive tsunami waves in these environments (Smit, 1999).

IMPLICATIONS FOR PETROLEUM GEOLOGY

It becomes clear through our studies that up to 250-m-thick lenticular bodies of pebble- to boulder-size breccia of the lower gravity-flow unit were formed on the eastern flank of the Yucatán platform. These lenticular bodies filled as much as 50-km-wide submarine channels that incised the underlying strata down to the Lower Cretaceous level. Consequently, Lower Cretaceous black-shale horizons should have been exposed on the channel walls and in direct contact with the lenticular breccia bodies. These lenticular breccia bodies are covered with as much as 400-m-thick calcarenite to calcilutite of the upper homogenite unit, which were quickly lithified and became impermeable after deposition because of their thickness. The presence of large lenticular breccia bodies with high porosity and permeability (because of the rare matrix) that are in direct contact with petroleum source rocks and overlain by thick impermeable mudrock is the ideal situation for development of an oil reservoir (e.g., Grajales-Nishimura et al., 2000). It is also worth noting that large organic-rich mudstone intraclasts in the lower gravity-flow unit also may serve as a source rock, especially in the case of the Peñalver Formation. Further investigation of the origin and depositional process of the K/T boundary megabeds is necessary to understand the origin as well as the generation and migration process of the petroleum associated with large bolide impact.

SUMMARY

Thick calcareous clastic megabeds of K/T boundary age are widely distributed in western Cuba. They are as much as 700-m thick and generally are composed of a lower gravity-flow unit and an upper homogenite unit. The lower gravity-flow unit was formed as a result of the collapse of the Yucatán, Cuban, and Bahamian platform margins surrounding Paleo-Caribbean Basin that triggered large-scale gravity flows. The collapse of platform margins most likely was triggered by the seismic wave induced by K/T boundary impact at Chicxulub, although it is also possible that the impact ballistic flow triggered the collapse of the Yucatán margin and the tsunami wave formed by this collapse caused slope failures of Bahamian and Cuban platform margins. The gravity-flow unit was deposited in the lower slope to basin-margin environments surrounding the Paleo-Caribbean Basin. The lower gravity-flow unit is characterized by coarse calcarenite to calcirudite less than 25-m thick except in submarine channels, in which lenticular bodies of pebble- to cobble-size breccia of more than 250 m in thickness were deposited, especially in the Yucatán margin.

The upper homogenite unit was formed as a result of large tsunamis associated with the K/T boundary impact. Although the exact cause of the tsunami still is uncertain, the filling and flowing out of the crater cavity after crater formation and/or large-scale submarine landslide due to the collapse of the east side of Yucatán platform margin seem to be the most likely mechanisms. The first tsunami wave possibly reached the middle to lower slope depth and extensively eroded and resuspended Upper Cretaceous hemipelagic sediments to form the resuspended sediment cloud that spread throughout the Paleo-Caribbean Basin and resulted in deposition of as much as 350 m of homogenite. The upper

homogenite unit is composed of upward-fining calcarenite to calcilutite with relatively uniform composition. Its thickness gradually decreases with decreasing water depth, probably pinching out at middle-slope depth. In the upper-slope to shelf environment, a sandstone complex less than 10-m thick was formed under the continuous influence of subsequent tsunami waves.

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