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Cretaceous Research 29 (2008) 217–236

CRETACEOUS RESEARCH

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Lateral lithological and compositional variations of the Cretaceous/Tertiary deep-sea tsunami deposits in northwestern Cuba

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Received 8 June 2006; accepted in revised form 28 April 2007
Available online 17 November 2007

Abstract

Lateral lithological, compositional, and grain size variations in the Peñalver Formation in northwestern Cuba, which is a Cretaceous/Tertiary (K/T) boundary deposit accumulated on the northwestern slope of the extinct Cretaceous Cuban arc and distributed over an area of 150 km, are examined in order to investigate the influence of a tsunami on the deep-sea bed. The lower part of the Peñalver Formation is composed of calcirudite containing grains derived from a shallow platform. It is considered to have been deposited by debris flows from the shallow carbonate platform triggered by the impact of the seismic wave. The upper part of the formation is composed of calcarenite to calcilutite hemipelagic to pelagic sediments. This has a distinctly different source to the lower part and is considered as having been formed under the influence of tsunami waves, judging from its regional homogeneity and the presence of serpentine lithic grains that were probably transported from central to eastern Cuba by a westward flowing water mass. An erosional surface between the two parts, together with sedimentary structures in the upper part indicative of current influence is more common with decreasing presumed depositional depth, which can be interpreted as stronger tsunami effect at the shallower depths. In addition, compositional and grain size oscillations that repeated >6 to 10 times are observed in the upper part, which may reflect repeated lateral injection of the sediments eroded from the shelf to the upper slope of the depositional basin by backwash of successive tsunami waves into the dense sediment suspended cloud that was formed by the first tsunami.

Keywords: Cretaceous/Tertiary boundary; Impact event; Tsunami deposit; Peñalver Formation; Cuba

1. Introduction

A large number of tsunami deposits have been reported from both outcrops and drill cores, and sediment transportation mechanisms induced by the tsunami have been investigated to evaluate the magnitude and generation of the past tsunamis (e.g. Atwater, 1987; Minoura and Nakaya, 1991; Kelsey et al., 2005). However, few studies have examined the influence and sediment transport mechanisms of tsunami on the deep-sea floor, because lithological characteristics of deep-sea tsunami deposits are not well understood. One example of a deep-sea deposit with strong evidence of a tsunami origin is reported from the Mediterranean Sea (Kastens and Cita, 1981; Cita et al., 1996; Cita and Aloisi, 2000). It has been shown that a large tsunami was generated by the eruption

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0195-6671/$ - see front matter
doi:10.1016/j.cretres.2007.04.004

of the Santorini volcano at approximately 3500 yr BP, and deep sea sediments are coeval with this event (Kastens and Cita, 1981). Kastens and Cita (1981) termed the deep sea deposit a homogenite, and interpreted it as a tsunami deposit based on (1) thick and massive appearance with monotonic upward fining, (2) grains of hemipelagic to pelagic origin, (3) absence of primary depositional structures, (4) absence of bioturbation, and (5) presence of the homogenite in the non-seismic area. However, the depositional mechanism of the homogenite is still uncertain, because it has only been sampled in piston cores, making it difficult to investigate the lateral and vertical lithological characteristics of the deposit in detail. Furthermore, it is uncertain whether all deep-sea tsunami deposits have features similar to the Santorini-generated homogenite, and whether or not there is significant lateral lithological variations which relate to changes in depositional depth and/or tsunami magnitude.

The impact of an extraterrestrial object into the ocean is one mechanism for generating a gigantic tsunami (e.g. Jansa, 1993; Ormö and Lindström, 2000; Gersonde et al., 2002; Dypvik and Jansa, 2003). For example, large tsunamis are believed to have been generated by the Chicxulub impact at the Cretaceous/Tertiary (K/T) boundary (e.g., Matsui et al., 2002). Several probable K/T boundary tsunami deposits have been reported around the Gulf of Mexico (e.g. Bourgeois et al., 1988; Alvarez et al., 1992; Smit et al., 1992, 1996; Smit, 1999; Lawton et al., 2005; Schulte et al., 2006), the proto-Caribbean sea (Maurrasse and Sen, 1991; Takayama et al., 2000; Tada et al., 2002, 2003), and in the Chicxulub crater (Goto et al., 2004).

Pszczolkowski (1986) investigated the Peñalver Formation in northwestern Cuba, an upward fining unit (Brönnimann and Rigassi, 1963; Iturralde-Vinent, 1992), and suggested that it was probably related to the K/T boundary impact. This proposal was later supported by Takayama et al. (2000) based on the biostratigraphy and the presence of impact-related materials. Takayama et al. (2000) interpreted the lower part of the Peñalver Formation as a gravity flow deposit triggered by the impact seismic wave, whereas the upper part was interpreted as a deep-sea tsunami deposit because of the similarity of the sedimentary features to those of the Santorini-generated homogenite in the Mediterranean Sea. However, their study was based on observations at only one locality with low-resolution analyses.

The Peñalver Formation is 180 m thick and widely distributed, thus high-resolution analyses are possible. In this study, the lateral and vertical lithological variations of the Peñalver Formation are examined to test the tsunami origin of the upper part and to evaluate the effect of changes in depositional depth and/or tsunami magnitude on lithology. In addition, high resolution petrographical, mineralogical, and grain size analyses were conducted to clarify its depositional mechanism.

2. Geological setting

The Cuban foldbelt is composed of five tectonic units (Iturralde-Vinent, 1994, 1998): (1) Bahamian platform and borderland, (2) allochthonous Cuban SW terranes, (3) allochthonous Northern ophiolite belt, (4) allochthonous Cretaceous island arc complex (=an extinct Cretaceous Cuban arc), and (5) Paleogene volcanic arc of southeastern Cuba.

The extinct Cretaceous Cuban arc is in tectonic contact above the Bahamian platform and Northern ophiolites belt in the north. It is composed of a deformed and partially metamorphosed arc complex of Aptian to Campanian age, which in turn is overlain by a system of post-arc latest Campanian through Paleogene sedimentary basins, some of which include a K/T boundary section (Iturralde-Vinent, 1994, 1998; Iturralde-Vinent et al., 2000; Díaz-Otero et al., 2000; Tada et al., 2003). In the Late Cretaceous, the extinct Cretaceous Cuban arc was located 500 to 700 km south–southeast of its present position (Rosencrantz, 1990; Pindell, 1994). In the Maastrichtian, the extinct arc complex was covered by the Cuban carbonate platform and several siliciclastic sedimentary basin units developed both above the arc and on the northern and southern slopes on the carbonate platform (Fig. 1, Tada et al., 2003). The Peñalver Formation was deposited in one basin located north–northwest of the Cuban carbonate platform (Iturralde-Vinent, 1992, 1994, 1998).

According to the palaeogeographic reconstruction of Cuba and surrounding areas at the time of the K/T boundary impact, the proto-Caribbean basin was bounded to the north by the Florida platform and slope deposits, to the northeast by the Bahamian carbonate platform and slope deposits, to the west by the Yucatán platform and slope deposits, and to the south by the Cuban carbonate platform (Tada et al., 2003). The basin extended southeastward to the Atlantic Ocean with a north–south width of over five hundred kilometers (Fig. 1, Tada et al., 2003). Between these shallow submarine platforms, continental slopes and a deep-sea basin developed with a thin oceanic crust (=proto-Caribbean basin) in the central part of the proto-Caribbean sea (Tada et al., 2003). The K/T boundary impact occurred in this palaeogeographic setting, and the K/T boundary deposits were laid down in the western proto-Caribbean basin (Tada et al., 2003).

3. Stratigraphic setting

The latest Campanian to Eocene hemipelagic sedimentary rocks in the Cuban foldbelt represent part of the sedimentary infill of basins originally located within the proto-Caribbean basin and above the extinct Cretaceous volcanic arc (Pszczolkowski, 1986; Iturralde-Vinent, 1992, 1994, 1998). These deposits, about 1200 m thick, have been designated in ascending order as the Vía Blanca, Peñalver, Apolo, Alkazar, and Capdevila formations (Brönnimann and Rigassi, 1963) or the Mercedes Group (Albear and Iturralde-Vinent, 1985).

The Vía Blanca Formation unconformably overlies the deformed Cretaceous volcanic arc sequences and Mesozoic ophiolite (Brönnimann and Rigassi, 1963; Albear and Iturralde-Vinent, 1985). It is 500-m thick and ranges in age from latest Campanian to latest Maastrichtian (Tada et al., 2003). Samples from the uppermost level of the Vía Blanca Formation in the Havana area yield latest Maastrichtian planktonic foraminifera (*Abathomphalus mayaroensis*, *Plummerita*

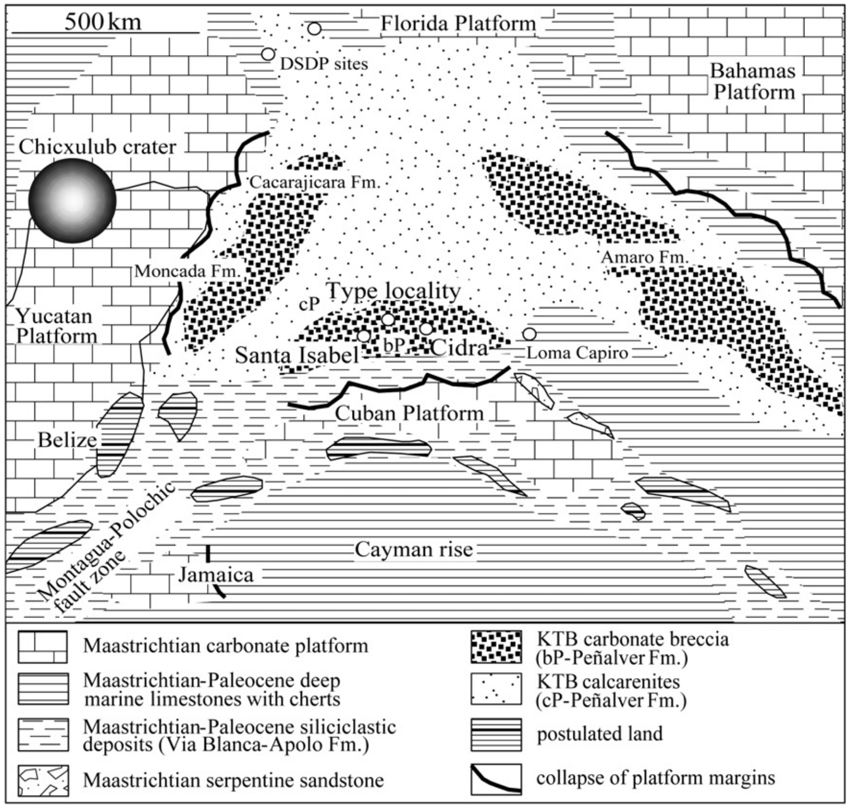

Fig. 1. Palaeogeotectonic setting of the Peñalver Formation in northwestern Cuba at the time of the K/T boundary impact (modified from Tada et al., 2003).

hantkeninoides and *Pseudoguembelina hariaensis*, Díaz-Otero et al., 2003). The formation is represented by well-bedded hemipelagic sandstones, with four or more intercalations of granule to pebble conglomerates. The clasts include lithics derived from the erosion of the extinct Cretaceous Cuban volcanic arc, ophiolites, and limestones (Brönnimann and Rigassi, 1963; Albear and Iturralde-Vinent, 1985). The depositional depth of the Vía Blanca Formation in the Havana area is estimated as 600 to 2000 m based on the ratio between planktic and benthic foraminifera (Brönnimann and Rigassi, 1963).

The Peñalver Formation is 20 to >180 m thick and overlies the Vía Blanca Formation with an erosional contact. It is a calcareous clastic unit at the type locality that fines upward from calcirudite to calcilutite and lacks bioturbation (Brönnimann and Rigassi, 1963; Takayama et al., 2000). The Peñalver Formation contains various species of planktonic foraminifera from Campanian to late Maastrichtian age with minor Cretaceous species younger than Aptian in age (Díaz-Otero et al., 2000; Takayama et al., 2000). Rudist fragments, including *Barrettia monilifera* and *Titanosarcolites giganteus* faunas that are found in the Maastrichtian carbonate platform deposits of Central Cuba (Rojas et al., 1995), are commonly observed in the lower 30 m of the Peñalver Formation (Takayama et al., 2000). Takayama et al. (2000) reported the presence of *Micula prinsii* from a large mudstone intraclast in the lower part of the formation, the occurrence of which is limited to the latest Maastrichtian and giving an age of between 65.4 and 65.0 Ma (Bralower et al., 1995). There are no Tertiary microfossils in the formation. Altered vesicular glass and shocked quartz grains of probable impact origin are found in the Peñalver Formation (Takayama et al., 2000; Goto et al., 2002; Nakano et al., in press). The biostratigraphical constraints and occurrence of impact materials indicate that the Peñalver Formation was deposited subsequent to the K/T boundary bolide impact event (Takayama et al., 2000; Tada et al., 2003).

The overlying 100 m-thick Apolo and Mercedes formations are not distributed around the type locality of the Peñalver Formation, but a part of it is exposed at a highway junction about 3 km to the southwest of the type locality of the Peñalver Formation (Takayama et al., 2000, fig. 4) and Minas area (Tada et al., 2003), approximately 4 km east from the type locality (Fig. 2). These formations are composed of hemipelagic turbiditic calcareous and clastic rocks (Brönnimann and Rigassi, 1963; Albear and Iturralde-Vinent, 1985), and the lithology of the Apolo Formation resembles that of the Vía Blanca Formation. Planktonic foraminifera within the Apolo Formation at Minas are of lower Danian age (*Parvularugoglobigerina eugubina* and *Globoconusa fringa*). The Apolo Formation grades upward into chalky limestone of the Upper Paleocene to Lower Eocene Alkazar Formation (Brönnimann and Rigassi, 1963; Albear and Iturralde-Vinent, 1985).

4. Studied localities

The localities examined herein are situated in northwestern Cuba, and extend a distance of over 150 km in an east-west direction. Field surveys were carried out at the type locality near Havana, Cidra approximately 90 km to the east of Havana, and

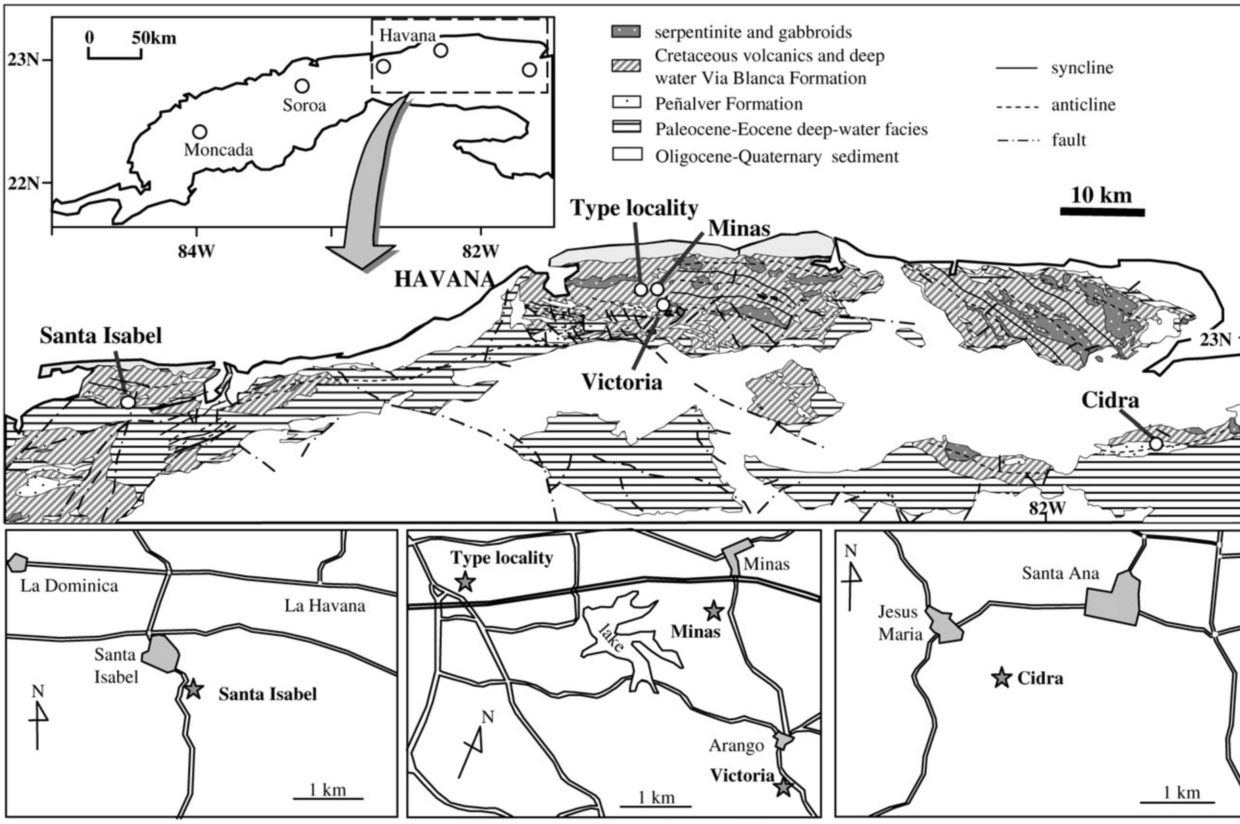

Fig. 2. Distribution of the Peñalver and related formations in northwestern Cuba and studied localities (modified from Mossakovsky et al., 1988; Brönnimann and Rigassi, 1963).

Santa Isabel approximately 60 km to the west of Havana (Fig. 2). The Peñalver Formation at Cidra and Santa Isabel contain various species of planktonic foraminifera from Campanian to late Maastrichtian in age (Díaz-Otero et al., 2003). Moreover, shocked quartz grains are also reported from these localities (Goto et al., 2002). The mixed nature of reworked microfossils, lithic fragments, and impact derived materials is similar to the K/T boundary ‘‘cocktail’’ deposits in the Gulf of Mexico (Bralower et al., 1998), suggesting that the Peñalver Formation in these localities were also related to the K/T boundary impact and were formed as a result of reworking.

The Havana area is situated at the western end of the east-west trending Havana-Matanzas anticline, and the Peñalver Formation is repeatedly exposed by folds with a wavelength of several kilometers (Fig. 2). The Peñalver Formation at the type locality is exposed in an abandoned quarry near the village of Peñalver (Fig. 2). The quarry is located on the northern flank of the east-west trending syncline. The Peñalver Formation in Cidra is exposed in an abandoned quarry located between Matanzas city and the village of Cidra, 1.5 km southwest of Santa Ana (Figs. 2 and 3). This quarry is situated in the east-west trending Havana-Matanzas anticline. The Peñalver Formation in the Santa Isabel area is exposed on small hills 2 km to the south of the road between the towns of Mariel and Cabañas (Figs. 2 and 3).

It is difficult to estimate palaeodepths of the Vía Blanca Formation at Cidra and Santa Isabel using the ratio between planktic and benthic foraminifers similar to the Havana area, because the preservation of fossils in the sediments just below the Peñalver Formation in these areas is poor. On the other hand, the Cidra and Santa Isabel areas are located approximately 15 and 20 km to the south relative to the type locality, respectively, when the east-west trend folds are restored. The restored positions of the three localities suggest that the Cidra and Santa Isabel areas were located closer to the Cuban Carbonate platform, and thus their depositional depths were probably shallower than the type locality.

5. Analytical methods

Petrographical, mineralogical, and grain size analyses were conducted to interpret the depositional mechanism of the Peñalver Formation. Sampling points are shown on Fig. 4. Grain composition was quantitatively investigated by point counting. Powdered samples were analysed using X-ray powder diffraction (XRD) to examine the mineral composition (Takayama et al., 2000). The siliciclastic mineral content was difficult to evaluate for most bulk samples, because these are highly calcareous (>85%). To examine the siliciclastic minerals, 10 to 20 g of bulk samples were treated with approximately 100 cc of 20% acetic acid for 12 h to remove calcite. Residues were then washed with H_2O, centrifuged, and dried. Dolomite is not dissolved by this treatment (Takayama et al., 2000). The insoluble residues were weighed to calculate calcium carbonate content.

The maximum sizes of carbonate and detrital silicate grains were measured under the petrographic microscope to examine

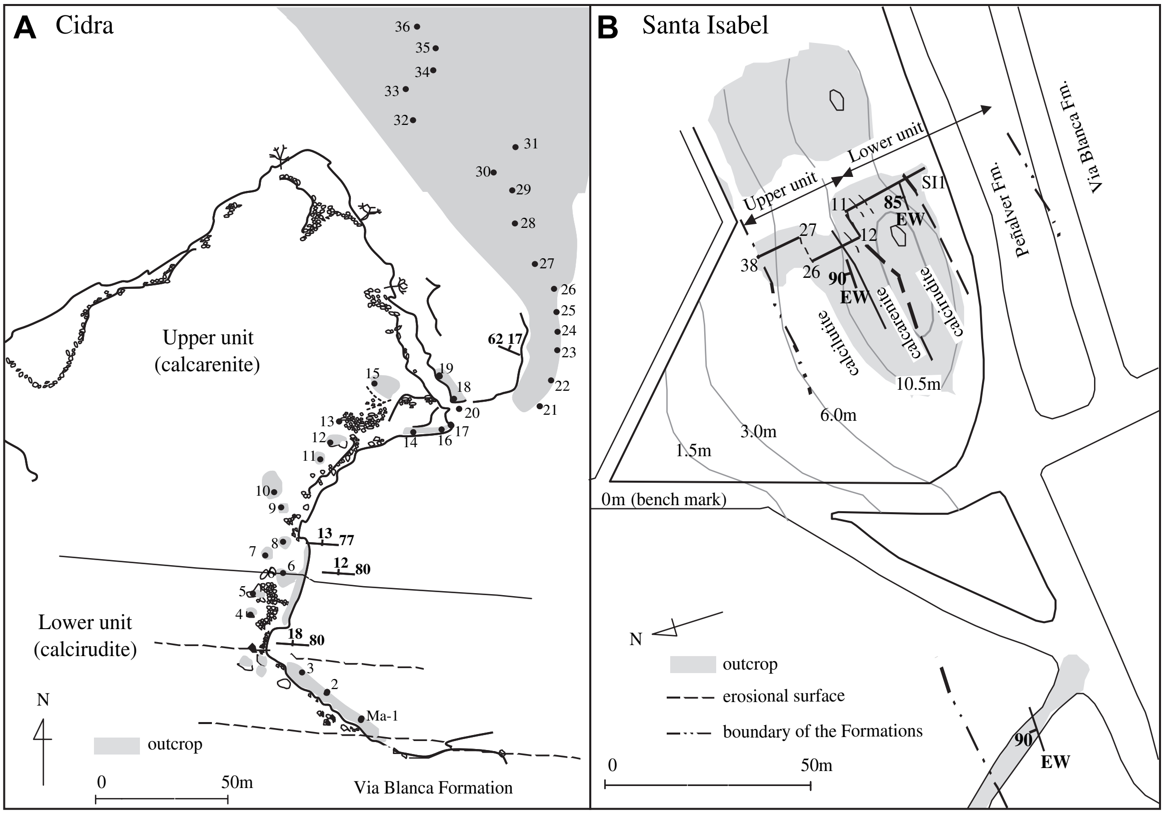

Fig. 3. Route maps with sampling position in the Peñalver Formation around (A) Cidra and (B) Santa Isabel. Route map of the type locality is described in fig. 5 of Takayama et al. (2000).

the grain size variation. Grain size distributions of insoluble residues from the upper part of the Peñalver Formation in Santa Isabel were analyzed to examine the relationship between calcium carbonate content and grain size distribution of the insoluble residue. Grain size distributions of the insoluble residues were determined using a Horiba LA-920 laser diffraction grain size analyzer. The residue was treated in about 50 cc of 0.2% aqueous solution of Na_4 (P_2O_7) to prevent coagulation of clay particles (see Takayama et al., 2000).

6. Results

6.1. Lithology and petrology of the Peñalver Formation

Takayama et al. (2000) divided the Peñalver Formation at the type locality into five members based on variations in lithology; Basal, Lower, Middle, Upper, and Uppermost in ascending order (Fig. 4). They further suggested that the depositional mechanism and the origin of the Basal member is different from the Middle to Uppermost members based on sedimentary structures and composition. The Lower member is interpreted as a transition between the Basal member and the Middle to Uppermost members. Using these observations, Tada et al. (2003) defined the Basal plus lower part of the Lower members into the Lower Unit, and the upper part of the Lower member plus Middle to Uppermost members as the Upper Unit. The Upper Unit is subdivided into subunits A and B, which correspond to the upper part of the Lower member plus the Middle to Upper members, and the Uppermost member of Takayama et al. (2000), respectively (Fig. 4). In this study, the litho-stratigraphic divisions of Tada et al. (2003) are used, because their divisions are also applicable for the Peñalver Formation at Cidra and Santa Isabel.

6.2. The type locality (Havana Province)

6.2.1. The Lower Unit

The sequence from the upper part of the Vía Blanca Formation to the upper part of the Subunit A of the Peñalver Formation is continuously exposed at the type locality (Takayama et al., 2000, fig. 5). Subunit B of the Peñalver Formation is in fault contact with Subunit A and the overlying Apolo Formation is not present at the locality.

The Lower Unit overlies the Vía Blanca Formation with an erosional surface. It is approximately 30 m thick, and the lower 25 m consists of a light to medium gray, poorly-sorted, granule to pebble grained calcirudite (Fig. 5A). There are common intraclasts up to 2 m in diameter, which are probably derived from the underlying Vía Blanca Formation (Takayama et al., 2000). The largest intraclast of approximately 10 m in width is observed in the Lower Unit of the Peñalver Formation in Victoria quarry (Fig. 6), which is located approximately 6 km to the east of the type locality (Fig. 2). The upper 5 m of the Lower Unit consists of light to medium grey,

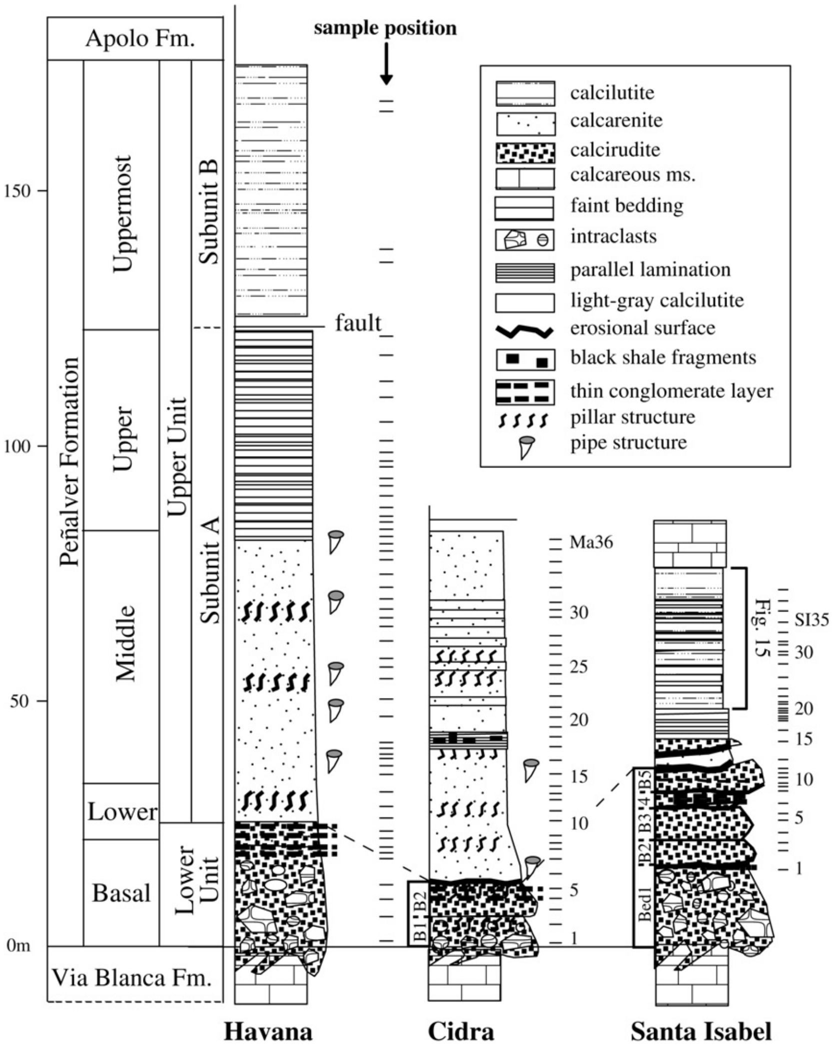

Fig. 4. Lithological sections of the Peñalver Formation and its subdivision into units and subunits. Subdivision of units by Takayama et al. (2000), and Tada et al. (2003) and this study are also shown.

poorly-sorted, medium to coarse grained calcarenite and is characterized by 36 intercalations of conglomerate beds, each a few centimeters thick. The conglomerates consist of rounded pebbles of greenish black mudstone lithics with uncommon rudist fragments and shallow-marine limestone lithics. There are pillar structures in the calcarenite (Takayama et al., 2000), similar to the stress pillars classified by Lowe (1975) as one type of fluidization channel and considered to have been formed during settling of a dense sediment cloud (Takayama et al., 2000).

The calcirudite and calcarenite of the Lower Unit are mainly composed of poorly-sorted, angular to subangular, biomicrite lithics (Fig. 7A) and shallow-water bioclasts dominantly composed of fragments of rudists (Fig. 7B), molluscs, and large calcareous benthic foraminifera (Fig. 8). Non-carbonate grains are composed of poorly sorted, angular to subangular, brownish mudstone and andesite lithics, mono- and poly-crystalline detrital quartz, and feldspar (Fig. 8). Altered vesicular glass fragments are reported in the Lower Unit and are similar in shape and texture to bubbly spherules of impact ejecta origin at other K/T boundary deposits (Takayama et al., 2000). Insoluble residue in the calcirudite is mainly composed of quartz, smectite, clinoptilolite-heulandite and plagioclase (Fig. 9). In thin section, the quartz and plagioclase occur in the calcirudite as individual detrital grains as well as <30 μm-sized detrital grains within the biomicrite, micritic limestone, and mudstone lithics. Smectite is mainly in the mudstone lithics, and it also partly replaces vesicular glass (Takayama et al., 2000). The maximum grain sizes of the micritic limestone lithics and detrital quartz grains show an upward decrease from 1240 to 720 μm and from 700 to 375 μm, respectively (Fig. 9).

6.2.2. *The Upper Unit*

The contact between the Lower and Upper units is gradational. The top of the Lower Unit is defined as the last occurrence of the thin conglomerate beds. The Upper Unit is more than 150 m thick and subdivided into subunits A and B. Subunit A is approximately 95 m thick and its lower 55 m consists of light to medium grey, massive, well-sorted, fine to medium grained calcarenite. Pillar structures are observed throughout (Fig. 5B) together with pipe structures (Fig. 5C), another

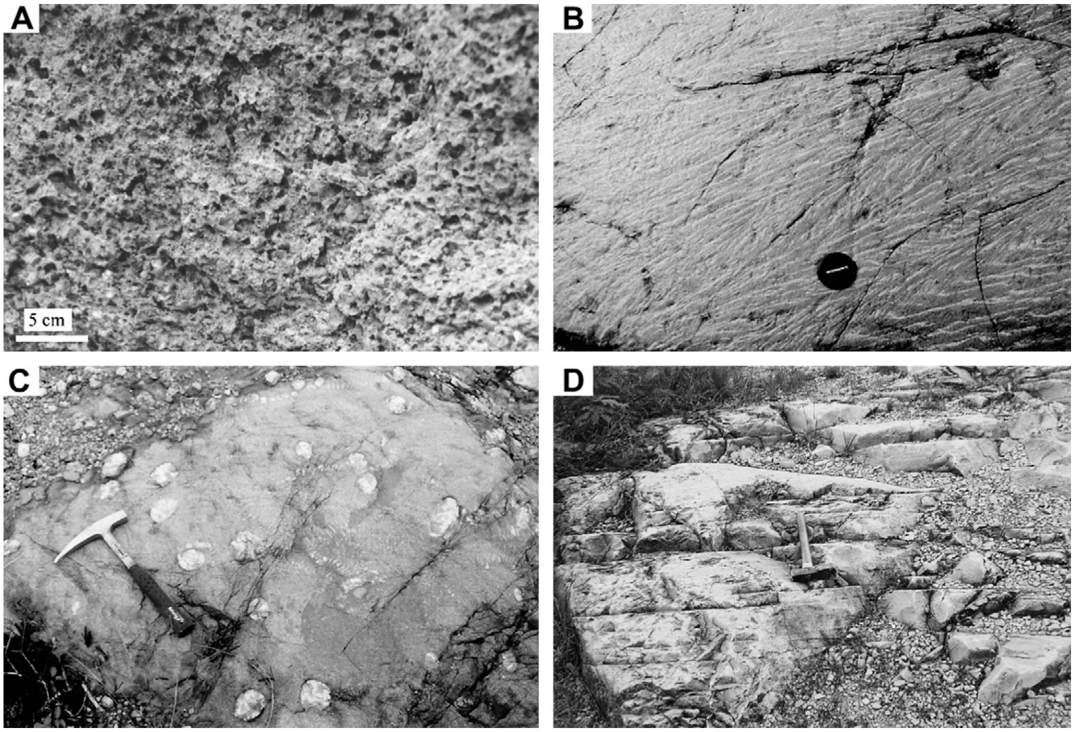

Fig. 5. (A). The calcirudite of the Lower Unit at the type locality. (B) Pillar structures in Subunit A at the type locality. (C) Pipe structures in Subunit A at the type locality. (D) Faint parallel bedding in the upper part of Subunit A at the type locality.

type of water escape structure (Takayama et al., 2000), identified within 5 beds at 18, 25, 35, 50 and 55 m above the base of the subunit. The pipe structures are 5–10 cm across and 20–50 cm long, and they are generally developed perpendicular to the bedding. The upper 40 m of Subunit A consists of light to medium gray, massive, well-sorted, very fine to fine grained calcarenite. In contrast to the lower 55 m of Subunit A, there are no water escape structures. Instead, this part is characterized by faint parallel bedding several centimeters to several meters thick (Fig. 5D).

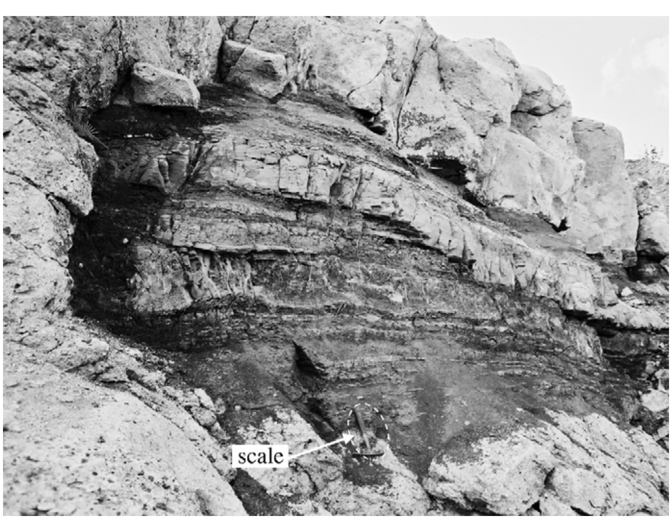

Fig. 6. A large intraclast observed in the basal part of the Lower Unit of the Peñalver Formation at Victoria quarry.

The calcarenite of Subunit A is mainly composed of well-sorted and well-rounded micritic limestone and crystalline carbonate lithics, together with planktonic and benthic foraminifers (Figs. 7C and 8A). The content of large fossil fragments of shallow-marine origin decreases rapidly from approximately 10 to 3% at the base of Subunit A (Fig. 8A). Non-carbonate grains are mainly composed of well-sorted, well-rounded serpentine lithics, mono-crystalline detrital quartz, and andesite lithics with smaller amounts of feldspar, brownish mudstone lithics, and minerals such as spinel, amphibole and biotite (Fig. 8B). Serpentine lithics usually show a mesh texture (Fig. 7D), suggesting alteration from olivine. Serpentine lithics, which are absent in the Lower Unit, appear at the base of Subunit A, rapidly increase upward in abundance and form approximately 50% of non-carbonate grains in the lower to middle part of Subunit A (Fig. 8B). The abundance of serpentine lithics gradually decreases upward with 5 to 15 m scale variation of content in the upper part of Subunit A. As shown in Fig. 9, analysis of the abundance of serpentine in the insoluble residues by XRD confirmed this observation. The insoluble residue is mainly composed of quartz, dolomite, smectite, clinoptilolite-heulandite, plagioclase and serpentine in the calcarenite of Subunit A (Fig. 9), with illite and siderite. The maximum grain size of micritic limestone lithics and detrital quartz grains in the Upper Unit shows an upward decrease from 850 to 150 μm and from 590 to 100 μm, respectively (Fig. 9). Slight oscillations in maximum grain size of micritic limestone and detrital quartz grains are observed in Subunit A.

Subunit B is in fault contact with Subunit A with an estimated thickness of at least 55 m. It consists of light to medium

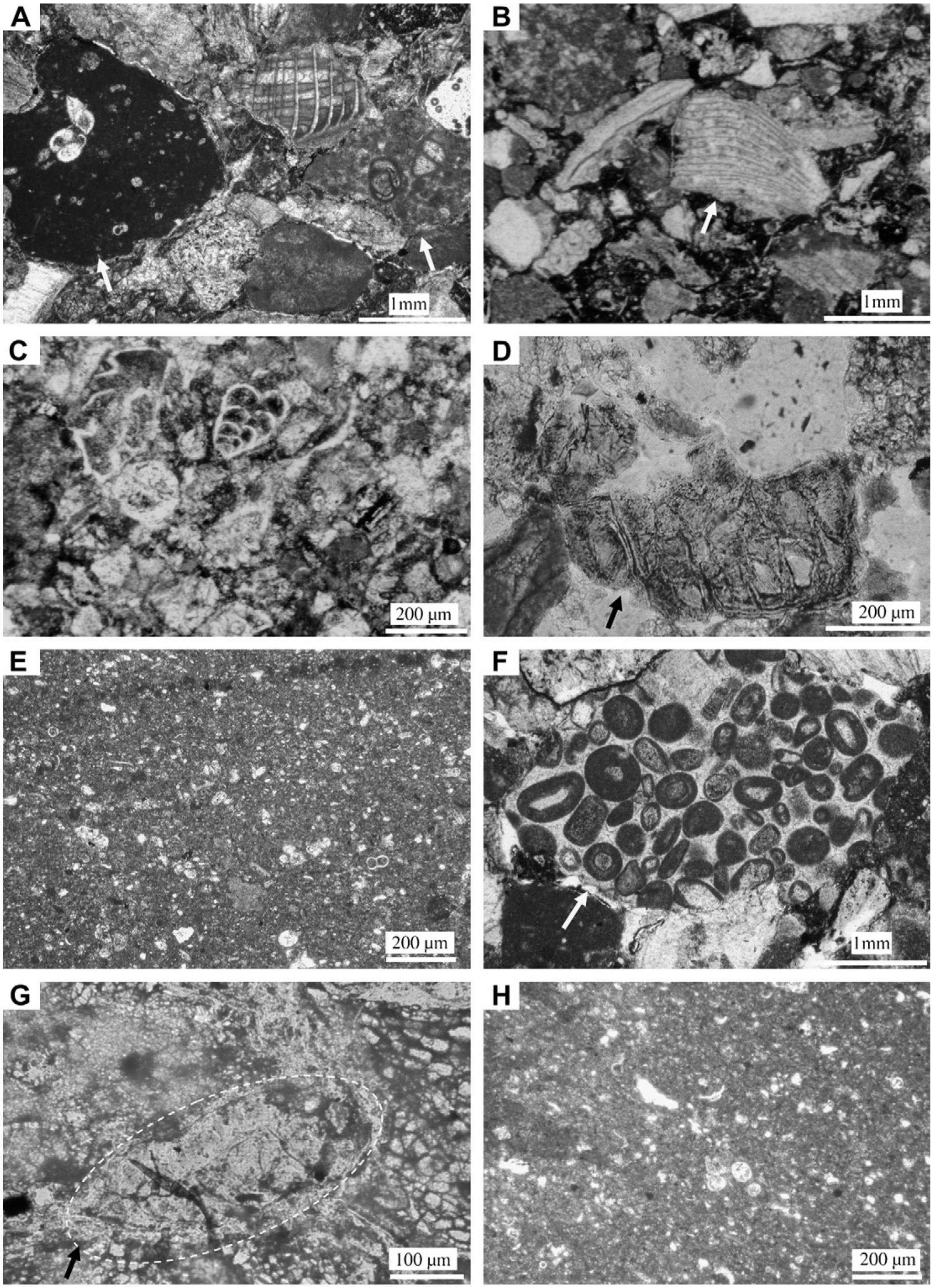

Fig. 7. (A). Biomicrite with planktonic and benthic foraminifers and (B) bioclast in the calcirudite of the Lower Unit at the type locality. (C) Planktonic foraminifera, and (D) serpentine lithics in the calcarenite of Subunit A at the type locality. (E) Calcilutite of the Subunit B at the type locality. (F) Oolite lithics in the first calcirudite bed at Cidra. (G) Clorite-replaced opaque grain in the fifth calcirudite bed, and (H) calcilutite of the Subunit B at Santa Isabel.

grey, massive calcilutite, mainly composed of clay-sized grains of coccoliths, micrite and brownish clay minerals and planktonic foraminifera (Figs. 7E and 8). The insoluble residue of the calcilutite is mainly composed of quartz, clinoptilolite-heulandite, smectite and plagioclase (Fig. 9) with siderite. Serpentine and dolomite are rare in Subunit B.

6.3. Cidra (Matanzas Province)

6.3.1. The Lower Unit

The upper part of the Vía Blanca Formation to the upper part of Subunit A of the Peñalver Formation is continuously exposed in an abandoned quarry near the village of Cidra.

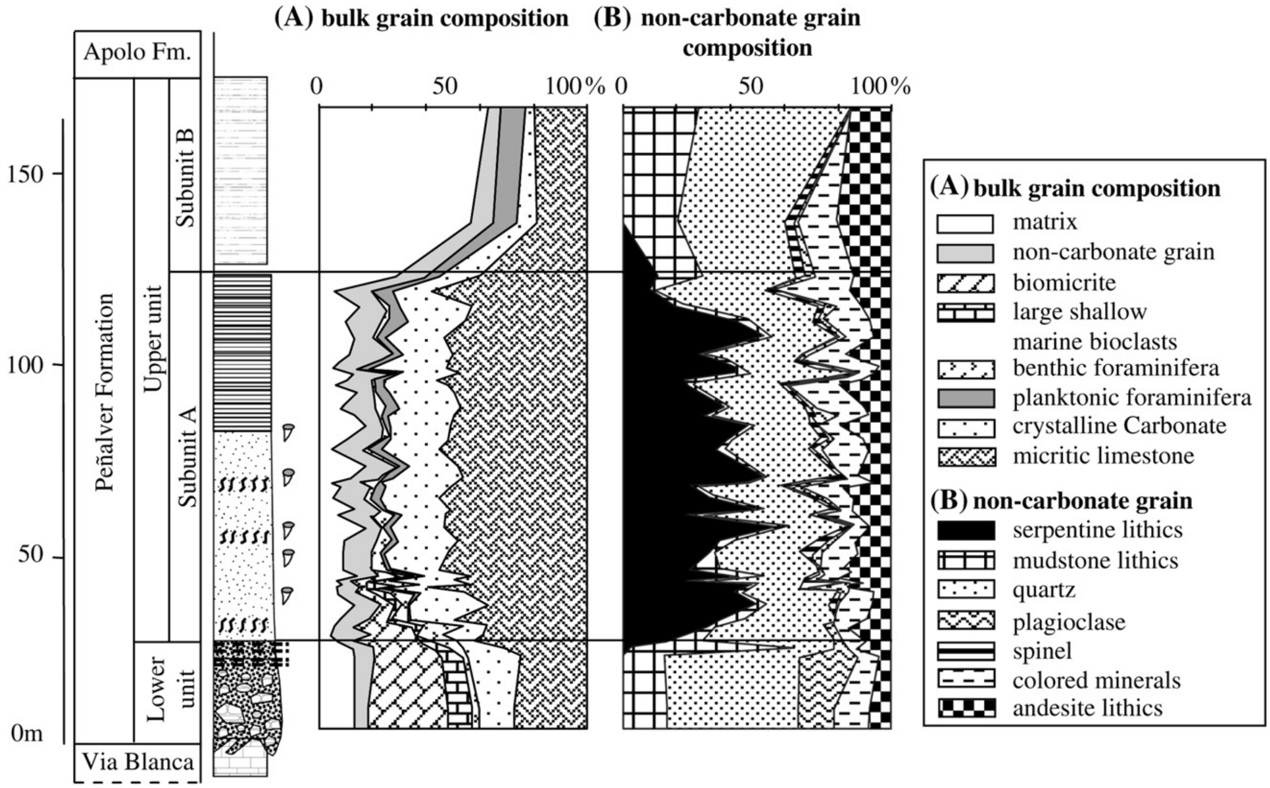

Fig. 8. Vertical variations in grain composition of the Peñalver Formation at the type locality based on point counting: (A) composition of bulk samples and (B) composition of non-carbonate grains. Legend of columnar section is same as in Fig. 4.

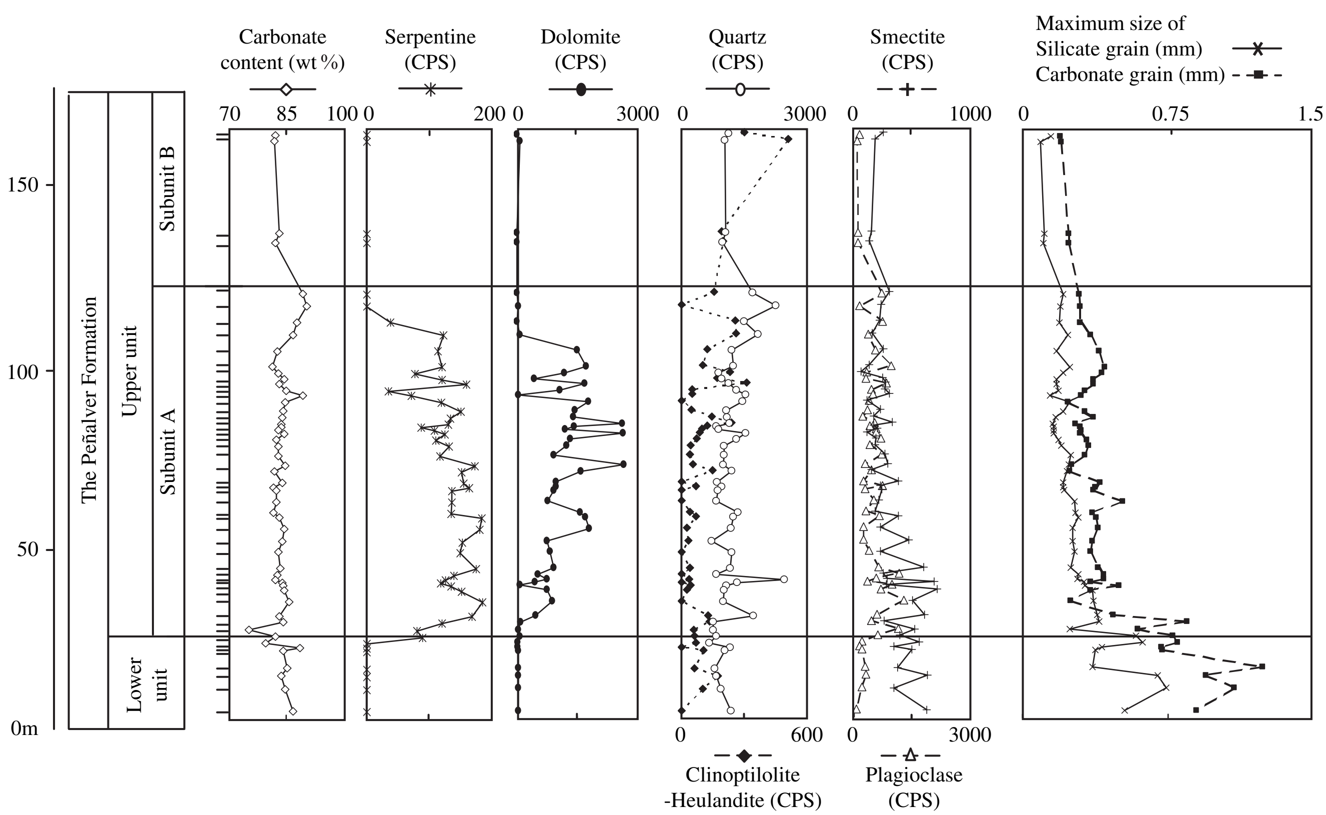

Fig. 9. Vertical variations in calcium carbonate content (wt %), and mineral compositions of insoluble residue based on XRD analysis (CPS), and maximum grain sizes of carbonate and silicate grains (mm) of the Peñalver Formation at the type locality.

The thickness of the exposed part of the Peñalver Formation is 85 m (Fig. 4). Subunit B and the overlying Apolo Formation are not exposed.

The Lower Unit at Cidra overlies the Vía Blanca Formation with an irregular erosional surface. The Lower Unit is 18 m thick and is composed of two 9 m-thick calcirudite to calcarenite beds, defined as calcirudite beds 1 and 2 in ascending order (Fig. 4). The contact between the beds 1 and 2 is sharp and conformable. Each bed fines upward from pebble-grained calcirudite to coarse-grained calcarenite. The calcirudite shows grain-supported fabric and contains abundant well-rounded macrofossil fragments of shallow-marine origin. Thin conglomerate beds are intercalated in the upper part of each unit and the occurrence of these beds is similar to that in the upper part of the Lower Unit at the type locality. The uppermost thin conglomerate bed in Bed 2 is deformed and its upper part is cut by the overlying calcarenite of the Upper Unit. Pillar structures occur in the upper part of Bed 1 and throughout Bed 2 (Fig. 10A).

Grain composition and size of the calcirudite and calcarenite of the Lower Unit at Cidra are different from that at the type locality (Figs. 11 and 12). In Bed 1, there are numbers of well-rounded oolite lithics (Fig. 7F) and minor black shale fragments ~1 mm in diameter are observed. Brownish mudstone lithics appear different from those at the type locality because they contain abundant detrital quartz and plagioclase grains with diameters less than 50 μm. Moreover, the maximum size of micritic limestone lithics in the Lower Unit at Cidra is coarser than those at the type locality, and show upward decrease from 2300 to 1700 μm (Fig. 12). The insoluble residue of the calcirudite in the Lower Unit is similar in composition to that at the type locality, although the content of clinoptilolite-heulandite in Cidra is slightly higher than that at the type locality (Fig. 12).

6.3.2. *The Upper Unit*

Subunit A of the Upper Unit overlies the Lower Unit with an irregular erosional surface. It is more than 67 m thick and composed of light grey, massive, well-sorted, medium to fine grained calcarenite. Pillar structures are observed throughout, although pipe structures occur at only two distinct levels, 1 and 20 m above the base of the subunit (Fig. 4). There is an approximately 1 m-thick interval with faint parallel lamination from 27 to 28 m above the base of this subunit. This interval is associated with a small amount of angular black shale fragments up to 20 cm in diameter (Fig. 10B), which tend to be aligned parallel to bedding. Above this interval, several centimeters to several meter-thick faint bedding is observed.

Grain composition and size of the calcarenite in Subunit A is similar to that at the type locality (Figs. 11 and 12). The content of shallow marine large fossils drastically decreases within the lower part of Subunit A. Serpentine lithics are not

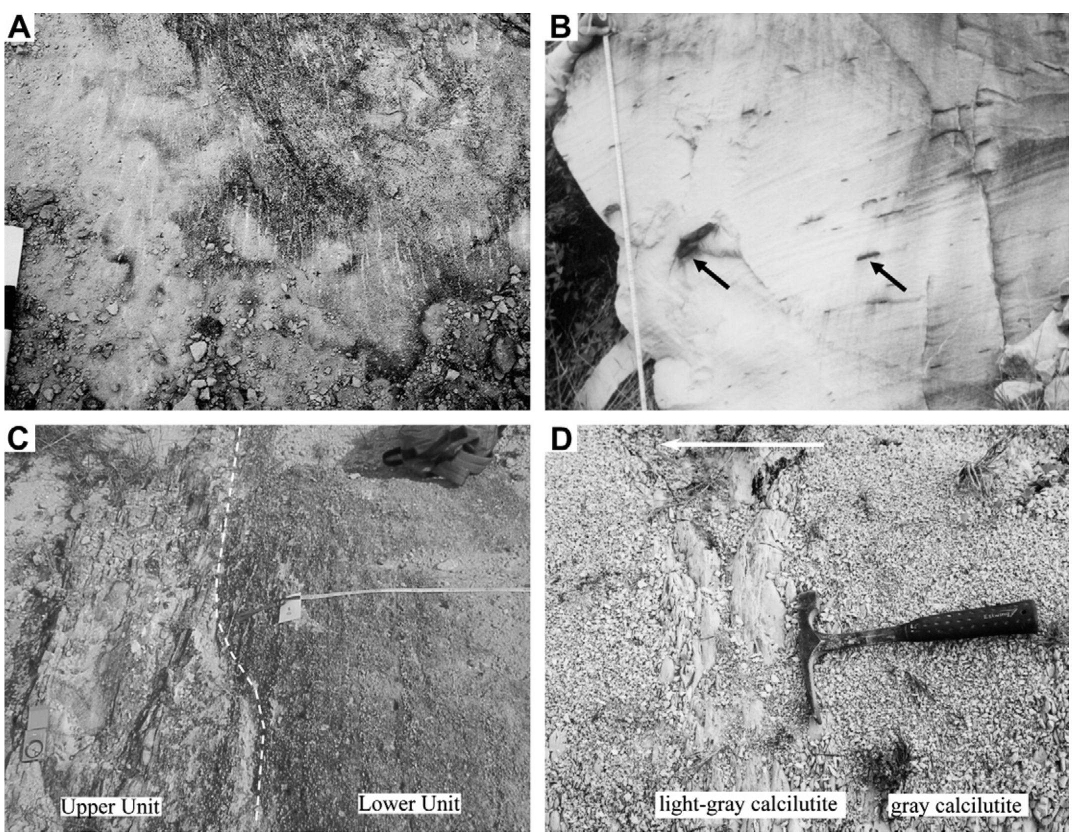

Fig. 10. (A) Pillar structures (white streaks) in the Lower Unit at Cidra. (B) Approximately 1 m thick interval at 27 to 28 m above the base of the Subunit A at Cidra. Small amount of angular black shale fragments are observed. (C) The irregular contact between the Lower and Upper units at Santa Isabel. (D) Alternation of grey and hard calcilutite bed and light grey and more calcareous bed in Subunit B at Santa Isabel.

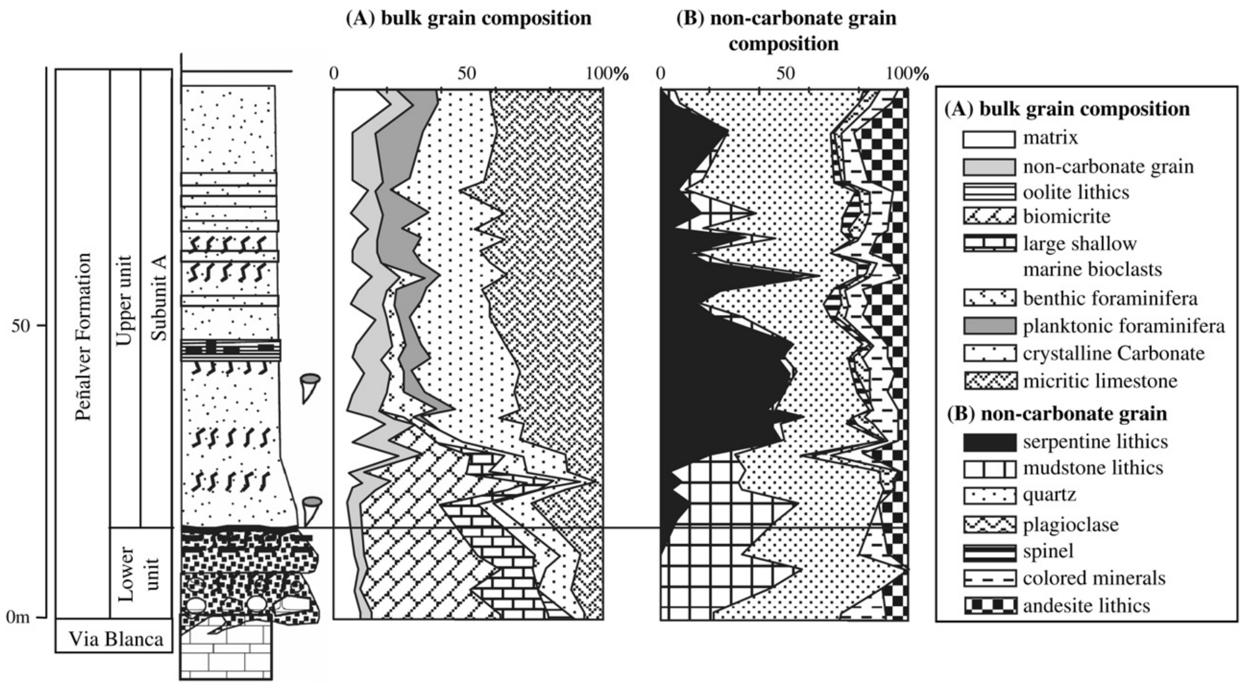

Fig. 11. Vertical variations in grain composition at Cidra.

found in the Lower Unit, but appear at 10 m above the base of Subunit A, where the content of large fossil fragment of shallow marine origin and biomicrite lithics decrease (Fig. 11). Serpentine lithics comprise more than 50% of non-carbonate grains between 10 and 27 m above the base of Subunit A and decrease upward with oscillations of their content between 0 and 50% (Fig. 11). Brownish mudstone lithics in Subunit A do not contain detrital quartz and plagioclase grains, indicating that mudstone lithics differ between the Lower and Upper units. The range of maximum grain size and upward decreasing trend of both micritic limestone lithics and detrital quartz grains in Subunit A at Cidra are almost the same as those at the

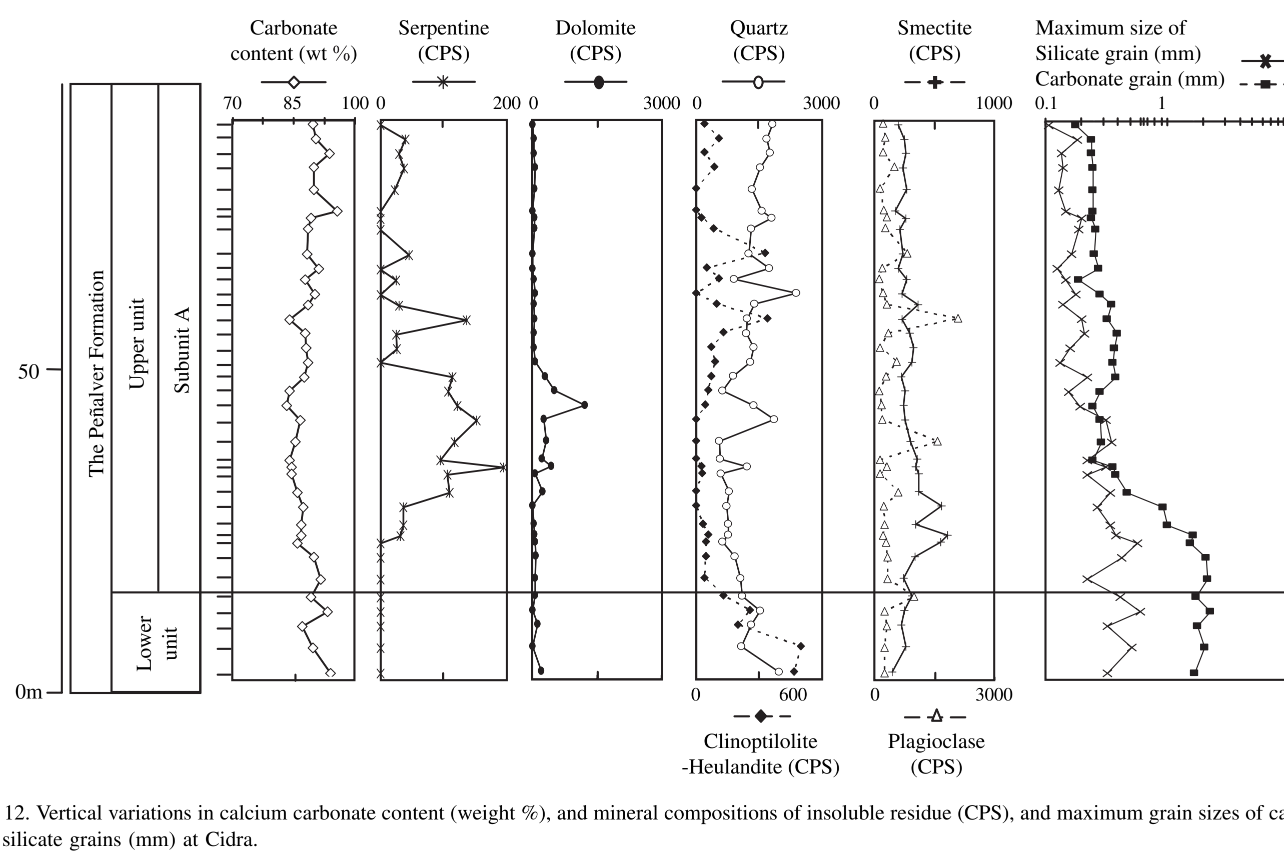

Fig. 12. Vertical variations in calcium carbonate content (weight %), and mineral compositions of insoluble residue (CPS), and maximum grain sizes of carbonate and silicate grains (mm) at Cidra.

type locality (Fig. 12). Insoluble residue in the calcarenite of Subunit A is similar to that at the type locality, including an upward increasing trend of quartz and clinoptilolite-heulandite, upward decreasing trend of smectite, and presence of serpentine only in Subunit A (Fig. 12).

6.4. Santa Isabel (Pinar del Rio Province)

6.4.1. The Lower Unit

The interval from the upper part of the Vía Blanca Formation to the lower part of the probable Apolo Formation is continuously exposed at Santa Isabel. The thickness of the Peñalver Formation in this area is approximately 80 m (Fig. 4).

The Lower Unit of the Peñalver Formation overlies the Vía Blanca Formation with an irregular erosional surface. The thickness of the Lower Unit is 45 m and is composed of five amalgamated calcirudite beds, which are defined as Beds 1 to 5 in ascending order (Fig. 4). Each bed shows upward-fining from cobble-grained calcirudite to coarse-grained calcarenite. The calcirudite shows a grain-supported fabric and contains abundant well-rounded macrofossil fragments of shallow-marine origin. Abundant intraclasts up to 2 m in diameter are entrained in Bed 1. Thin conglomerate beds are intercalated in the upper part of beds 1, 4 and 5, and these are similar to those observed in the upper part of the Lower Unit at the type locality and Cidra. Channel-type erosional surfaces are observed in the basal parts of beds 2, 4 and 5. Axes of these erosional channel surfaces trend in a N–S direction and plunge 3° to the north with respect to bedding.

Grain composition and size of the calcirudite of the Lower Unit at Santa Isabel is different from that at the type locality and Cidra (Fig. 13). Large calcareous benthic foraminifera are not observed in Bed 1. Brownish mudstone lithics are different from those at the type locality, but similar to those at Cidra in that they contain abundant detrital quartz and plagioclase less than 50 μm in diameter. There is no significant compositional variation between beds 1 to 4, whereas chlorite-replaced grains are observed in Bed 5 (Fig. 7G). The insoluble residue of the calcirudite in the Lower Unit is similar in composition to that at the type locality (Fig. 14). In Bed 5, quartz is more and smectite less abundant than in beds 1 to 4, and chlorite and minor dolomite are present. The maximum size of micritic limestone lithics in the Lower Unit at Santa Isabel is coarser than those at the type locality and Cidra, and show an upward decrease in size from 7300 to 1300 μm (Fig. 14).

6.4.2. The Upper Unit

The Upper Unit overlies the Lower Unit with an irregular erosional surface (Fig. 10C). The Upper Unit is approximately 35 m thick and subdivided into subunits A and B. Subunit A is 8 m thick and consists of medium grey, massive, well-sorted, very fine to fine grained calcarenite. The lower 2 m of Subunit A is composed of an alternation of fine and very fine calcarenite. An approximately 1.6 m deep channel-type erosional surface is observed 2 m above the base of Subunit A. The channel axis trends approximately N77°W and plunges 10° to the west relative to bedding. No water escape structures are observed in Subunit A. Grain composition and mineral composition of

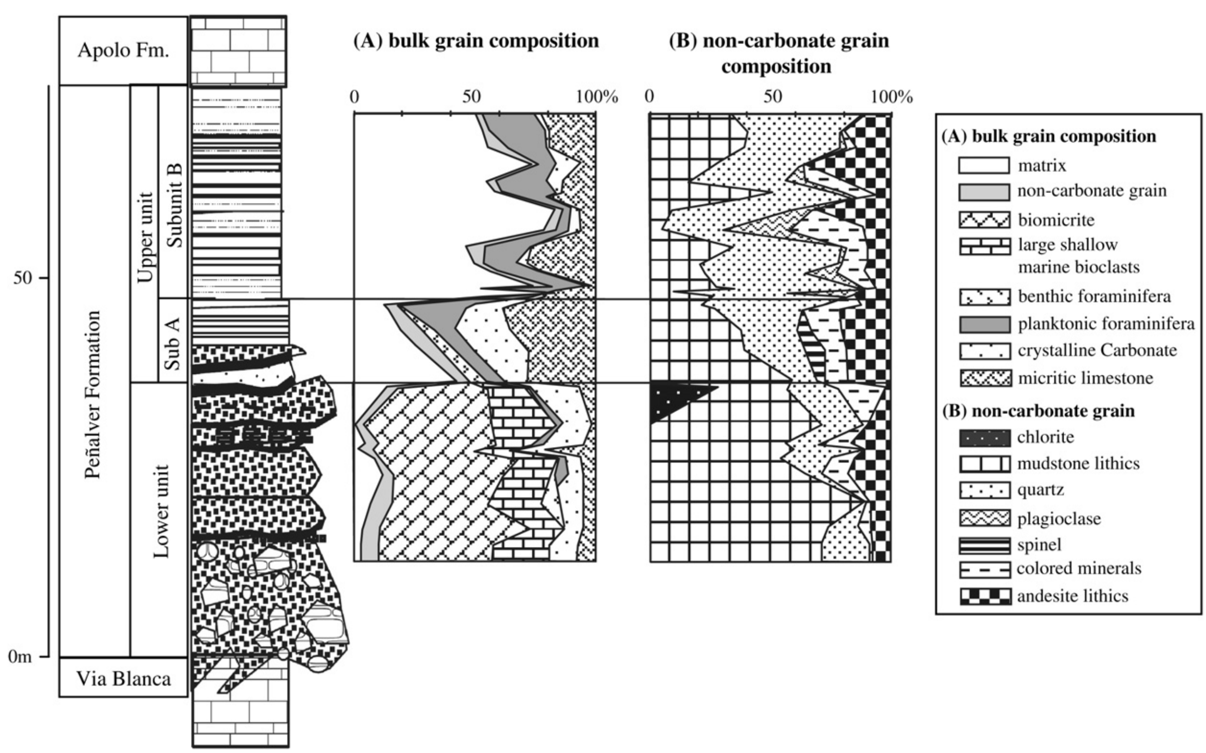

Fig. 13. Vertical variations in grain composition at Santa Isabel.

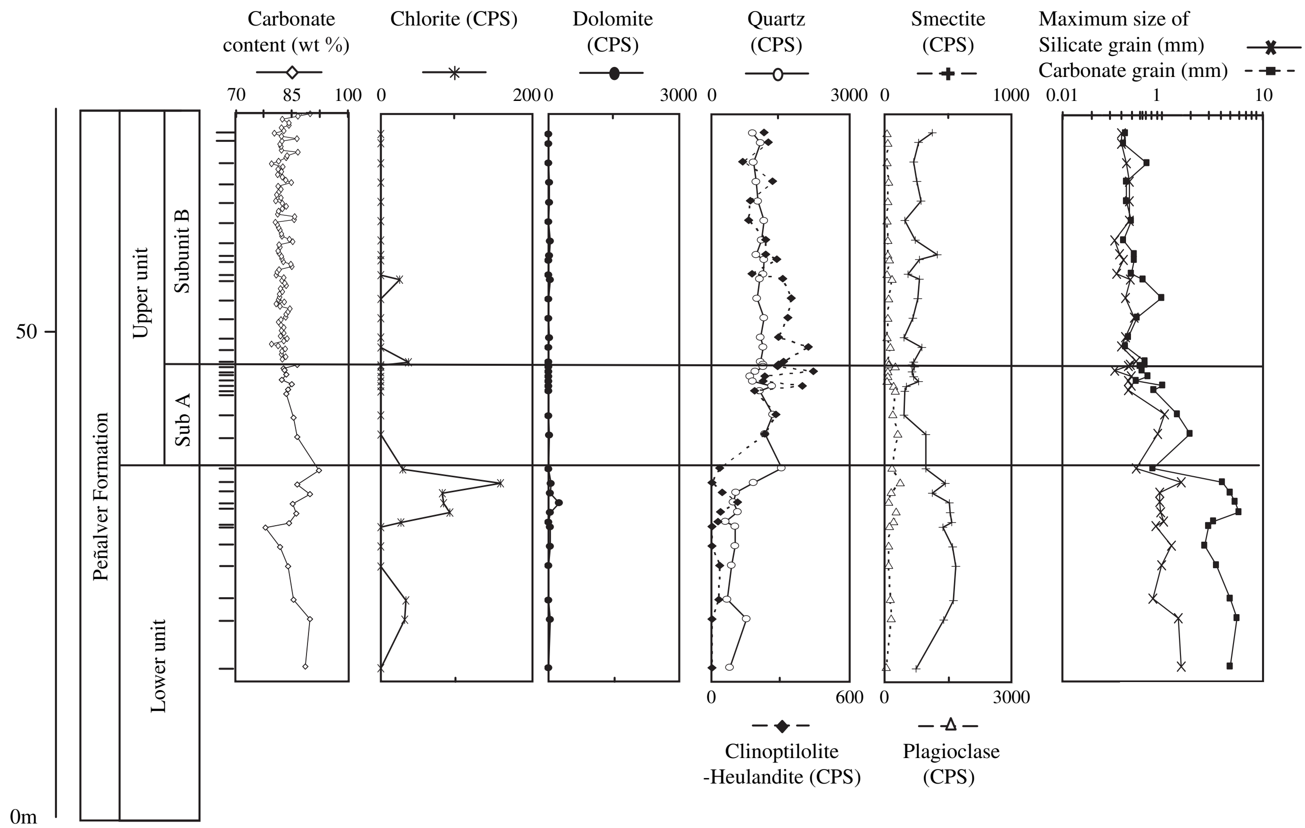

Fig. 14. Vertical variations in calcium carbonate content (wt %), and mineral compositions of insoluble residue (CPS), and maximum grain sizes of carbonate and silicate grains (mm) at Santa Isabel.

insoluble residues of the calcarenite is similar to that at the upper part of Subunit A of the type locality and Cidra, except for the absence of serpentine lithics and dolomite (Figs. 13 and 14). The range of maximum grain size and upward decreasing grain size trend of both micritic limestone lithics and detrital quartz grains in Subunit A are similar to those at the type locality and at Cidra (Fig. 14).

Subunit B overlies Subunit A with a sharp conformable contact. It is approximately 27 m thick and is characterized by ten alternations of grey argillaceous calcilutite beds 1 to 4 m thick and light-grey calcilutite beds several to several tens centimeter thick (Figs. 10D and 15). The carbonate content of light-gray calcilutite beds is 3 to 8% higher than the grey argillaceous calcilutite beds (Fig. 15). The grain-size distribution of insoluble residue in the calcilutite shows an uni-modal distribution (Fig. 16). The average mode and maximum diameters of the insoluble residue of the light-grey calcilutite beds are approximately 5.1 and 20 μm, whereas those of the grey argillaceous calcilutite beds are approximately 5.9 and 45 μm, respectively. Furthermore, the grey argillaceous calcilutite beds have broader grain-size distributions than those of the light-grey calcilutite beds. The calcilutite in Subunit B is mainly composed of clay-sized grains such as coccolith and micrite matrix with small amount of well preserved planktonic foraminifera (Figs. 7H and 13); secondary calcite is rare. The light-grey calcilutite beds contain a larger amount of micritic limestone lithics and planktonic foraminifera than the grey argillaceous calcilutite beds. The contents of coccolith and micrite matrix are also higher in the light-grey calcilutite beds. On the other hand, the grey argillaceous calcilutite beds contain more detrital quartz and andesite lithics than the light-grey calcilutite beds.

At the top of the Subunit B, there is a 2 to 7 cm thick brown calcilutite bed with burrows. An iridium concentration anomaly (179 ± 30 ppt) is observed in this bed, and slightly decreases to 91 ± 16 ppt just above the bed (Hatsukawa et al., 2007). These values are well above the background level (<47 ppt, Hatsukawa et al., 2007), but low when compared with other K/T boundary deposits around the proto-Caribbean sea and the Gulf of Mexico (e.g., Smit et al., 1992). Above this bed, there is a 4 m thick light-grey massive calcilutite interpreted as the Apolo Formation.

7. Discussion

7.1. Lateral variation in lithology of the Peñalver Formation

The results of this study indicate that the thickness and sedimentary structures of the Peñalver Formation show significant and systematic lateral variations. The Peñalver Formation is more than 180 m thick at the type locality, more than 85 m at Cidra, and approximately 80 m at Santa Isabel (Fig. 4 and Table 1). Notably, at Santa Isabel and Cidra, the Lower Unit comprise a larger number of calcirudite beds, contains a larger

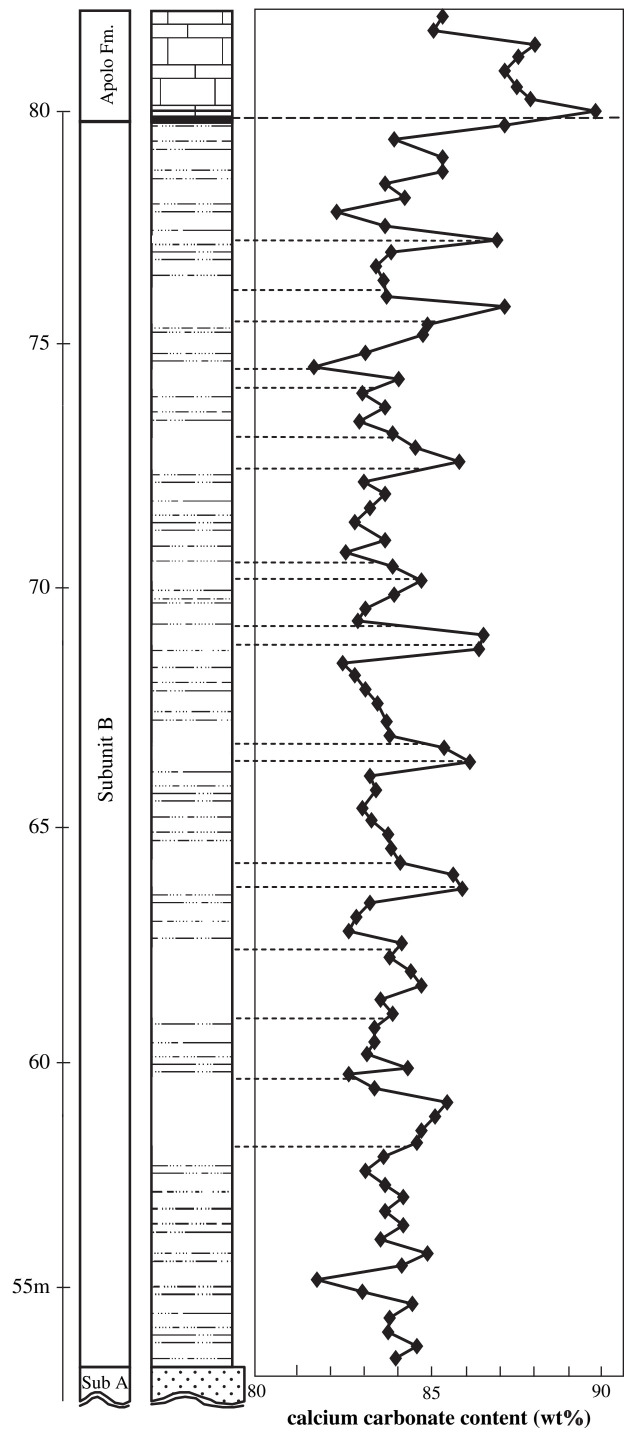

Fig. 15. Vertical variation in calcium carbonate content (wt %) in the Subunit B at Santa Isabel.

amount of biomicrites and shallow marine fossil fragments, and is coarser grained than at the type locality (Table 1). This suggests that the Peñalver Formation at Cidra and Santa Isabel were deposited at shallower depths and closer to the source area than at the type locality. This is consistent with the finding that, of the three localities, the type locality was located northward and furthest away from the Cuban carbonate platform when restored to its original position.

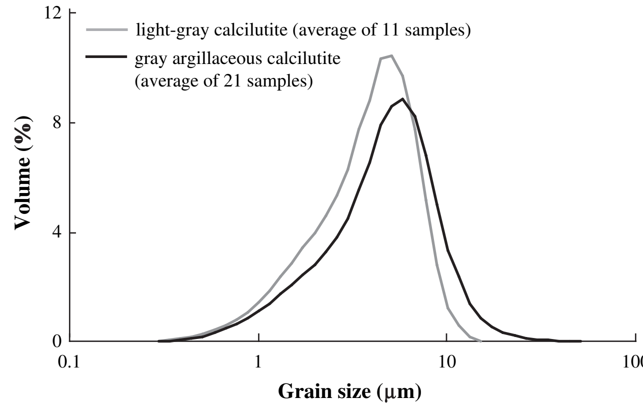

Fig. 16. Grain size distributions of insoluble residues of the Subunit B at Santa Isabel (μm).

7.2. Origin and depositional mechanism of the Lower Unit

The Lower Unit of the Peñalver Formation overlies the Vía Blanca Formation with an irregular erosional basal contact, and entrains calcareous mudstone blocks of the Vía Blanca Formation as intraclasts at all localities studied. The calcirudite in the Lower Unit is poorly sorted with a grain-supported fabric, and is composed of abundant well-rounded macrofossil fragments of shallow-marine origin. It includes pillar type water escape structures at both the type locality and Cidra. All these features in the Lower Unit are consistent with those of debris flow deposits (Middleton and Hampton, 1976).

Dypvik and Jansa (2003) mentioned that the Peñalver Formation was derived not from the Cuban volcanic arc but from a continental margin due to the collapse of the outer shelf edge, based on the presence of quartz and microcline grains. However, these grains are also observed in the sediments of the Vía Blanca Formation and have not necessarily been

Table 1
Lateral variations of thickness and sedimentary features of the Penalver Formation

	Type locality	Cidra	Santa Isabel
Total thickness	>180 m	>85 m	80 m
Depositional area	Offshore	Near the arc	Near the arc
Lower unit			
Thickness	30 m	18 m	45 m
Number of calcirudite beds	1	2	5
Relative depositional depth	Deep	Shallow	Shallow
Upper unit			
Thickness	>150 m	>67 m	35 m
Basal contact	Gradual	Weakly eroded	Strongly eroded
Current structure	No	Yes	Yes
Compositional oscillation	Subunit A	Subunit A	Subunit B
Number of oscillation	>6	>7	10

transported from a continental margin. Moreover, the rudist taxa (Rojas et al., 1995), the presence of andesite lithics in the Lower Unit, and N–S direction of channels developed in the basal part of beds 2, 4 and 5 at Santa Isabel suggest that the calcirudite of the Lower Unit was derived from the extinct Cretaceous Cuban arc exposed to the south of the depositional area of the Peñalver Formation and from the underlying conglomeratic beds of the Vía Blanca Formation, as previously proposed by Takayama et al. (2000). Well-rounded oolite fragments are only observed in Bed 1 at Cidra and chlorite-replaced grains are observed only in Bed 5 at Santa Isabel. Furthermore, the maximum grain size of carbonate and silicate grains in each bed in the Lower Unit is different. Differences in grain and mineral composition, and maximum grain size of carbonate and silicate grains in the calcirudite of the Lower Unit among the studied localities suggest a local source for the debris flows.

According to Goto et al. (2002), there are no shocked quartz grains in the calcirudite Bed 1 at Cidra and in beds 1 to 3 at Santa Isabel. Because shocked quartz grains probably settled around the impact site within several hours after the impact (Kring and Durda, 2002; Tada et al., 2003), the debris flows, which led the deposition of these beds, were generated and deposited within several hours after the impact before the arrival of shocked quartz grains to the sea floor. One of the earliest impact-related phenomena arriving at the sites are the seismic waves (e.g. Smit et al., 1996; Smit, 1999), which may have arrived at the studied area within several minutes after the impact. Their effect continued for several hours, and peak amplitude of the seismic waves could have reached several meters (Boslough et al., 1996), enough to cause large slope failures (Takayama et al., 2000; Tada et al., 2003). Alternatively, large-scale tsunami created by large-scale slope failure along the Yucatán platform margin may have served as triggers of debris flows (Tada et al., 2003). Since the distance between the Yucatán platform margin and the depositional area of the Peñalver Formation was approximately 400 km, the first tsunami could have arrived at the depositional area approximately 1 h after slope failure (Matsui et al., 2002).

7.3. Origin of the Upper Unit

In the Upper Unit of the Peñalver Formation, hemipelagic grains such as micritic limestone lithics and planktic and benthic forams are major components of the calcarenite, suggesting a distinct difference in the source compared to the Lower Unit. Planktonic foraminiferal assemblages in the Upper Unit at the type locality are characterized by a mix of various species with various diagnostic ages ranging from Campanian to Maastrichtian (Takayama et al., 2000), which overlap with the age of the Vía Blanca Formation. Similar micritic limestone lithics and skeletons of planktic and benthic forams are abundant in turbidites in the Vía Blanca Formation, suggesting that the major source of the Upper Unit was unconsolidated sediment of the Vía Blanca Formation on the slope of the Cuban carbonate platform rather than the actual carbonate platform sediments. This is postulated because there are no carbonate lithics derived from the carbonate platform in Subunit A at the type locality. Debris flows, which led to deposition of the Lower Unit, may have contributed to resuspension of the unconsolidated sediments of the Vía Blanca Formation, because debris flows usually erode and entrain sediments down slope (Postma et al., 1988). However, the presence of serpentine lithics, which occupy less than 50% of total non-carbonate grains, and nannofossils and planktonic foraminifera of Aptian age in the Upper Unit are difficult to explain simply by resuspension of sediments from the Vía Blanca Formation by debris flows, because these are not present in the Vía Blanca Formation in the study area.

Although there is no serpentinite and serpentine sandstone beds in the Vía Blanca Formation, serpentinite and related rocks are present in sections beneath the Vía Blanca Formation in the Havana area and a small amount of serpentine pebbles of the same origin are observed in the Lower Unit of the Peñalver Formation in Victoria. However, these serpentinite exposures and serpentine pebbles have grain sizes very different from sand-size serpentine lithics in the Upper Unit. On the other hand, Maastrichtian serpentine-rich sandstones and conglomerates, related to allochthonous ophiolites bodies, are exposed in central to northeastern Cuba. For example, Maastrichtian serpentine-rich sandstones at south of Moa approximately 500 km to the east of Havana (La Picota Formation, Mossakovsky et al., 1988) are composed of well-sorted, subangular to rounded, fine to medium grained serpentine grains. Another possible source is Loma Capiro, central Cuba, because at this locality there are calcarenites with serpentine lithics of Maastrichtian age. The grain size distribution and roundness of these serpentine grains are similar to serpentine lithics in the Upper Unit of the Peñalver Formation (Figs. 17 and 18). Such similarities suggest that serpentine sandstone in central to northeastern Cuba could be the source of serpentine lithics in the Upper Unit at the type locality and Cidra.

There are no serpentine lithics in the Upper Unit at Santa Isabel. However, medium to coarse grained calcarenite is absent in the Upper Unit at Santa Isabel. Serpentine lithics are abundant in medium to coarse grained calcarenites in the lower to the upper part of Subunit A at the type locality and

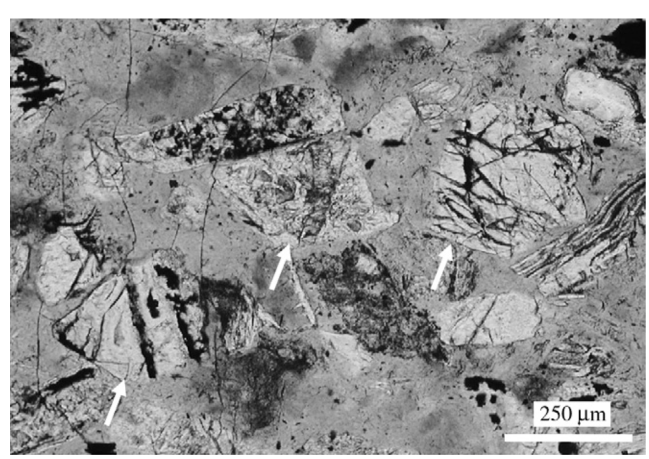

Fig. 17. Serpentine lithics in the serpentine sandstone at Moa area.

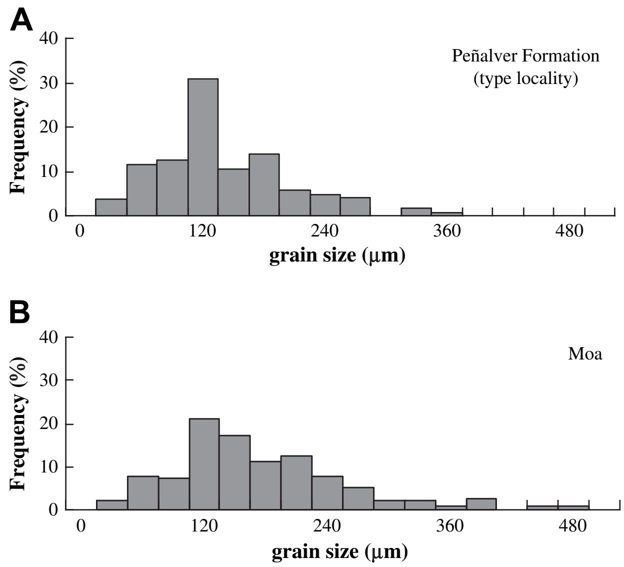

Fig. 18. Grain size distributions of serpentine lithics (μm) in (A) Subunit A at the type locality, and (B) Cretaceous serpentine sandstone at Moa area based on thin section observation.

Cidra, but they are rare in very fine to fine calcarenite in the uppermost part of Subunit A at the type locality (Fig. 9). Consequently, the absence of serpentine lithics in Santa Isabel could be explained by absence of the medium to coarse grained calcarenite at the base of Subunit A at Santa Isabel. The presence of an erosional surface at the base of Subunit A suggests that medium to coarse sized calcarenite with serpentine lithics were not deposited but carried downslope as will be discussed in the next section. Alternatively, serpentine lithics may not have reached this area, because either this area was located in the western side of the basin or was at shallower depths compared to the other two localities.

7.4. Depositional mechanism of the Upper Unit

The large thickness, presence of abundant water escape structures and finer grain size with monotonous upward fining feature of the Upper Unit compared with that of the Lower Unit together with its homogeneous appearance with no bioturbation at the type locality implies rapid sedimentation from a dense sediment suspended cloud (Takayama et al., 2000). Grain and mineral composition and maximum grain sizes of the micritic limestone lithics and detrital quartz grains of the calcarenite and calcilutite in the Upper Unit are similar at the 3 localities, suggesting that the Upper Unit was formed from a homogeneous dense sediment suspension cloud at least 150 km wide in an east-west direction and 20 km wide in a north–south direction. This feature is similar to that of the Santorini-generated homogenite and implies that the dense sediment suspension cloud was generated by tsunami (Takayama et al., 2000). Subunit A of the Upper Unit contains serpentine lithics that are not contained in the underlying Vía Blanca Formation, but similar to those reported from central to northeastern Cuba. Moreover, there is no erosional surface at the base of the Upper Unit at the type locality. These observations suggest that serpentine lithics may have been transported not by sediment gravity flow but as suspension generated by mass water motion. This, in turn, suggests that sediment particles may have been transported by tsunami because usual marine currents cannot transport thick clouds of sediment particles (e.g. Kastens and Cita, 1981).

The occurrence of K/T-boundary tsunami deposits in the deep-sea has been suspected with the main argument that impact-generated tsunamis cannot affect the deep-sea bottom, due to the diminishing power of currents with increasing water depth (e.g., Bohor, 1996). However, according to the small-amplitude water wave theory (e.g., Horikawa, 1978), the influence of a tsunami does not diminish downwards. This suggests that sediment particles on the ocean bottom have the potential to become suspended by passing tsunami waves (Dypvik and Jansa, 2003), depending on their wave height and period.

Examination of the lateral lithological variation of the Upper Unit revealed that it is thinner at Santa Isabel and Cidra (Fig. 4 and Table 1). At these two localities, an erosional surface is recognized at the base and parallel lamination was recognized in the middle part of the Upper Unit (Table 1). A channel-type erosional surface is observed 2 m above the base of Subunit A at Santa Isabel, which has an axial direction different from those observed in the basal part of beds 2, 4 and 5 of the the Lower Unit. This probably suggests that the erosional surface in Subunit A was created by a process different from that in the Lower Unit. Considering that depositional depths in the Cidra and Santa Isabel area could have been shallower than that of the type locality, the presence of erosional surfaces and parallel lamination in these areas probably reflects the larger near-bottom current velocities of tsunami due to the shallower depositional depths, because the near-bottom current velocity of the tsunami becomes larger with decreasing depositional depth.

7.5. Compositional oscillations in the Upper Unit

Analysis of grain and mineral compositions of the insoluble residue in Subunit A at the type locality reveals more than 6 repeated oscillations in serpentine content (Figs. 8 and 9). Serpentine lithics, which were probably derived from central to northeastern Cuba, were mixed with sediment particles resuspended from the Vía Blanca Formation and unconsolidated sediments on the Cuban platform, probably by the first tsunami wave to form a sediment suspension cloud. This is based on the observation that serpentine lithics appear and markedly increase upward from the base of Subunit A. Based on the grain composition analysis, serpentine content is negatively correlated with contents of andesite and micritic limestone lithics (Fig. 8). Moreover, higher contents of micritic limestone and andesite lithics tend to coincide with the coarser maximum size of micritic limestone lithics, suggesting that oscillations in serpentine content could reflect variation of the mixing ratio between two end-members characterized by serpentine lithics with smaller grain sizes, and micritic limestone plus andesite lithics with larger grain sizes, respectively. This can be explained by sediment particles, including coarser micritic limestone and andesite lithics derived from the slope of the extinct Cretaceous Cuban arc, being repeatedly injected into an initial dense sediment suspension cloud characterized by serpentine lithics. Since there are no erosional structures at the bottom of the intervals where micritic limestone and andesite lithic contents increase, the lateral supplies of the sediment particles characterized by serpentine lithics to the initial dense sediment suspended cloud should not have been in the form of gravity flows running down on the ocean floor but rather as lateral injection of the suspended particles into the suspended cloud by northward water mass movement such as repeated tsunami backwashes (Fig. 19).

The calcilutite of Subunit B at the type locality is massive and without any sedimentary structures, suggesting that the influence of tsunami at the type locality ceased before deposition of Subunit B and the suspended sediment particles settled monotonously through the ocean column (Fig. 19). In contrast, 10 repeated compositional oscillations, characterized by variations in calcium carbonate content, are observed in Subunit B at Santa Isabel. The grey argillaceous calcilutite beds are characterized by coarser grain size of insoluble residues, higher amounts of detrital quartz and andesite lithics, and lower contents of planktonic foraminifers and micritic limestone lithics as compared to light-grey calcilutite beds. This suggests that oscillations in calcium carbonate content indicate variations of the mixing ratio between two end-members characterized by a higher content of carbonate grains such as planktonic foraminifers and micritic limestone lithics with smaller grain sizes, and a higher content of detrital quartz and andesite lithics with larger grain sizes, respectively. This suggests that, compared to the light grey calcilutite beds, the grey argillaceous calcirudite beds contain larger amount of sediment particles transported from the area of the extinct Cretaceous Cuban arc. By analogy with the depositional mechanism of Subunit A at the type locality and Cidra, compositional oscillations in Subunit B at Santa Isabel is considered to reflect repeated injection of the sediment particles derived from the Cretaceous Cuban arc characterized by lower calcium carbonate content and larger grain sizes into the dense sediment suspended cloud characterized by higher content of calcium carbonate particles and smaller grain sizes as a result of repeated tsunami backwashes.

Compositional oscillation is observed in Subunit A at the type locality and Cidra, whereas it is observed in Subunit B at Santa Isabel. It is possible that compositional oscillations in Subunit B at Santa Isabel were formed by the same tsunami which formed the oscillations in Subunit A at the type locality and Cidra, because the Peñalver Formation at Santa Isabel was probably deposited in shallower depth than at the type locality and it is consequently the silt size grains in the Subunit B at Santa Isabel were settled earlier than those in Subunit B at the type locality. Our preliminary calculation suggests that oscillations in Subunit A at the type locality and those in Subunit B at Santa Isabel could have been formed around the same time (Goto et al., 2002).

7.6. Lithological and compositional similarities of K/T boundary deposits in the proto-Caribbean sea and the Gulf of Mexico

There is a similarity between the lithology and composition of the K/T boundary deep-sea tsunami deposits in the Upper

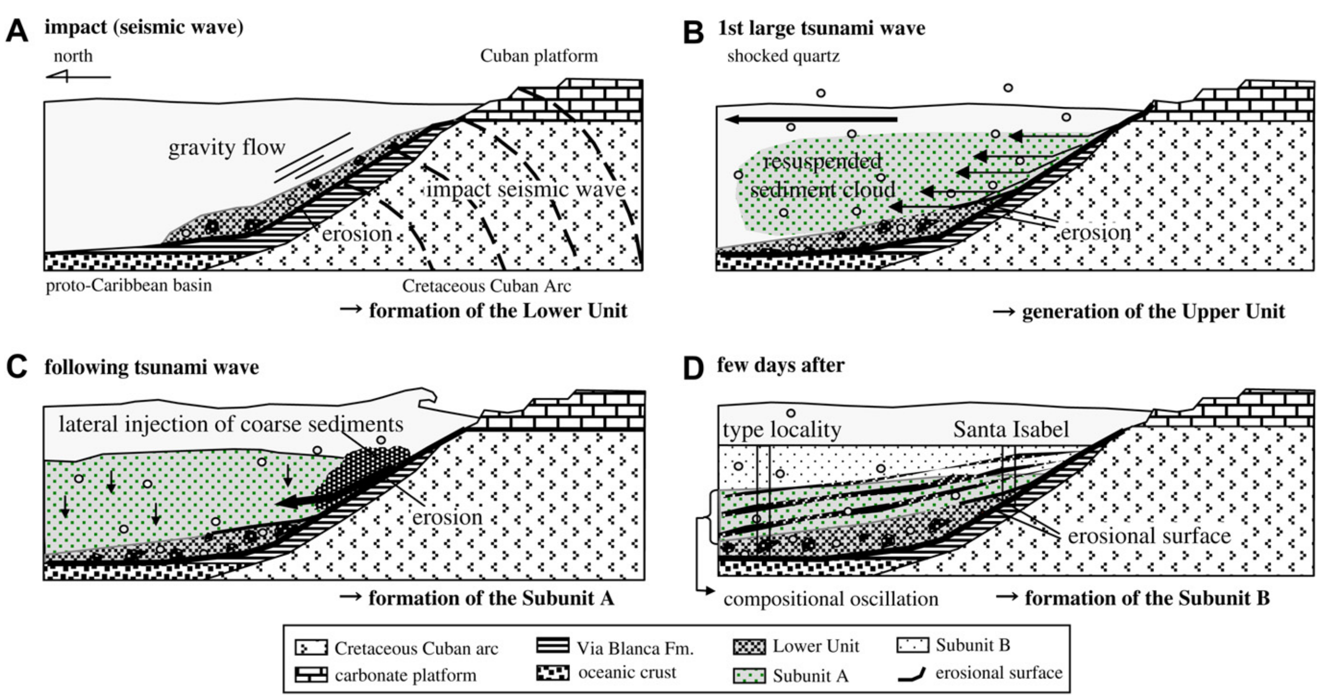

Fig. 19. A cartoon showing the depositional processes of the Peñalver Formation. (A) The impact seismic wave triggered the debris flows, (B) first large tsunami wave and backwash associated with the impact eroded the deep sea floor and formed the dense sediment suspended cloud, (C) following tsunami waves eroded the slope sediments and backwashes of tsunami transported the sediments into the dense sediment suspended cloud, and (D) re-suspended silt size sediment particles settled down.

Unit of the Peñalver Formation, and the 450 m thick calcarenite and calcilutite part of the Cacarajícara Formation in Cuba (Tada et al., 2003), corresponding to the Middle Grainstone plus Upper Lime Mudstone members of Kiyokawa et al. (2002). Notably, the depositional areas of the Peñalver and the Cacarajícara formations were 400–500 km apart at the time of the impact (Fig. 1). Moreover, Alegret et al. (2005) also inferred a similarity in lithology and composition of between 4.5-m thick calcarenite and calcilutite parts of the K/T boundary deposit at Loma Capiro with the Upper Unit of the Peñalver Formation. The deposit at Loma Capiro is approximately 10 m thick and was formed along the Cuban volcanic arc approximately 250 km apart from the Havana area (Fig. 1). These similarities in lithology and composition probably suggest that a sediment suspended cloud of more or less the same composition was formed and spread throughout the basin of the proto-Caribbean sea at least along the Yucatán and Cuban carbonate platforms.

In addition, the approximately ~350-m-thick late Maastrichtian Amaro Formation, which was formed on the Bahama Platform (Fig. 1, Iturralde-Vinent, 1992), is reported as the possible K/T boundary deposits (Pszczolkowski, 1986; Iturralde-Vinent, 1992; Tada et al., 2003). Although its K/T boundary impact origin has not been confirmed, it is speculated as the K/T boundary deposits based on the similarity in lithology and composition with the Peñalver Formation (Tada et al., 2003). If the Amaro Formation was formed in association with the K/T boundary impact, a sediment suspended cloud might have been formed and spread throughout the basin of the proto-Caribbean and resulted in deposition of the thick, homogeneous, sandy to silty single-graded sediments, so-called "homogenite unit (Tada et al., 2003)", throughout the deeper part of the proto-Caribbean basin.

On the other hand, the calcarenite and calcilutite parts of the K/T boundary deep-sea deposits at DSDP sites 536 and 540, which are located on a submarine ridge along the base of the Campeche and Florida escarpments (Fig. 1), have grain and mineral compositions (Alvarez et al., 1992) different from those of the Upper Unit of the Peñalver Formation. The difference in composition between the Upper Unit of the Peñalver Formation and the calcarenite and calcilutite parts at the DSDP sites suggests that sediment suspended cloud was heterogeneous at a larger scale.

In the Atlantic Ocean, only millimeter-thick to centimeter-thick distal ejecta layers have been found (e.g., Norris and Firth, 2002) and there seems to be no distinct K/T boundary tsunami deposit. This suggests that the effect of the tsunami was restricted within the proto-Caribbean sea and the Gulf of Mexico regions. At the time of the K/T-boundary impact, the impact site was surrounded by land in the north and west, and shallow carbonate platforms existed in the south and east (Tada et al., 2003). Therefore, the energy of the tsunami might have been trapped in the Gulf of Mexico and the proto-Caribbean regions (Dypvik and Jansa, 2003).

The Peñalver Formation is characterized by the >6–10 compositional and grain size oscillations that probably reflects the repeated tsunamis. Similar numbers of repetitions of tsunami are inferred from the K/T boundary deposits characterized by repeated bi-directional cross laminations at La Lajilla in the coastal region of the Gulf of Mexico, which repeated more than 9 times (Smit et al., 1996). Furthermore, Tada et al. (2002) reported that the Moncada Formation in eastern Cuba has ripple cross-laminations at several levels that indicate north–south trending palaeocurrent directions with reversals (Tada et al., 2002). Tada et al. (2002) inferred that the Moncada Formation was formed by repeated tsunami based on repetition of upward fining units, reversing current directions between the units, systematic upward decreases in unit thickness, and an absence of basal erosional surfaces. They also reported grain size oscillations in detrital quartz grains that repeated more than 10 times and were interpreted as representing the influence of currents (Tada et al., 2002). This agreement in number of tsunami around the impact site suggests that sedimentation of the Peñalver Formation could have been caused by the same tsunami waves that caused the sedimentation of these K/T boundary tsunami deposits.

8. Conclusion

Lateral lithological, compositional and grain size variations of the Peñalver Formation were examined to evaluate the depositional mechanism. The Lower Unit of the Peñalver Formation is a debris flow deposit derived from the carbonate platform developed on the extinct Cretaceous Cuban arc together with the Vía Blanca Formation deposited on the slope. The Upper Unit was deposited from the dense sediment suspended cloud generated by the impact-induced tsunami. The regional homogeneity of source materials of pelagic to hemipelagic origin and presence of allochtonous materials such as serpentine lithics support the interpretation that the Upper Unit was formed by tsunami. Examination of the lateral lithological variations revealed that the thickness and sedimentary structures of the Peñalver Formation change systematically with changing depositional depth, which probably reflects the difference of influence of tsunami. The sediments on the slope of the extinct Cretaceous Cuban arc were repeatedly eroded by tsunami and transported by backwashes into the initial dense sediment suspended cloud, which caused compositional oscillations in Subunit A at the type locality and Cidra and in Subunit B at Santa Isabel.

Acknowledgements

This research was made possible thanks to an agreement between the Department of Earth and Planetary Science, the University of Tokyo and the Museo Nacional de Historia Natural (Agencia del Medio Ambiente) and the Instituto de Geología y Paleontología del Ministerio de Industria Básica de Cuba. We wish to thank specially the important support provided to field research in Cuba by Mitsui & Co., Ltd. as well as the manager A. Nakata in Havana. We also thank G. Price, D. Tappin and P. Schulte for their critically reading of the manuscript and giving many valuable suggestions, and H. Takayama for his participation in the early stage of this project. The study was supported by Grant-in-Aid for Japan Society for the Promotion of Science (JSPS) provided to T. Matsui (no. 17403005) and research funds donated to the University of Tokyo by NEC Corp., I. Ohkawa, T. Yoda, K. Ihara, and M. Iizuka, and the above mentioned institutions in Cuba.

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