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The Cretaceous–Tertiary transition in Guatemala: limestone breccia deposits from the South Petén basin

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Abstract Limestone breccia deposits in southern Mexico, Guatemala and Belize have recently been interpreted as proximal to distal ballistic fallout deposits, generated by a bolide impact that struck Yucatan at K/T boundary time. We review the age, lithology and the depositional environment of five K/T boundary sections in the South Petén area of Guatemala (Caribe, Aserradero, Chisec, Actela, Chemal) in order to evaluate the nature and origin of K/T limestone breccia deposition. The sections are located 500 km south of the proposed impact site at Chicxulub and trend in an east–west direction from the Guatemala/Mexico border to southern Belize. In four of the five sections examined, a breccia unit up to 50 m thick overlies reef-bearing shallow-water limestones of late Cretaceous (Campanian-Maastrichtian) age. Rhythmically bedded limestones, marls and siltstones of early Danian age overlie the breccia and were deposited under middle-to outer-neritic conditions. The breccia consists of differently coloured layers of shallow-water limestones. Clast size generally decreases upsection to thin layers of predominantly rounded clasts, and these fine-grained rudstones grade into grainstones at the top. In at least one section (EI Caribe) diagenetically altered glass spherules are present in the uppermost layers of the grainstone. These glass spherules are of stratigraphic position and chemical composition similar to black and yellow glass from Beloc, Haiti and Mimbral, Mexico, which some workers have chemically linked to melt glass within the breccia of the Chicxulub cores. We suggest that breccia deposition in Guatemala may have been multi-event, over an extended time period, and related to the collision of the Yucatan and Chortis plates as well as related to a major impact or volcanic event at the end of the Cretaceous.

Key words Guatemala · K/T boundary · Biostratigraphy · Limestone breccias · Chicxulub impact?

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Introduction

The circular subsurface structure at Chicxulub in northern Yucatan is widely thought to represent the crater of the Cretaceous/Tertiary (K/T) boundary bolide impact (Hildebrand et al. 1991, 1994a, 1995; Pope et al. 1991; Sharpton et al. 1992, 1993, 1996; Pilkington and Hildebrand 1994; Schuraytz et al. 1994, 1996; Kring 1995; Buffler et al. 1995; Schultz and D'Hondt 1996). Based on this scenario limestone breccia deposits in southern Mexico (Chiapas), Guatemala, Belize and northeastern Brazil have recently been interpreted as proximal to distal ballistic fallout and megatsunami deposits that were generated by this Yucatan bolide impact (Smit et al. 1994, 1996; Hildebrand et al. 1993, 1994b; Ocampo and Pope 1994; Ocampo et al. 1995, 1996; Montanari et al. 1994; Albertão et al. 1994; Koutsoukos 1995). This interpretation is based on the stratigraphic proximity of the breccias to the K/T boundary, the regional distribution close to the proposed impact location near Chicxulub (Fig. 1), the presence of glass spherules in Haiti and northeastern Mexico with chemical composition similar to melt rock in Chicxulub breccias (Hildebrand et al. 1991; Sharpton et al. 1992, 1996; Schuraytz et al. 1994; Cedillo et al.

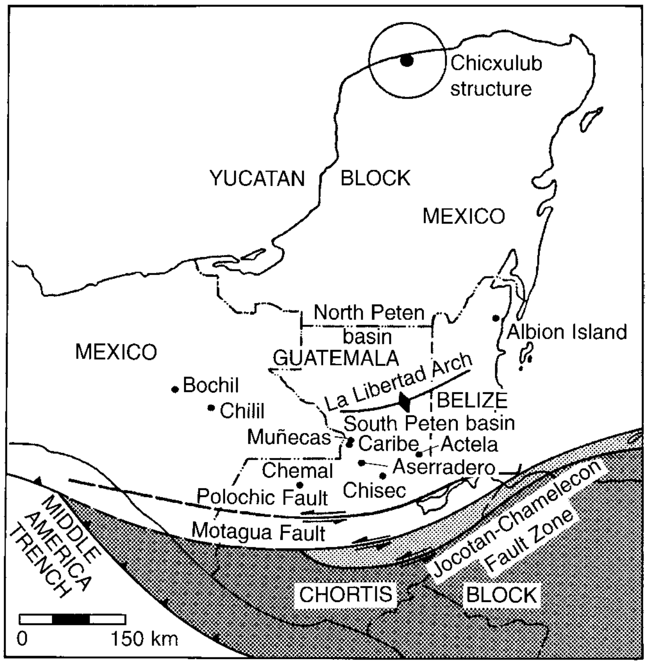


Fig. 1 Geographic and geotectonic location of K/T boundary sections with limestone breccia deposits in Guatemala, Belize and southern Mexico (Chiapas). *Circle* illustrates the position and postulated size of the Chicxulub impact structure

1994; Koeberl 1993; Koeberl et al. 1994; Chaussidon et al. 1996), $^{39}Ar/^{40}Ar$ age of 65 Ma in some glass particles (Sharpton et al. 1992; Swisher et al. 1992), shocked mineral grains (Hildebrand et al. 1991; Sharpton et al. 1992, 1996; Schuraytz et al. 1994) and elevated iridium values in some Chicxulub breccia particles (Sharpton et al. 1992; Schuraytz et al. 1996).

All interpretations on the nature and origin of the breccia deposits in the region depend, however, on the exact stratigraphic position of these sediments, and Meyerhoff et al. (1942), Ward et al. (1995) and Keller and Stinnesbeck (1996) have recently addressed this point. These authors cautioned against declaring Chicxulub as the K/T impact crater based on the timing of the limestone breccia which is only poorly constrained by biostratigraphic data. There is increasing evidence that apparently coeval siliciclastic deposits in northeastern Mexico are long-term deposits. This is indicated by the presence of several discrete horizons of bioturbation within the siliciclastic deposits, discrete layers of normal hemipelagic sedimentation, and mineralogically and sedimentologically discrete horizons correlatable over 300 km (Stinnesbeck et al. 1993; Keller et al. 1994a, 1997; Ekdale and Stinnesbeck, in press; Adatte et al. 1996). Moreover, deposition may have preceded the K/T event by tens of thousands of years as evidenced by a Maastrichtian-age marl layer which overlies the siliciclastic deposits (Lopez-Oliva and Keller 1996). A similar stratigraphic relationship is also indicated for siliciclastic or breccia deposits from Texas to Brazil (Keller and Stinnesbeck 1996).

In order to further examine the age, origin and nature of deposition of the breccias and their relationship to the Chicxulub event, we examined near-K/T breccia deposits in Guatemala. We report here on the stratigraphy, lithology and depositional environment of K/T boundary sections containing breccias at El Caribe, El Aserradero, El Chisec, Actela and Chemal in the South Petén area of Guatemala (Fig. 1). Our investigations shed new light on the depositional nature of these deposits and suggest that at least deposition of the top breccia layers containing spherules was coeval with the spherule events at Haiti and northeastern Mexico.

Regional geology and stratigraphy

The Petén basin is an intra-cratonic basin on the Yucatan block that covers most of central and northern Guatemala and extends northwards and westwards into Mexico and onshore Belize. To the south the Petén basin is bordered by the transcurrent fault systems of Polochic-Motagua and Jocotan-Chamelecon which separate the Yucatan and Chortis blocks and have been active since the late Cretaceous (Fig. 1). The two blocks collided during the late Campanian to Maastrichtian and caused pervasive compressional deformation and burial of the southern Yucatan platform carbonate sequence by up to 2500 m of turbiditic serpentinite-bearing flysch (Rosenfeld 1981; Dengo 1982; Donelly et al. 1990; Pindell and Barrett 1990; Fourcade et al. 1994).

The stratigraphic column of the Petén Sur basin consists of a thick Cretaceous to Tertiary sequence of marine carbonates and clastic rocks, which overlie upper Jurassic continental sediments. The lower to upper Cretaceous (Albian to Turonian) Coban formation consists of limestones, dolomites and evaporites that were deposited in a restricted carbonate environment. Overlying the Coban formation is the Campur formation which consists of rudist-bearing limestones of Coniacian to Campanian age. Locally, the Campur formation may extend into the Maastrichtian. For the type section near the village of Campur and for the Altos Cuchumatanes region of western Guatemala (e.g. Chemal), Michaud et al. (1992) and Fourcade et al. (1994) added an upper member to the Campur formation. This member consists of chert-bearing limestones with globotruncanids of late Campanian age and indicates deeper water and drowning of the platform. Rhythmically bedded pelagic marls, silts and sandstones of the Sepur formation overlie the carbonate sequence of the Coban and Campur formations and indicate a change from a stable platform environment to a mobile orogenic belt environment. The base of the

Sepur formation is time transgressive. At Chemal (Fig. 1) we determined an early late Maastrichtian (*Gansserina gansseri* zone) age; in other localities (Caribe, Aserradero, Chisec, Actela) the lower part of the unit is of early Danian age (*P. eugubina* zone).

Limestone breccias have been reported from different stratigraphic horizons and ages of both the Campur and the Sepur formations as well as between these formations (Vinson 1962; Blount and Moore 1969; Millan 1985; Donelly et al. 1990; Michaud et al. 1992; Fourcade et al. 1994). Recently, Smit et al. (1994), Hildebrand et al. (1993, 1994b) and Pêcheux and Michaud (1997) interpreted one of these breccia layers as the K/T impact breccia, although these authors provide no distinguishing characteristics beyond the stratigraphic proximity to the K/T boundary and geographic proximity to Chicxulub, Yucatan, that would separate this particular breccia unit from those above or below.

Sample collection and analysis

Samples were collected from five K/T transitions spanning from Cretaceous carbonate breccias to Tertiary limestones and marls. Sections were cleaned of weathered surface sediments to expose fresh bedrock. Samples were taken at 2- to 5-cm intervals across the K/T transition and at 20- to 25-cm intervals through several metres of Danian marls above and Cretaceous limestones below the breccia.

For microfacies analysis, thin sections were prepared using standard techniques. Samples for foraminiferal studies were crushed using a mortar and pestle and then soaked overnight in a weak solution of H_2O_2. Strongly indured samples were subsequently cooked with a strong detergent (Miramine) for 24 h. Samples were then washed through a 63-μm screen and dried in an oven for biostratigraphic analysis. Preservation is generally poor in the marly limestone samples of the El Caribe section and the limestone breccia of all sections examined. In contrast, preservation is good to fair in the shales and marls of Chisec, Aserradero, Actela and Chemal sections. Carbonate dissolution was observed at Chisec in some outcrop samples along the river bank and in the siliciclastic sediments at Chemal.

Identification of benthic foraminifera and palaeoecologic interpretations are based on Robinson (1968), Luterbacher (1970, 1984), Cole and Applin (1970), Murray and Wright (1974), Gorsel (1978), Van Morkhoven et al. (1986), Keller (1988b, 1992), Murray (1991) and Bolli et al. (1994). Planktic foraminiferal identifications are based on commonly used taxonomy and illustrations including Keller (1988a, 1993), Keller and Benjamini (1991), MacLeod (1993), Robaszynski et al. (1984) and Keller et al. (1996). Danian planktic foraminifera from the Aserradero section of Guatemala are shown in Figs. 3–5.

Biozonation

Zone P0: K/T boundary clay

The planktic foraminiferal zonation of Keller (1993) was used as shown in Fig. 2 along with other commonly used zonal schemes. The earliest Tertiary Zone P0 marks the boundary clay in complete K/T sequences and spans the interval from the first appearance datums (FAD) of Tertiary species (e.g. *Eoglobigerina fringa*, *E. simplicissima*, *Globoconusa conusa*, *Woodringina hornerstownensis*; Figs. 3 and 4) to the FAD of *Parvularugoglobigerina eugubina* or *P. longiapertura* (Fig. 5). The estimated duration of Zone P0 is 40–50 kyr (see MacLeod and Keller 1991a, b). Calculated sedimentation rates in Zone P0 are always very low (<1 cm/1000 years) and lithology consists of dark brown or black organic-rich clay with very low carbonate content. A maximum thickness of 55 cm for Zone P0 was observed at the El Kef, Tunisia, K/T stratotype section (Smit 1982; Keller 1988; Keller et al. 1996), but generally the Zone P0 boundary clay layer is only a few centimetres thick (e.g. Caravaca and Agost in Spain, Nye Klov and Stevns Klint in Denmark; see Canudo et al. 1991; Schmitz et al. 1992; Keller et al. 1993) and is frequently missing due to a hiatus (e.g. Negev, Mexico and deep sea; see MacLeod and Keller 1991a, b; Keller and Benjamini 1992; MacLeod 1995; Lopez-Oliva and Keller 1996). Zone P0 was not observed in the five sections analysed in Guatemala and may indicate the presence of a hiatus as discussed below.

Zone P1a

Zone P1a marks the interval from the first to the last occurrence of *Parvularugoglobigerina eugubina* or *P. longiapertura* (Figs. 2, 5). This early Danian planktic foraminiferal assemblage consists of approximately 15 small unornamented species with simple morphology (Figs. 3–5). They are generally short ranging and most disappear in Zone P1b–c where new, larger species are abundant. Rocks generally consist of grey shales or marls and calculated sediment-accumulation rates exceed 1.5 cm/1000 years. Zone P1a is estimated to span 180 kyr and, together with Zone P0, spans the interval of chron 29R above the K/T boundary. In four Guatemala sections (El Caribe, El Aserradero, Chemal and Actela), Zone P1a is well represented by 0.8–1.2 m of grey shales and marls which disconformably overlie the carbonate breccia deposits. At El Chisec a truncated Zone P1a is present in the top 5–10 cm of the breccia unit.

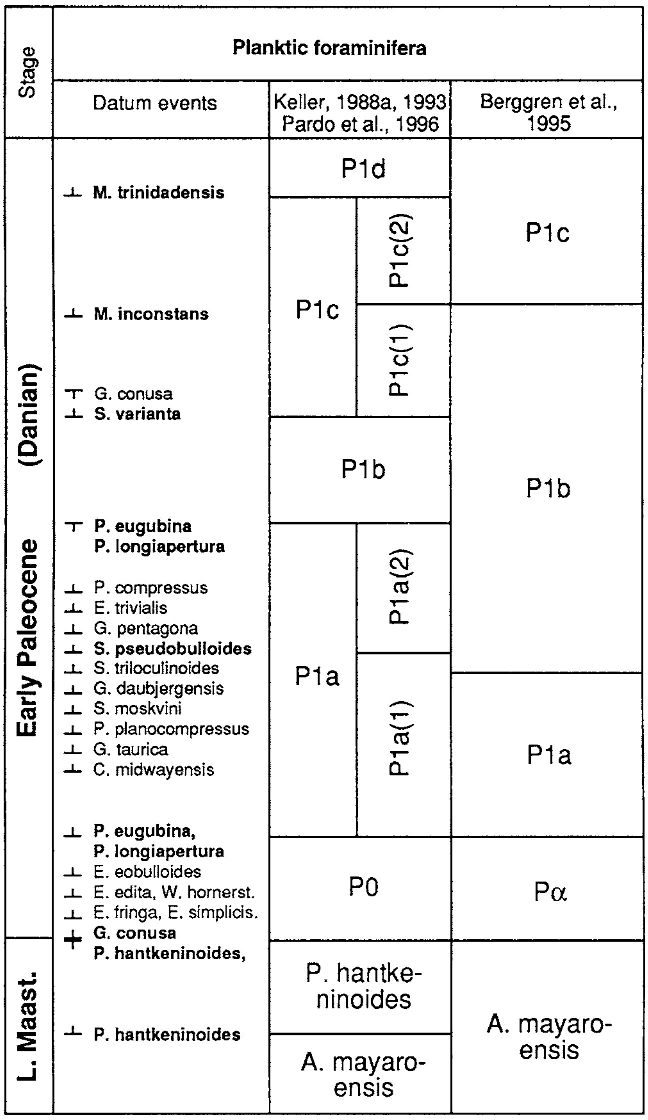


Fig. 2 Correlation of commonly used planktic foraminiferal schemes for the K/T transition. *Plummerita hantkeninoides* Zone spans the last 170–200 kyr of the Maastrichtian. Zones P0 and P1a span the first 50 and 180 kyr of the Paleocene respectively (MacLeod and Keller 1991a, b; Pardo et al. 1996)

Zone P1b

Zone P1b marks the interval from the last occurrence of *P. eugubina* or *P. longiapertura* to the FAD of *Subbotina varianta* (Figs. 4, 5). This zone is relatively thin and represents a transition from the first Tertiary planktic foraminiferal assemblages of Zone P1a to the establishment of a more diverse assemblage in Zone P1c (Fig. 2). Sediments of Zone P1b usually span less than half to Zone P1a thickness. No absolute age determinations have been made for Zone P1b or subsequent zones because of insufficient palaeomagnetic control. In the Guatemalan sections, Zone P1b sediments generally consist of marls with higher carbonate content than in Zone P1a. Zone P1b has been identified at the Aserradero and El Chisec sections, but is only questionably present at El Caribe (*S. varianta* not observed) and Actela (covered interval).

Zone P1c

Zone P1c marks the interval from the FAD of *Subbotina varianta* to the FAD of *Morozovella trinidadensis* (Figs. 2, 4). This interval can be further subdivided into subzones P1c(1) and P1c(2) based on the first appearance of *Morozovella inconstans* (Fig. 3). In the Guatemalan sections, P1c is well represented in the Caribe, Aserradero, Chisec and Actela sections.

Zone P1d

Zone P1d marks the interval from the FAD of *M. trinidadensis* to the FAD of *M. uncinata* (Fig. 2). In Guatemala this interval was sampled at the Actela and El Chisec sections and at Las Muñecas near El Caribe.

Lithostratigraphy, biostratigraphy and depositional environment

Caribe

The El Caribe outcrop is located along the improved road that connects the Rubelsanto oil field with the village of Tierra Blanca, and is approximately 1 km southeast of the village of El Caribe (UTM coordinates: E: 788|750; N: 1|780|500; Fig. 1). The outcrop spans a 20-m high and 30-m wide cliff on a hillside on which a military camp is situated. We examined 52 samples spanning 4.2-m of the upper breccia unit and overlying marly limestone (Fig. 6).

An additional section was measured on a hillside behind the school of Las Muñecas (E: 789|000; N: 1|781|250), located on the unpaved road between Rubelsanto and Tierra Blanca at approximately 250 m from the junction with the road to Yalpemech. This section is only 1 km north of the El Caribe outcrop and also shows limestone breccias underlying marly limestones. Upsection, the marly limestones grade first into pelagic marls and then a rhythmic sequence of siltstones, shales and thin sandstones (Fig. 7).

The oldest sedimentary rocks that crop out at El Caribe are massive dolomitized limestones of the Campur formation with rudists visible on weathered surfaces. We were unable to identify specific rudist genera or other fossil organisms. An erosional disconformity separates these dolomitized limestones from the overlying

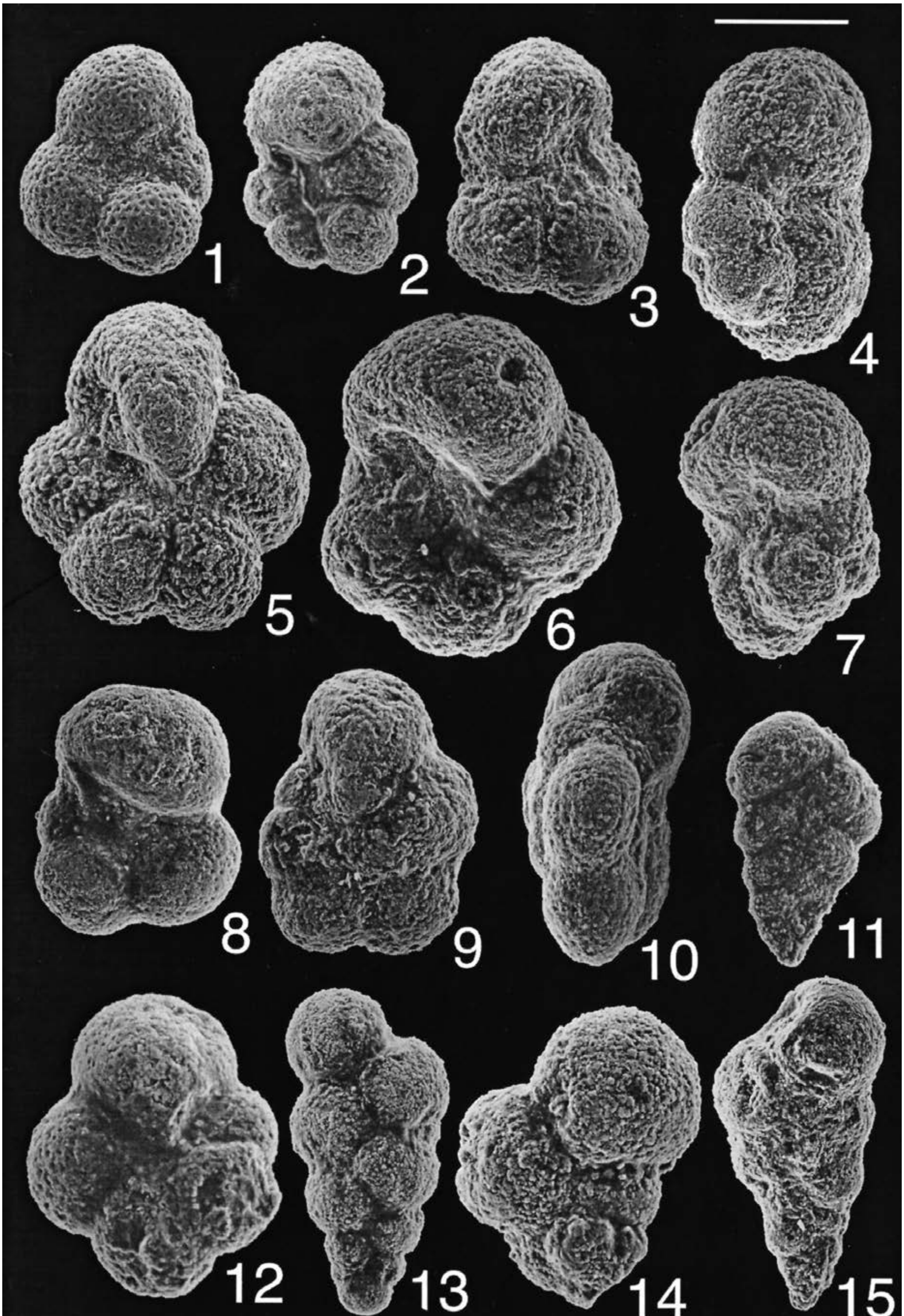


Fig. 3

limestone breccia, and we tentatively mark the boundary between the Campur and Sepur formations at this disconformity. The breccia unit is massive at the base and contains angular to subrounded limestone clasts up to 10 cm in diameter in a cement of sparry calcite. Many of the clasts and matrix contain rudist and inoceramid fragments and indicate their origin from the underlying Campur formation. Breccia clast size decreases upsection over 5 m and grades into tuffaceous microbreccias, followed by detrital limestones of rudite- and finally arenite-sized limestone clasts. These latter fine-grained breccias are poorly cemented and contain bioclastic rudstones and grainstones that are microlayered (e.g. 1–2 cm thick) and mark changes between lighter and darker grey layers (Figs. 6 and 8), that suggest multi-event deposition. The breccia unit is rich in fragmented bivalves (mostly rudists and inoceramids), large benthic foraminifers (e.g. orbitoids, *Chubbina*, praerhapydioninids), a low-diversity assemblage of small shallow marine benthic foraminifera dominated by miliolids (*Quinqueloculina* spp., >60%), *Anomalinoides nobilis* and *Cibicidoides simplex* and rare upper Cretaceous planktic foraminifers (e.g. *Heterohelix globulosa*, *Globigerinelloides aspera*). This assemblage is indicative of a very shallow marine environment at a depth of less than 20 m (Luterbacher 1970; Murray and Wright 1974). The presence of this assemblage suggests either transport from shallow into deeper water, or a rapid sea-level change. The depositional age of the breccia is probably Maastrichtian as suggested by foraminifera (*Anomalinoides nobilis*, *Cibicidoides succedens*, *H. globulosa*, *G. aspera*).

In the basal 5 cm of the marly limestone layer, late-Maastrichtian-age planktic foraminifera (e.g. *Globotruncana aegyptiaca*, *Rosita walfishensis*, *Rugoglobigerina rugosa*, *Globotruncanella petaloidea* and *Globigerinelloides aspera*) are present, mixed with the first Danian species (*Parvularugoglobigerina eugubina*, *Eoglobigerina fringa* and *Globoconusa daubjergensis*; Figs. 8 and 9). This Danian assemblage indicates a Zone P1a age. The absence of Zone P0 and the undulating erosional surface at the top of the breccia suggests a hiatus. Many additional Zone P1a species appear in rapid succession within the first 30 cm above the breccia unit along with isolated reworked Maastrichtian species (Fig. 9). Zone P1a spans the first 120 cm above the breccia. The following 1.3 m above Zone P1a are of Zone P1b–c age. These zones are undifferentiated because the index species (*S. varianta*) was not observed. At Las Muñecas the pelagic marls and shales overlying the early Danian limestones contain P1c through P1d and P2 planktic foraminiferal associations (Fig. 7). Upsection, these marls and shales grade into a turbidite sequence consisting of alternating silts, shales and sandstones, suggesting a flysch environment.

Benthic species show an abrupt faunal change from the miliolid-dominated breccia to an inner to middle-neritic assemblage in the overlying limestones (e.g. *Cibicidoides lobatulus*, *C. newmanae*, *C. simplex*, *Anomalinoides nobilis*, *Pulsisiphonina prima*; Fig. 9). This suggests that the underlying breccia clasts were probably transported from shallower waters and deposited at these depths. Alternatively, it is possible that sea level was shallower (inner neritic) during breccia deposition, but this assumes that deposition occurred over at least 100 000 years for which we see no evidence at this time.

Another benthic assemblage change occurs in Zone P1a at the 10-cm-thick yellow shale layer that overlies the basal 30-cm-thick marly limestone (Fig. 9). At this interval a large number of middle to outer-neritic species appear including gyroidinids, bolivinids, cibicidoids, alabaminids and anomalinids. This assemblage suggests a depositional environment of 150–200 m depth. A return to shallower middle neritic depths is indicated between the upper part of Zone P1a and into P1b–c, where assemblages are dominated by *Cibicidoides newmanae*, *Anomalinoides praeacuta*, *Coryphostoma incrassata gigantea*, *Gaudryina pyramidata* and *Maronella oxycona*. At the nearby Las Muñecas section, many of these species disappear in Zone P1c and P1d indicating a deeping environment. The evidence for deepening in the early Danian Zone P1a followed by temporary shallowing near the P1a/P1b boundary and further deepening recorded in Zones P1c–d may reflect the well-documented global sea-level fluctuations during the Danian (e.g. Peypouquet et al. 1986; Brinkhuis and Zachariasse 1988; Keller 1988, 1989, 1992; Schmitz et al. 1992; Savrda 1993; Keller and Stinnesbeck 1996a, b).

◀

Fig. 3 Early Paleocene planktic foraminifera from the El Aserradero section of Guatemala. Digital images from scanning electron microscope. *1 Eoglobigerina simplicissima*, umbilical view, Zone P1a, scale bar = 85.45 μm; *2 Subbotina pseudobulloides*, umbilical view, Zone P1a, scale bar = 85.45 μm; *3 Eoglobigerina trivialis*, umbilical view, Zone P1a, scale bar = 85.45 μm; *4 Globanomalina pentagona*, apertural view, Zone P1a, scale bar = 85.45 μm; *5 Eoglobigerina simplicissima*, umbilical view, Zone P1a, scale bar = 85.45 μm; *6 Subbotina varianta*, umbilical view, Zone P1c, scale bar = 49.68 μm; *7 Subbotina varianta*, apertural view, Zone P1c, scale bar = 74.52 μm; *8 Subbotina triloculinoides*, umbilical view, Zone P1b, scale bar = 85.45 μm; *9 Morozovella inconstans*, umbilical view, Zone P1c, scale bar = 85.45 μm; *10 Planorotalites compressus*, apertural view, Zone P1a, scale bar = 49.68 μm; *11 Chiloguembelina midwayensis*, plan view, Zone P1c, scale bar = 85.45 μm; *12 Planorotalites compressus*, umbilical view, Zone P1c, scale bar = 56.45 μm; *13 Woodringina hornerstownensis*, plan view, Zone P1a, scale bar = 85.45 μm; *14 Woodringina claytonensis*, plan view, Zone P1a, scale bar = 57.09 μm; *15 Chiloguembelina morsei*, plan view, Zone P1c, scale bar = 85.45 μm

El Aserradero

The El Aserradero section outcrops along the roadside from Raxruja to Yalpemech approximately 20 km from

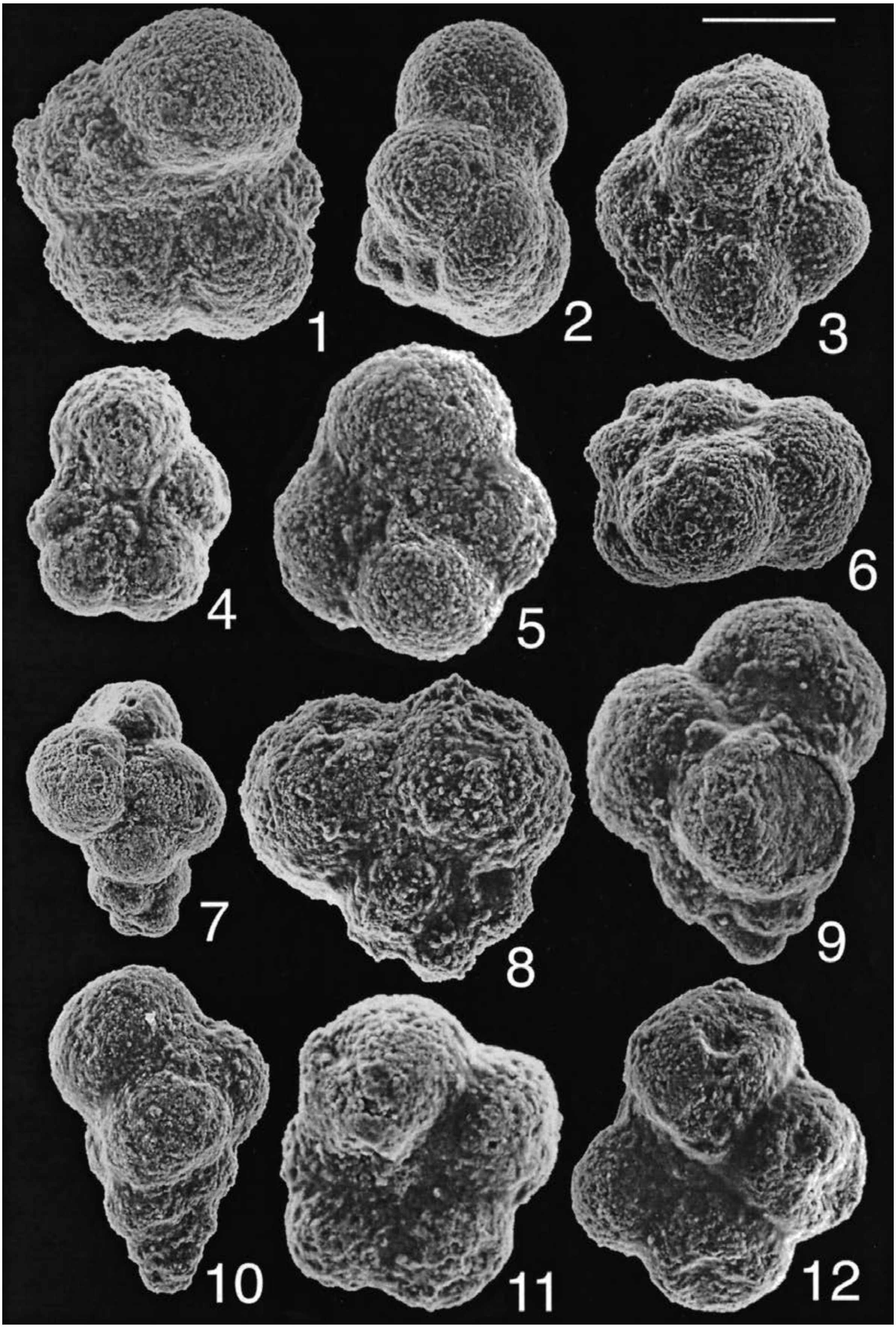


Fig. 4

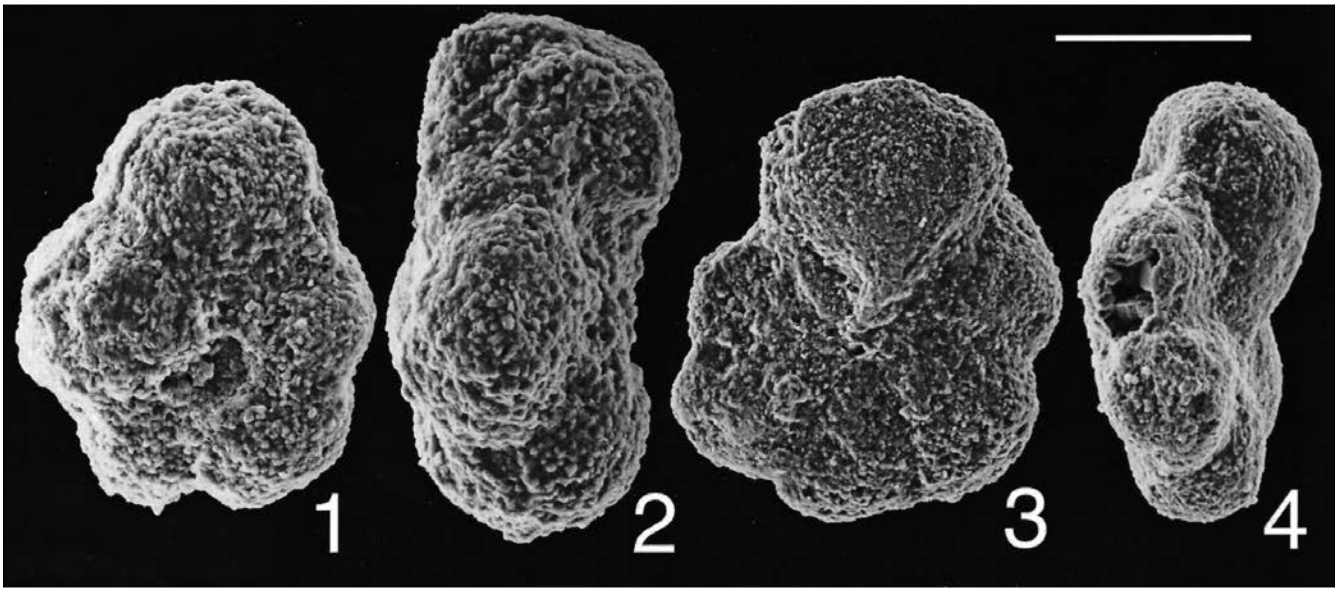


Fig. 5 Early Paleocene planktic foraminifera from the El Aserradero section of Guatemala. Digital images from scanning electron microscope. *1 Parvularugoglobigerina eugubina*, umbilical view, Zone P1a, scale bar = 42.55 µm; *2 Parvularugoglobigerina eugubina*, apertural view, Zone P1a, scale bar = 38.40 µm; *3 Parvularugoglobigerina longiapertura*, umbilical view, Zone P1a, scale bar = 59 µm; *4 Parvularugoglobigerina longiapertura*, apertural view, Zone P1a, scale bar = 59 µm

El Caribe (Fig. 1). This section differs from El Caribe primarily by its predominantly marly lithology, rather than marly limestone, above the breccia unit. Only the top 1 m of the breccia is well exposed, and this is overlain by several metres of marls and shales. Within the breccia, angular to subrounded clasts average 2 cm in diameter and fine upwards in the top 50 cm to less than 0.5 cm in diameter. Bedding and colour changes between individual breccia layers suggest multi-event deposition, similar to El Caribe. The top of the breccia contains horizontal burrows of possible *Planolites* and is marked by an undulose erosional surface and disconformity. No spherules were observed in this breccia unit. No planktic foraminifera were observed in the breccia clasts or in the matrix and no age determination could be made of this breccia unit.

A 1-cm-thick coarse-grained sandy marl overlies the top of the breccia, followed by a 9-cm-thick yellow layer of laminated shale and marl with small concretions at the top. This interval contains a well-preserved typical Zone P1a planktic foraminiferal assemblage

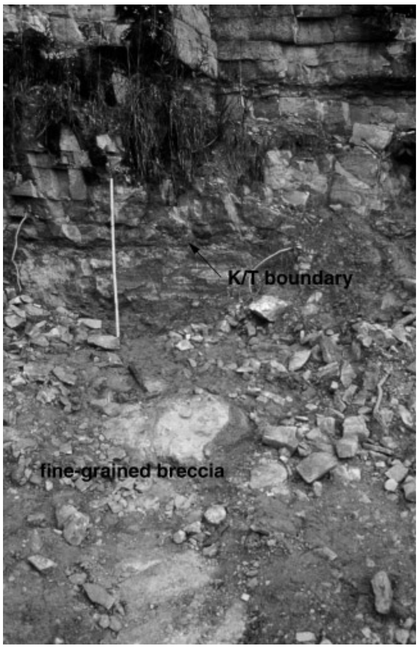


Fig. 6 K/T boundary transect at El Caribe. Upward-fining rudstones and grainstones of the breccia unit underlie marly limestones of the basal Sepur formation

Fig. 4 Early Paleocene planktic foraminifera from the El Aserradero section of Guatemala. Digital images from scanning electron microscope. *1 Globanomalina hemisphaerica*, umbilical view, Zone P1a, scale bar = 59.62 µm; *2 Globanomalina hemisphaerica*, apertural view, Zone P1a, scale bar = 85.45 µm; *3 Globoconusa conusa*, umbilical view, Zone P1a, scale bar = 85.45 µm; *4 Globanomalina taurica*, umbilical view, Zone P1a, scale bar = 64.40 µm; *5 Globoconusa daubjergensis*, umbilical view, Zone P1a, scale bar = 43.04 µm; *6 Globoconusa conusa*, apertural view, Zone P1a, scale bar = 49.68 µm; *7 Guembelitria irregularis*, apertural view, Zone P1c, scale bar = 85.45 µm; *8 Globoconusa daubjergensis*, apertural view, Zone P1a, scale bar = 42.73 µm; *9 Guembelitria cretacea*, oblique view, Zone P1a, scale bar = 47.52 µm; *10 Guembelitria danica*, oblique view, Zone P1c, scale bar = 57.09 µm; *11 Eoglobigerina edita*, umbilical view, Zone P1a, scale bar = 47.52 µm; *12 Eoglobigerina edita*, umbilical view, Zone P1a, scale bar = 47.52 µm

Fig. 7 K/T boundary section at Las Muñecas, 1 km north of El Caribe. Pelagic marls and rhythmically bedded siltstones and shales of the Sepur formation of Paleocene age

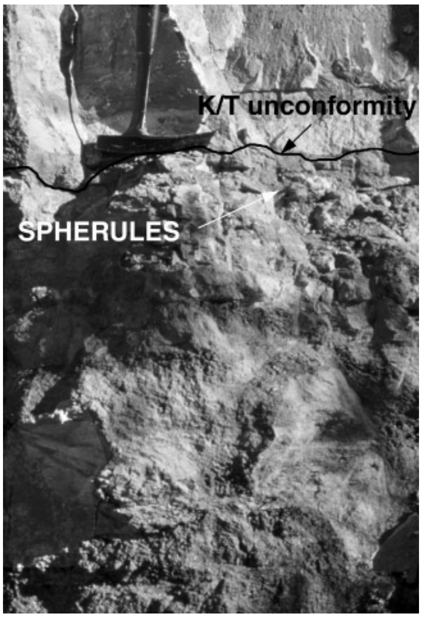


Fig. 8 Closeup of K/T boundary at El Caribe with top of breccia unit and basal marly limestones. Note differently coloured breccia beds composed of coarser and finer-grained clasts suggesting multi-event deposition

(e.g. *P. eugubina*, *P. longiapertura*, *E. fringa*, *E. edita*, *E. simplicissima*, *G. conusa* and *W. hornerstownensis*; Fig. 10) suggesting normal open marine conditions. The Zone P1a assemblage, absence of a K/T boundary clay and Zone P0, and undulating erosional surface at the top of the breccia suggests the presence of a hiatus. In the 65-cm upsection, the predominantly grey marls contain a typical Zone P1a assemblage dominated by *P. eugubina* and the *G. pentagona-hemisphaerica* as well as biserial groups (including *W. hornerstownensis*, *W. claytonensis*, *C. midwayensis* and *C. crinita*) in the upper part. Upsection the fauna is dominated by biserial and triserial taxa (e.g. *G. irregularis*, *G. cretacea*, *W. hornerstownensis*) as well as subbotinids and *Globoconusa daubjergensis*. The first appearance of *Subbotina varianta* which marks the base of Zone P1c occurs within this assemblage along with *Morozovella inconstans* (Fig. 10).

The depositional environment at El Aserradero is similar to the El Caribe section. The breccia contains large rotaliids and abundant miliolids, principally *Quinqueloculina* spp. (>70%) and *Chubbina* spp. This assemblage indicates that original deposition, prior to brecciation and redeposition, occurred in a very shallow marine environment with a water depth of less than 20 m (Robinson 1968; Luterbacher 1970; Murray and Wright 1974). In contrast, miliolids are absent in the marls and shales above the breccia where a deeper water upper-bathyal to outer-neritic (200–300 m) assemblage is present (e.g. *Osangularia cordieriana*, *Nutallides florealis*, *Anomalinoides rubiginosus*, *Cibicidoides hyphalus*; Fig. 10). This abrupt change in fossil assemblages is likely due to transport and redeposition of shallow-water limestones as breccia into deeper waters.

Near the top of Zone P1a and into Zone P1b, benthic foraminifera indicate shallowing to middle/outer-neritic depths similar to El Caribe (Fig. 10). This shallowing is indicated by the temporary disappearance of *O. cordieriana*, *N. florealis* and *C. hyphalus* among others, decreased abundance of *A. rubiginosus* and appearance of middle-shelf taxa, including *Cibicidoides newmanae*, *Coryphostoma midwayensis* and *Praebullimina ovata*). During deposition of Zone P1c sea level rose again as suggested by the appearance of upper-bathyal to outer-neritic species (*N. florealis*, *Gyroidinoides nitidus* and *G. subglobosa*).

El Chisec

The El Chisec section is located northeast of the village of Chisec where it is exposed on the banks and in the river bed of the Rio San Simon. Chisec is approximately 40 km from El Caribe and 60 km from Aserradero (Fig. 1). Approximately 50 m of breccia are exposed along the river (Fig. 11). The absolute thickness is difficult to estimate because a fault runs through the section in the river bed and the sequence is offset and repeated.

The base of the breccia is well exposed and an undulating unconformity marks the contact with the underlying tan-coloured limestone of the Campur formation (Fig. 12). The breccia contains many large rounded clasts (10–20 cm in diameter) at the base (Fig. 12), and clast size decreases upsection. Distinct beds of larger breccia clasts alternate with beds of smaller-sized clasts, and beds of angular to subrounded clasts alternate with beds of rounded clasts which suggests multi-event deposition and transport by water. The upper 10–15 m up to 2 m below the top of the breccia unit consist of

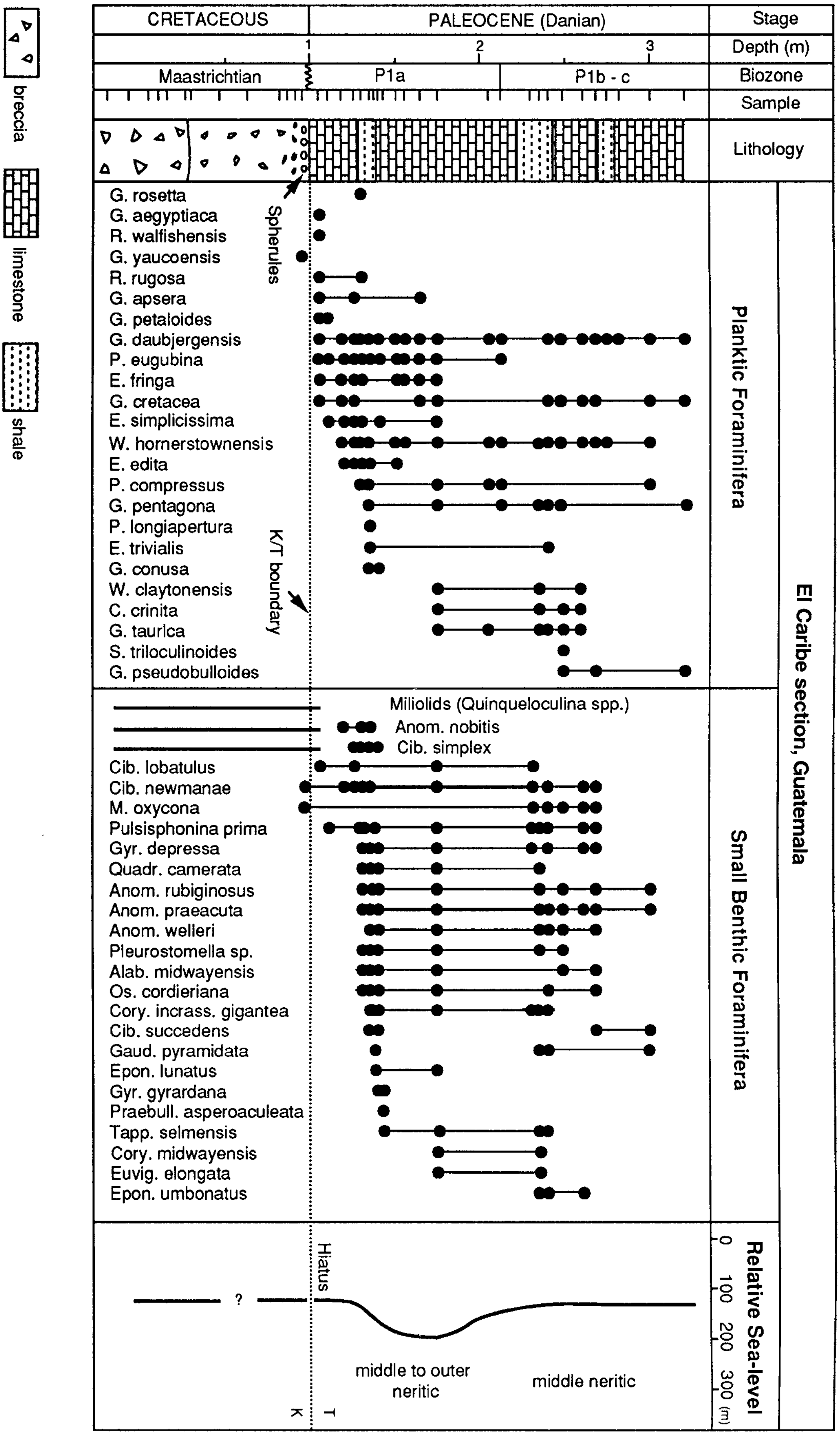


Fig. 9 Stratigraphic ranges of planktic and benthic foraminifera across the K/T boundary at El Caribe and interpretation in terms of relative sea level

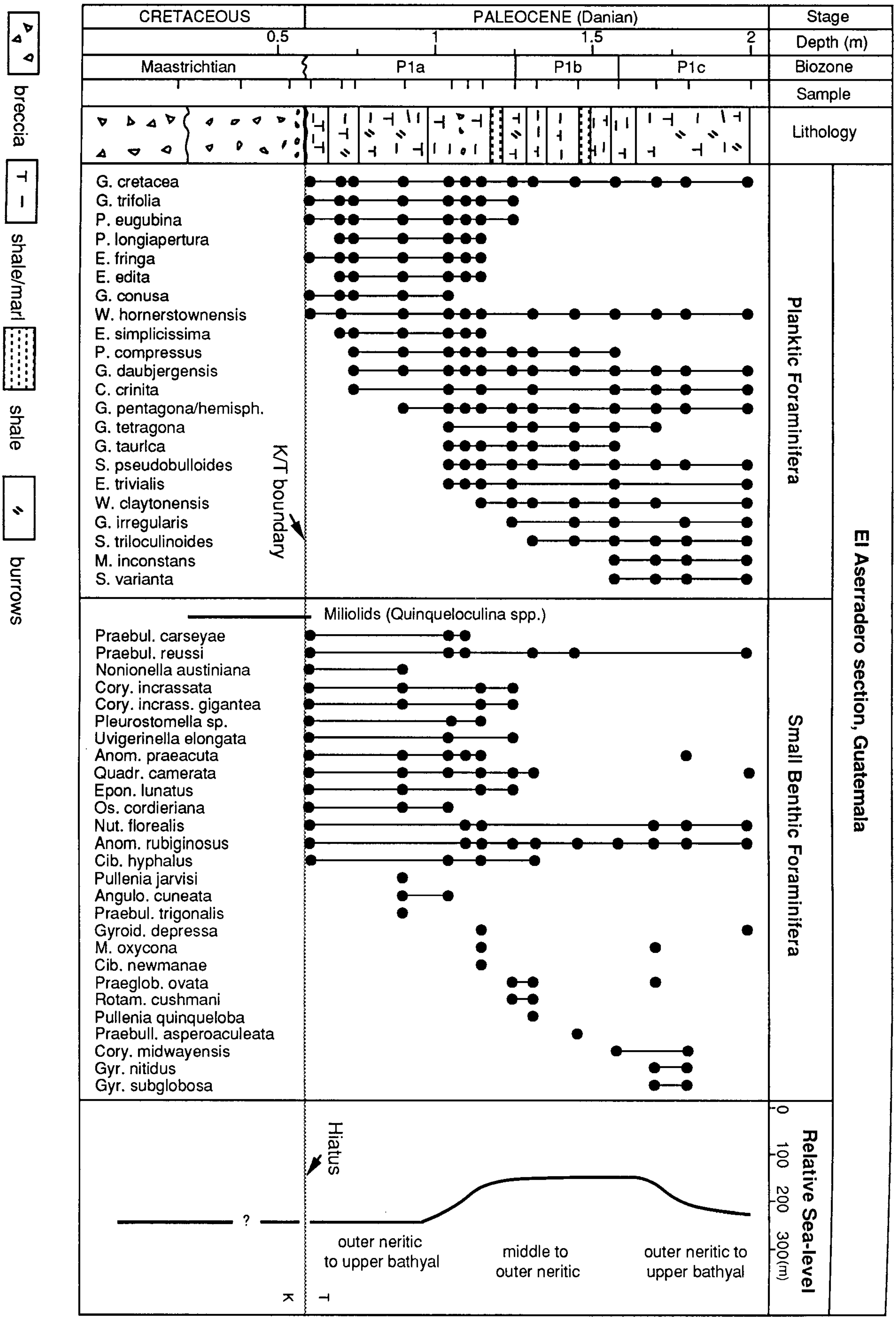

breccia
shale/marl
shale
burrows
CRETACEOUS
PALEOCENE (Danian)
Stage
0.5
1
1.5
2
Depth (m)
Maastrichtian
P1a
P1b
P1c
Biozone
Sample
Lithology
G. cretacea
G. trifolia
P. eugubina
P. longiapertura
E. fringa
E. edita
G. conusa
W. hornerstownensis
E. simplicissima
P. compressus
G. daubjergensis
C. crinita
G. pentagona/hemisph.
G. tetragona
G. taurica
S. pseudobulloides
E. trivialis
W. claytonensis
G. irregularis
S. triloculinoides
M. inconstans
S. varianta
K/T boundary
Planktic Foraminifera
Miliolids (Quinqueloculina spp.)
Praebul. carseyae
Praebul. reussi
Nonionella austiniana
Cory. incrassata
Cory. incrass. gigantea
Pleurostomella sp.
Uvigerinella elongata
Anom. praeacuta
Quadr. camerata
Epon. lunatus
Os. cordieriana
Nut. florealis
Anom. rubiginosus
Cib. hyphalus
Pullenia jarvisi
Angulo. cuneata
Praebul. trigonalis
Gyroid. depressa
M. oxycona
Cib. newmanae
Praeglob. ovata
Rotam. cushmani
Pullenia quinqueloba
Praebull. asperoaculeata
Cory. midwayensis
Gyr. nitidus
Gyr. subglobosa
Small Benthic Foraminifera
El Aserradero section, Guatemala
Hiatus
?
outer neritic to upper bathyal
middle to outer neritic
outer neritic to upper bathyal
K
T
0
100
200
300(m)
Relative Sea-level

Fig. 11 Massive limestone breccia with poor large-scale cross-stratification at El Chisec

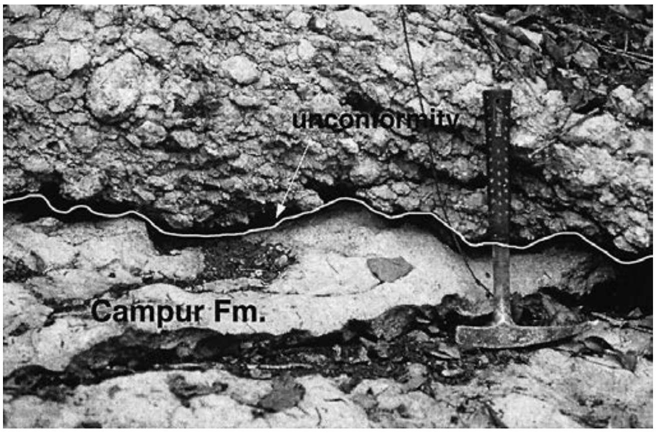


Fig. 12 Undulating unconformity between shallow-water limestones of the Campur formation and base of limestone breccia at El Chisec. Note that clasts float in a fine-grained matrix of lime mud. Clasts are subrounded to well rounded

massive skeletal rudstone (clasts are 0.5–2 cm in diameter) that present poor large-scale cross-stratification (Fig. 11). The top 2 m consist of distinct 5- to 20-cm-thick beds of alternating fine-grained (0.5–2 cm) rudstones and grainstones which also indicate multi-event deposition by water (Fig. 13). An undulating erosional surface marks the top of the breccia, and is overlain by a 10-cm-thick brown clay layer with small breccia pebbles at the base as well as a few larger ones up to 5 cm in diameter.

Similar to El Aserradero and El Caribe, the breccia is dominated by miliolids (*Quinqueloculina* spp., *Chubbina* aff. *jamaicaensis*) and indicates original deposition in a shallow shelf or lagoonal marine environment (Murray 1991), prior to brecciation and redeposition. According to Cole and Applin (1970, p. 46), *Chubbina* is of late Campanian to Maastrichtian age. The presence of rare planktic foraminifers including *Pseudoguembelina*

Fig. 10 Stratigraphic ranges of planktic and benthic foraminifera across the K/T boundary at El Aserradero and interpretation in terms of relative sea level

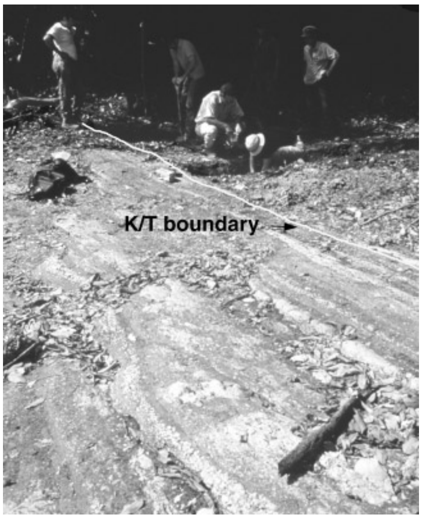
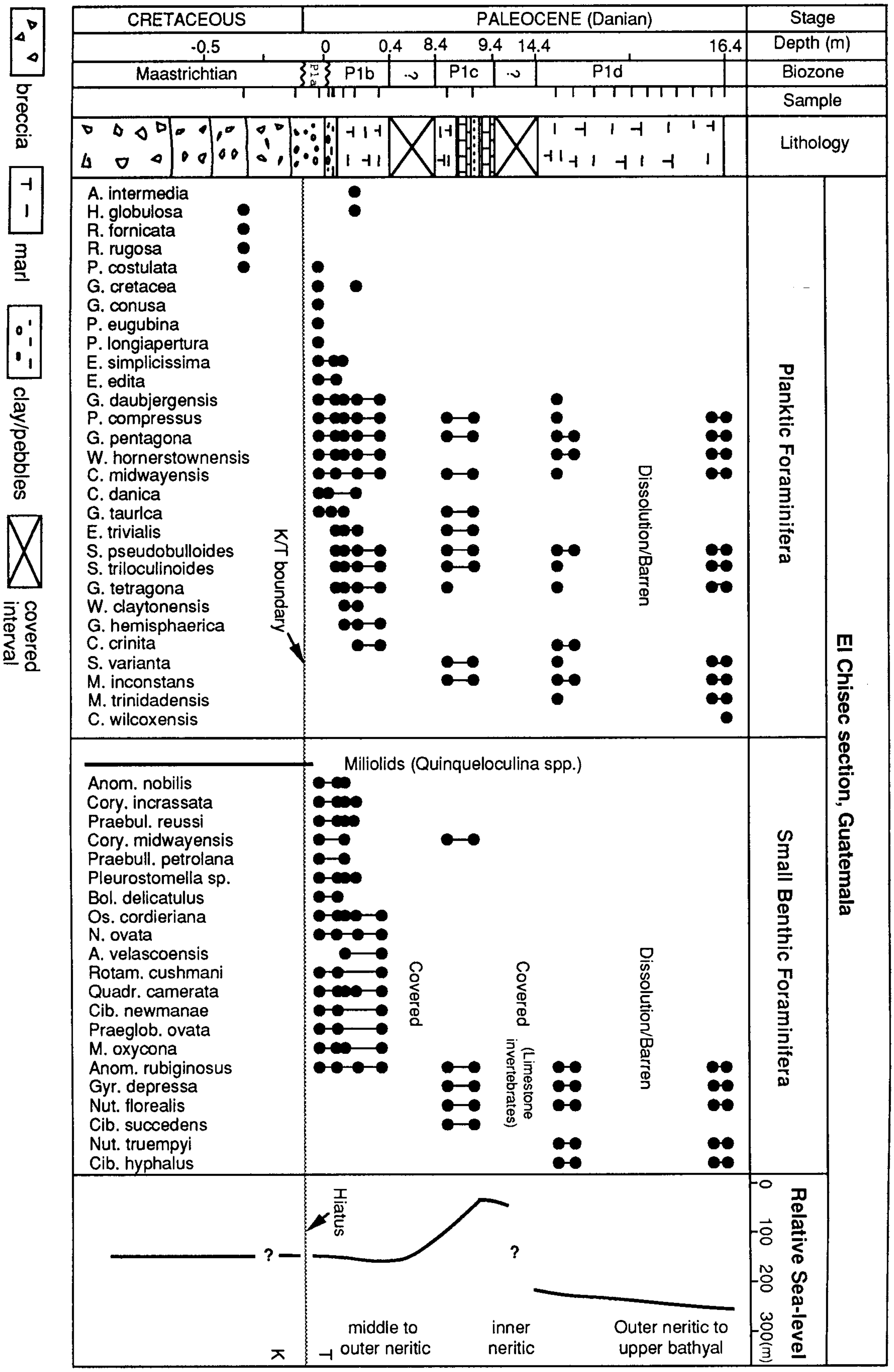


Fig. 13 K/T boundary transect at El Chisec. To the left top of limestone breccia unit consisting of distinct beds of alternating larger and smaller pebbles suggesting multi-event deposition and transport by water. Note that top 10 cm of breccia contain early Danian Zone P1a (*P. eugubina*) planktic foraminiferal assemblages (Fig. 14). The top of the breccia is marked by an undulating erosional surface. Poorly exposed gray marls of Zone P1b age overlie the breccia (in trench to the right)

costulata, *Heterohelix globulosa*, *Rosita fornicata* and *Rugoglobigerina rugosa* (Fig. 14) suggests a Maastrichtian age up to 10 cm below the top of the breccia. Within the top 10 cm of the breccia a well-preserved and diverse (12 species) Zone P1a planktic foraminiferal assemblage is present. This suggests that the top of the breccia unit is reworked into lower Danian sediments at the disconformity between the breccia and Danian marls. The Zone P1a assemblage terminates at the top of the breccia and is therefore much reduced by erosion. Two interpretations are possible: (a) breccia deposition continued well into the early Danian and (b) the breccia is reworked and redeposited into Zone P1a sedimentation with a subsequent hiatus removing most of Zone P1a. We suggest that the latter interpretation is more likely since breccia deposition has not yet been observed to range into the Danian, although this remains a possibility. Outcrop contamination is not a likely possibility because Zone P1a index taxa, *P. eugubina* and *P. longiapertura*, as well as several other P1a species, are absent in the overlying sediments.

A 10-cm-thick brown clay layer with breccia pebbles at its base overlies the erosional surface at the top of the breccia. This clay layer and the following 30 cm of grey marls contain an abundant and well-preserved planktic foraminiferal assemblage of Zone P1b (Fig. 14). A covered interval spans the next 8 m and is followed by marls of Zone P1c age, interlayered with several limestone beds rich in oysters, gastropods, worm tubes and other invertebrates. Above the limestone beds,



breccia
marl
clay/pebbles
covered interval
CRETACEOUS
PALEOCENE (Danian)
Stage
-0.5
0
0.4
8.4
9.4
14.4
16.4
Depth (m)
Maastrichtian
P1a
P1b
P1c
P1d
Biozone
Sample
Lithology
A. intermedia
H. globulosa
R. fornicata
R. rugosa
P. costulata
G. cretacea
G. conusa
P. eugubina
P. longiapertura
E. simplicissima
E. edita
G. daubjergensis
P. compressus
G. pentagona
W. hornerstownensis
C. midwayensis
C. danica
G. taurlca
E. trivialis
S. pseudobulloides
S. triloculinoides
G. tetragona
W. claytonensis
G. hemisphaerica
C. crinita
S. varianta
M. inconstans
M. trinidadensis
C. wilcoxensis
K/T boundary
Dissolution/Barren
Planktic Foraminifera
Miliolids (Quinqueloculina spp.)
Anom. nobilis
Cory. incrassata
Praebul. reussi
Cory. midwayensis
Praebull. petrolana
Pleurostomella sp.
Bol. delicatulus
Os. cordieriana
N. ovata
A. velascoensis
Rotam. cushmani
Quadr. camerata
Cib. newmanae
Praeglob. ovata
M. oxycona
Anom. rubiginosus
Gyr. depressa
Nut. florealis
Cib. succedens
Nut. truempyi
Cib. hyphalus
Covered
Covered
(Limestone invertebrates)
Dissolution/Barren
Small Benthic Foraminifera
El Chisec section, Guatemala
Hiatus
?
?
K
T
middle to outer neritic
inner neritic
Outer neritic to upper bathyal
0
100
200
300(m)
Relative Sea-level

approximately 5 m of the outcrop is covered in the riverbed followed by a 2-m-thick marl of Zone P1d age (FAD *M. trinidadensis*) with many samples barren of foraminifera due to dissolution.

Discontinuous outcrops and intermittent carbonate dissolution permits only tentative environmental interpretations at El Chisec. In Zones P1a to P1b the presence of a benthic foraminiferal assemblage dominated by bolivinids, praebuliminidis, and *A. rubiginosus* and *C. newmanae* suggests a middle- to outer-neritic environment between 100 and 200 m depth (Fig. 14). Above the covered interval in Zone P1c and in the marl interlayers of the limestone beds the presence of *Cibicidoides succedens*, *Coryphostoma midwayensis* and *Nuttallides florealis* suggests a middle- to outer-neritic environment. The limestone layers with their abundant shallow-water invertebrates and low-diversity benthic foraminifers, probably *Quasiborelis*, suggest a water depth of less than 50 m. This indicates shallowing to inner neritic depths during the time of limestone deposition in Zone P1c and may correlate with the shallowing observed at El Caribe. Upsection, in Zone P1d, the presence of *Nuttallides truempyi* and *Cibicidoides hyphalus* suggests deepening to outer-neritic or upper-bathyal depths (Fig. 14).

Actela

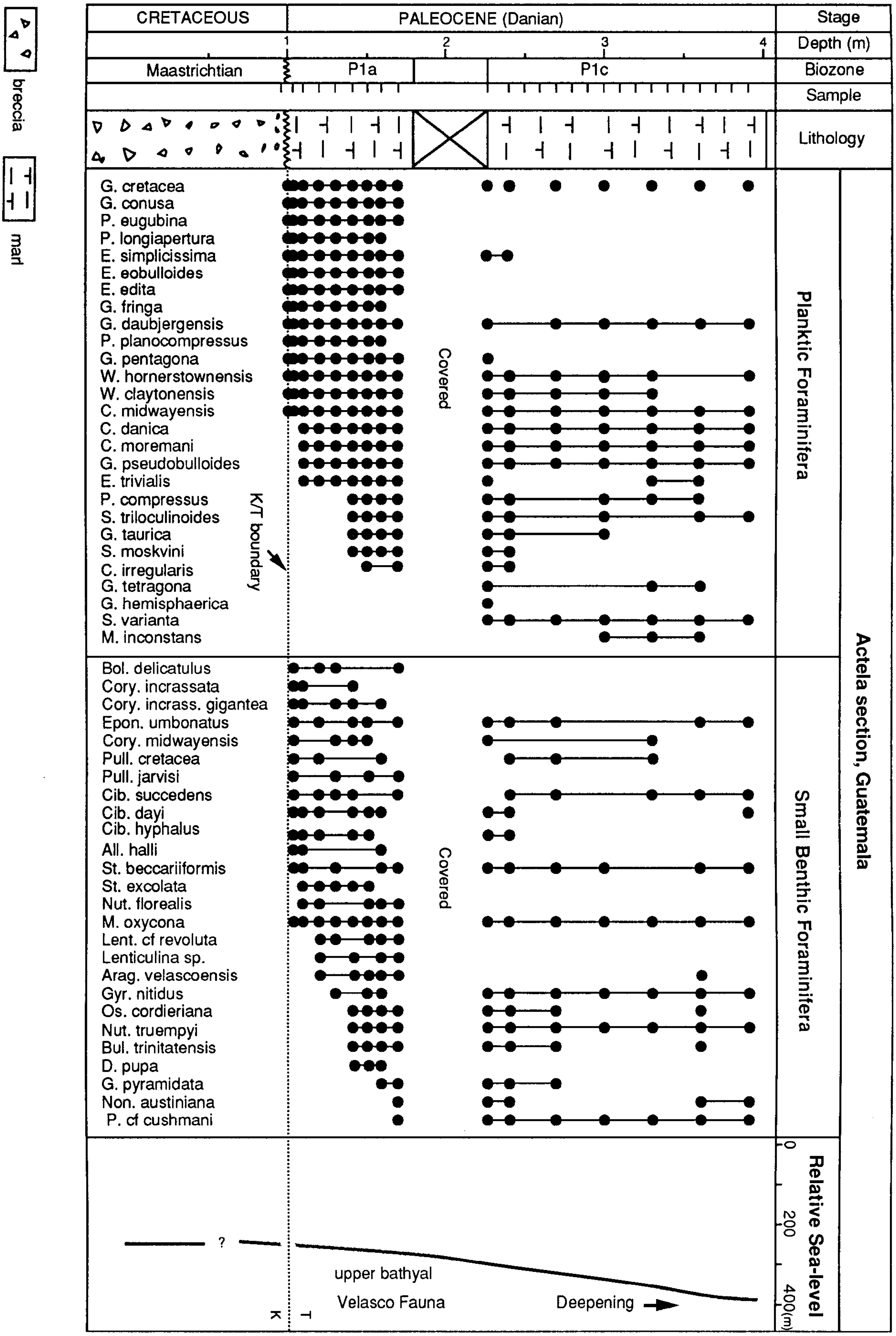
The Actela section is located 30 km southeast of San Luis, El Petén, and 30 km west of the Guatemala/Belize border. At least 15 m of massive limestone breccia are present in this outcrop, but only the top 2 m are well exposed. Near the base, clasts reach as much as 70 cm in diameter and are thus much larger than in other outcrops. Clasts are subangular to subrounded and densely packed with little sediment matrix, probably due to stylolithic pressure solution. Many clasts contain rudist fragments. Clast size decreases upsection and the sediment grades into less consolidated tuffaceous microbreccias and into bioclastic rudstones near the top of the unit (Fig. 15). The uppermost layer of the breccia appears to have been deposited by a different event. This layer is well cemented, poorly cross-stratified and contains bigger clasts of up to 2–3 cm diameter (Fig. 15). The thickness of this bed varies from 30 cm to more than 100 cm over a distance of 20 m. The top of the breccia is marked by an undulose erosional surface followed by 20 cm of yellow-brown marls with isolated limeclasts.

The age of the breccia deposit at Actela is uncertain. The breccia contains abundant fragments of invertebrates (rudists, inoceramids, echinoids) and benthic foraminifera (miliolids, orbitoids, *Sulcoperculina*), suggesting a Maastrichtian age (Fig. 16). Planktic foraminifera are absent. The first 80 cm of yellow-brown marls above the breccia contain a well-preserved Zone P1a planktic foraminiferal assemblage including *G. conusa*, *P. eugubina*, *P. longiapertura*, *E. fringa* and *G. daubjergensis* (Figs. 3–5). The next 30-cm interval is covered and above it Zone P1c index taxa *Subbotina varianta* and *Morozovella inconstans* are present within an assemblage dominated by biserial and triserial taxa. Upsection, the outcrop is exposed in the nearby river bed where Zone P1c spans over 12 m up to limestone layers rich in shallow-water gastropods and bivalves, similar to the Zone P1c limestone layers at El Chisec.

The depositional environment at Actela appears to have been similar, though significantly deeper, than in the other sections. Limestone breccia clasts contain abundant rudists, inoceramids, echinoids, and benthic foraminifera (e.g. *Quinqueloculina* and other miliolids) which indicate original deposition in shallow marine environments with water depths of less than 20 m, and subsequent brecciation, transport and redeposition. Above the breccia, marls and shales of zones P1a to P1c indicate a deeper water environment as suggested by the abundance of planktic foraminifera and a Velasco type benthic foraminiferal assemblage dominated by *Cibicidoides dayi*, *C. hyphalus*, *Stensioina beccariiformis*, *S. excolata*, *Coryphostoma midwayensis*, *C. incrassata*, *C. incrassata gigantea*, *Nuttallides florealis* and *Maronella oxycona* (Fig. 16). This assemblage suggests deposition in an upper-bathyal environment during deposition of Zone P1a. The presence of a limestone layer rich in gastropods, bivalves and miliolid foraminifers, principally *Quasiborelis*, upsection in Zone P1c suggests a short-term shallowing to water depths of less

Fig. 15 Closeup of limestone breccia deposit at Actela. Poorly cemented fine-grained rudstones and grainstones underlie a well-cemented limeclast breccia with clast size up to 3 cm suggesting deposition in different events

Fig. 14 Stratigraphic ranges of planktic and benthic foraminifera across the K/T boundary at El Chisec and interpretation in terms of relative sea level



breccia
marl
CRETACEOUS
PALEOCENE (Danian)
Stage
Depth (m)
1
2
3
4
Maastrichtian
P1a
P1c
Biozone
Sample
Lithology
Covered
K/T boundary
G. cretacea
G. conusa
P. eugubina
P. longiapertura
E. simplicissima
E. eobulloides
E. edita
G. fringa
G. daubjergensis
P. planocompressus
G. pentagona
W. hornerstownensis
W. claytonensis
C. midwayensis
C. danica
C. moremani
G. pseudobulloides
E. trivialis
P. compressus
S. triloculinoides
G. taurica
S. moskvini
C. irregularis
G. tetragona
G. hemisphaerica
S. varianta
M. inconstans
Planktic Foraminifera
Bol. delicatulus
Cory. incrassata
Cory. incrass. gigantea
Epon. umbonatus
Cory. midwayensis
Pull. cretacea
Pull. jarvisi
Cib. succedens
Cib. dayi
Cib. hyphalus
All. halli
St. beccariiformis
St. excolata
Nut. florealis
M. oxycona
Lent. cf revoluta
Lenticulina sp.
Arag. velascoensis
Gyr. nitidus
Os. cordieriana
Nut. truempyi
Bul. trinitatensis
D. pupa
G. pyramidata
Non. austiniana
P. cf cushmani
Small Benthic Foraminifera
Actela section, Guatemala
?
upper bathyal
Velasco Fauna
Deepening
K
T
Relative Sea-level
0
200
400(m)

than 50 m. This limestone layer is separated from the interval shown in Fig. 16 by a covered interval of approximately 10 m. At Chisec a similar coeval shallow-water invertebrate-rich limestone layer is present in a river bed, also separated from the interval shown in Fig. 14 by a 10- to 15-m covered interval.

Chemal

The Chemal section is located in western Guatemala, approximately 30 km north of Huehuetenango in the Sierra Los Cuchumatanes, on an unpaved road that connects Huehuetenango with Soloma 2 km south of a location known of as Chemal (Fig. 1). This section differs from the others in that the breccia is only 1 m thick and occurs within a turbiditic sequence of alternating sand and siltstones. A similar section in the area of Chemal was described by Michaud et al. (1992) and Fourcade et al. (1994b).

At Chemal thick-bedded platform limestones of probable Campanian age and consisting of poorly stratified peloidal packstones and bioclastic grainstones with rudists, oysters, echinoids and abundant benthic foraminifers (e.g. orbitoids, *Chubbina*, *Sulcoperculina*, miliolids) are overlain by 20 m of relatively thin-bedded pelagic limestones with chert nodules and lenses. The latter unit is characterized by calcisphere (*Pithonella*) packstones and contains planktic foraminifers of the late Campanian *G. calcarata* Zone (e.g. *G. calcarata*, *G. linneiana*, *G. arca*, *G. stuartiformis*, *G. bulloides*). Above this limestone, the basal Sepur formation consists of 17 m of rhythmically bedded brown shales, silts and sandstones (Fig. 17) containing a late Maastrichtian planktic foraminiferal assemblage (e.g. *Racemiguembelina intermedia*, *P. costulata*, *P. punctulata*, *H. pulchra*, *H. globulosa*, *H. dentata*, *R. rugosa*, *R. macrocephala*, *Globotruncana arca*, *G. bulloides*). A hiatus separates the late Maastrichtian from the late Campanian limestones. The flysch-like character of these late Maastrichtian sediments is strengthened by the presence of small olistolithic limestone blocks and a 1-m-thick sandstone turbidite. A limeclast breccia, more than 1 m thick, is also present in this flysch sequence and contains small (0.5–0.2 cm in diameter) subangular to subrounded limestone clasts with rudists, echinoids and benthic foraminifers (e.g. miliolids, *Chubbina*, *Sulcoperculina*, orbitoids) and clasts of pelagic wackestones with rare planktonic foraminifers (primarily *H. globulosa*). Above the breccia layer, rare Maastrichtian species are present (e.g. *Guembelitria cretacea*, *Globigerinelloides aspera*, *Heterohelix globulosa*, *Rugoglobigerina rugosa*, *Pseudoguembelitria costulata*) followed by an early Danian assemblage dominated by biserial and triserial taxa (e.g. *G. cretacea*, *G. trifolia*, *G. irregularis*, *Woodringina hornerstownensis*, *W. claytonensis*, *C. moremani*, *C. midwayensis* and *Globoconusa daubjergensis*) and rare *P. eugubina*. The presence of *P. eugubina* suggests a Zone P1a assemblage, followed by Zones P1b-c which do not contain *P. eugubina*. Benthic foraminifera are rare and suggest deposition in an outer-neritic to upper-bathyal environment (e.g. gyroidinids, cibicidoids, praebuliminids).

Fig. 16 Stratigraphic ranges of planktic and benthic foraminifera across the K/T boundary at Actela and interpretation in terms of relative sea level

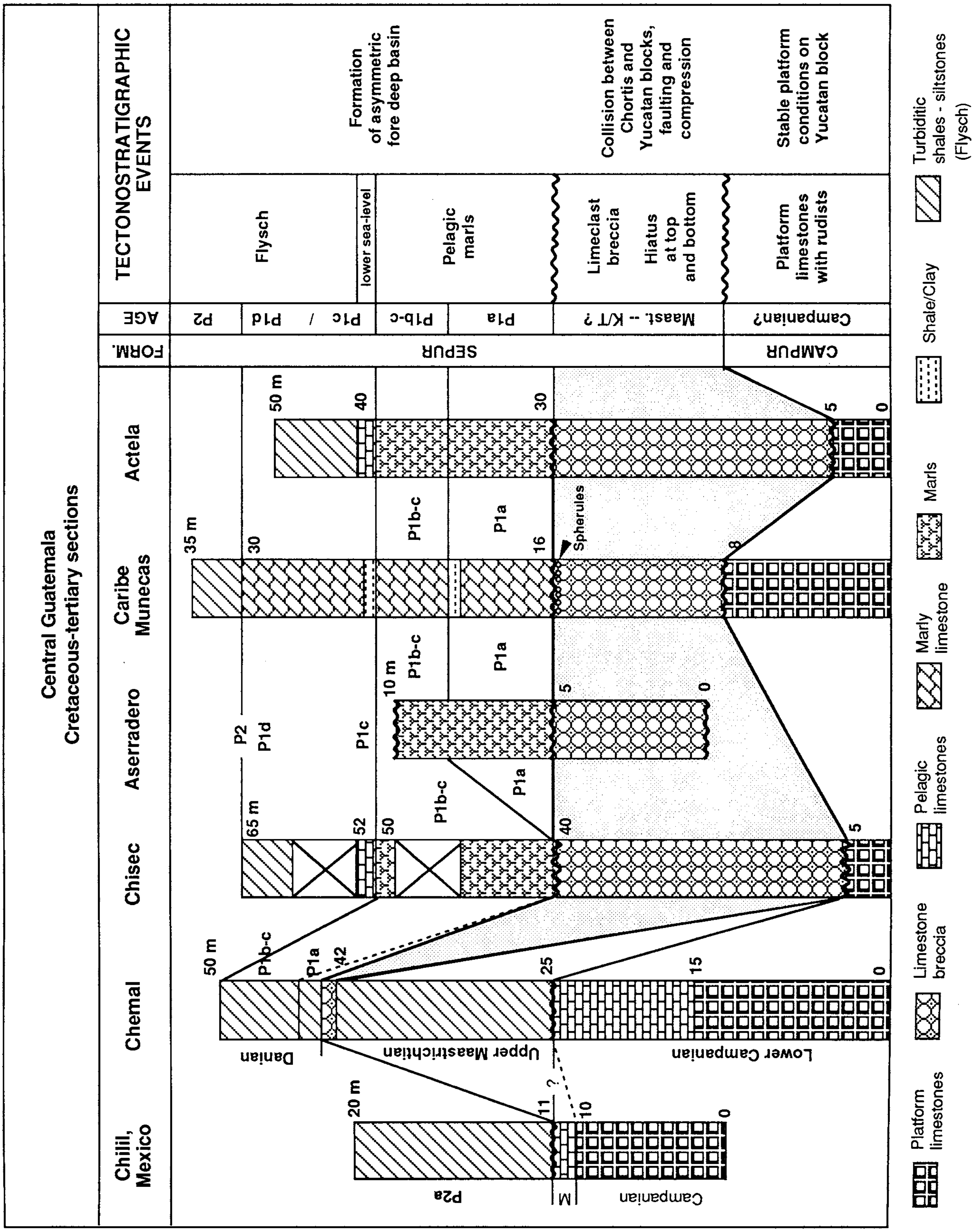
Fig. 17 Chemal. Rhythmically bedded shales, siltstones and thin size-graded sandstone layers of the basal Sepur formation. Scale is 50 cm

Michaud et al. (1992) and Fourcade et al. (1994b) recognized several limestone breccia layers within the flysch unit in the Chemal area. Based on the fauna in these limestone breccia clasts, they attributed a Maastrichtian age to the Sepur formation. Our investigation confirms their observations.

Discussion

Age and depositional environment

The K/T boundary sections of Caribe, Aserradero, Chisec and Actela are very similar in lithology, biostratigraphy and depositional sequence, though their palaeodepths vary (Fig. 18). The Chemal section differs in that only a very small breccia unit is present and that no major unconformity marks the contact with the underlying strata. In each of the five sections examined, the breccia unit is of Maastrichtian to K/T boundary age, though a more specific age resolution was not possible. However, in each section early Danian



Central Guatemala
Cretaceous-tertiary sections
Chilil, Mexico
Chemal
Chisec
Aserradero
Caribe Munecas
Actela
FORM.
AGE
TECTONOSTRATIGRAPHIC EVENTS
SEPUR
CAMPUR
P2
P1c / P1d
P1b-c
P1a
Maast. -- K/T ?
Campanian?
Flysch
lower sea-level
Pelagic marls
Limeclast breccia
Hiatus at top and bottom
Platform limestones with rudists
Formation of asymmetric fore deep basin
Collision between Chortis and Yucatan blocks, faulting and compression
Stable platform conditions on Yucatan block
P2a
M
Campanian
Danian
Upper Maastrichtian
Lower Campanian
Spherules
20 m
11
10
0
50 m
P1b-c
P1a
42
25
15
65 m
52
50
40
5
P2
P1d
P1c
P1b-c
P1a
10 m
35 m
30
16
8
Platform limestones
Limestone breccia
Pelagic limestones
Marly limestone
Marls
Shale/Clay
Turbiditic shales - siltstones (Flysch)

sediments overlie the breccia which suggests that its deposition may have occurred, or at least ended, at or near the K/T boundary. Breccias in all sections are similar in that they contain very shallow-water limestone clasts dominated by miliolids which indicate that original deposition occurred in an inner-neritic environment under normal-marine salinities and at depths of less than 20 m and possibly as shallow as 5–10 m (Luterbacher 1970; Murray and Wright 1974). Larger miliolacean foraminifers (*Chubbina*) and distinctive rotaliids (referred to *Smouthina* or *Kathina*) are also frequent in these limestone clasts and indicate depth ranges of 5–65 m (Murray 1991). Original deposition in a shallow-water, external carbonate-platform environment is also confirmed by the presence of abundant rudists, other bivalves and echinoids. However, deposition of the breccia is not likely to have occurred in these shallow waters, but via transport as debris flows into deeper-middle to outer-neritic or upper-bathyal depths (ca. 100–400 m). This is suggested by the presence of deeper-water benthic foraminifera above and below (at Chemal) the breccia unit, as well as by rare Maastrichtian planktic foraminifera within the breccia. In all sections the top of the breccia is marked by a disconformity characterized by an undulating erosional surface and often breccia clasts at the base of the overlying shale or marl. Although we were unable to estimate the amount of erosion or time missing at this unconformity, the presence of a Zone P1a assemblage directly above the breccia at Caribe, Aserradero and Actela indicates that at least Zone P0 and the lower part of Zone P1a is missing, as well as probably part of the uppermost Maastrichtian in most sections (Fig. 18).

The Danian depositional environment in the four sections were very similar, though palaeodepths varied (Figs. 9, 10, 14 and 16). During Zone P1a deposition occurred in a middle- to outer-neritic (100–200 m) environment at El Caribe and El Chisec and a deeper outer-neritic or upper-bathyal (>200 m) environment at El Aserradero, Chemal and Actela. Water depth decreased during deposition of the upper part of Zone P1a and P1b to middle-neritic depth at El Caribe and middle- to outer-neritic depths at El Chisec and El Aserradero. Thereafter, water depth generally increased into zones P1c and P1d, though this trend is interrupted in Zone P1c by a shallow-water limestone at Chisec and Actela which indicates a sea-level drop or regional tectonic uplift at this time. In general, however, a trend towards deeper (upper slope to bathyal) flysch environments is indicated upsection. Flysch deposition started during deposition of Zone P2 at Caribe/Muñecas, during deposition of Zone P1c to P1d at Actela and much earlier during the Maastrichtian at Chemal (Fig. 18).

Fig. 18 Lithostratigraphic correlation of five K/T boundary sections in Guatemala and the Chilil section from Chiapas (southern Mexico), all showing the transition from shallow water platform limestones (the Campur formation in Guatemala and Angostura formation in Chiapas) towards pelagic marl and siliciclastic flysch deposition of the Sepur formation (in Guatemala) and Soyatal formation (in Chiapas). Note that four of the five sections in Guatemala (all except Chemal) are characterized by thick limestone breccia deposits disconformably overlying the Campur and underlying the Sepur formation. At Chemal a breccia unit of late Maastrichtian to K/T boundary age is present within the Sepur formation. At Chemal and Chilil, a unit of pelagic limestones of late Campanian *calcarata* Zone (at Chemal) and early late Maastrichtian *gansseri* zone age (at Chilil) conformably overlies the shallow-water limestones. This indicates that the onset of pelagic sedimentation is at different geological times and unrelated to the events at the K/T boundary. Thickness of lithological units is relative and not to scale

Multi-event nature and origin of the breccia

Was breccia deposition multi-event and over an extended time period during the Campanian–Maastrichtian, or was it single event, short term and restricted to the K/T boundary? The recent interpretation that the subsurface circular gravity anomaly structure near Chicxulub, Yucatan, represents the K/T boundary bolide impact has led many workers to reinterpret near K/T boundary breccia and siliciclastic deposits in the Caribbean and Central America as impact-generated ballistic fallout and tsunami megawave deposits. This also has been suggested for breccia deposits of Guatemala and Belize (Fig. 1) by several workers (Ocampo and Pope 1994; Ocampo et al. 1995, 1996; Hildebrand et al. 1993, 1994b; Smit et al. 1994; Pêcheux and Michaud 1997). However, among these, only Ocampo et al. (1995, 1996) have supported their interpretation with any physical evidence. These authors observed dolomite spherules and striated clasts which they found in the Belize sections. They concluded that based on mineralogical analyses of the dolomite spherules and silt matrix, these spherules precipitated at high temperatures, likely by condensation from vapour after the impact. In contrast, Hildebrand et al. (1993, 1994b), Smit et al. (1994) and Pêcheux and Michaud (1997) based their impact interpretation solely upon the assumed age proximity of the breccia in Guatemala to the K/T boundary.

Impact or volcanic origin

Our analysis of the Guatemalan sections provides evidence for both long-term and multi-event deposition as well as a regional short-term event near the top of the breccia unit. Evidence for a short-term event is present in abundant altered glass spherules in some microbreccia layers near the top of the breccia unit at El Caribe (Fig. 19). Some breccia layers contain up to approximately 10–15% spherules but no anomalous iridium concentrations were detected (R. Rocchia, pers. commun.). The spherules are generally rounded with some

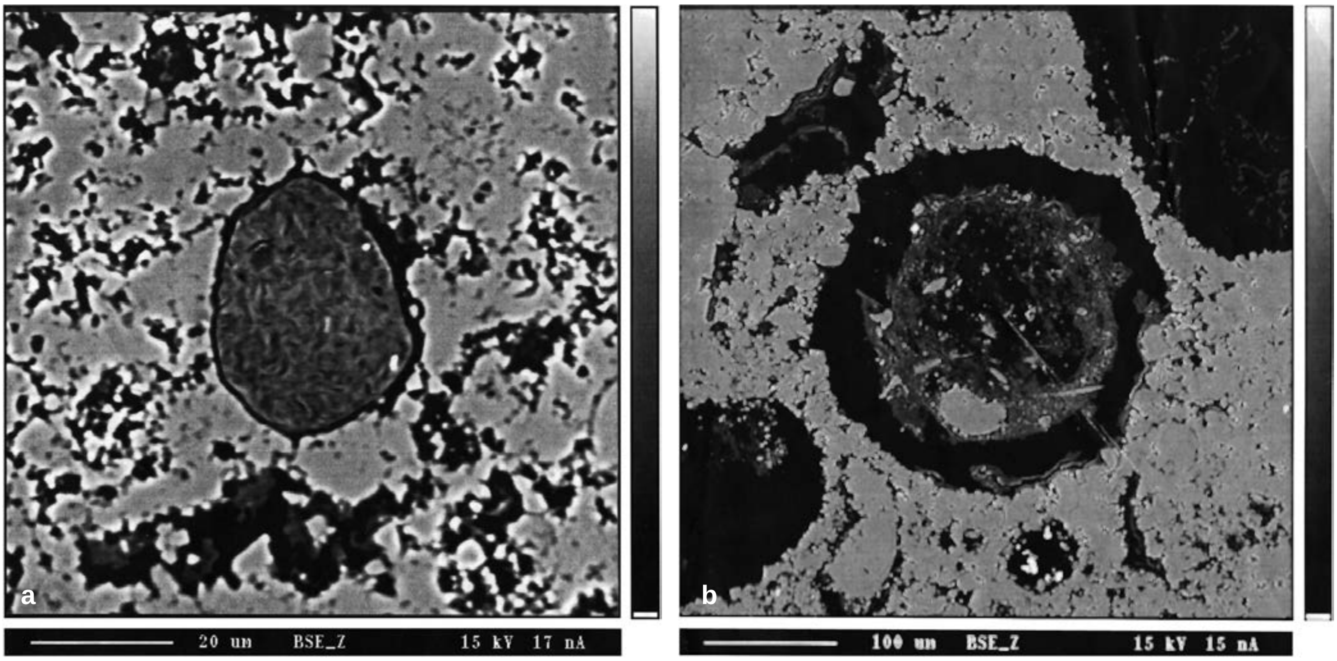


Fig. 19a, b Electron microprobe images of spherules from the breccia unit of El Caribe, **a** Glassy spherule #1 from Table 1. Note that the rim is smectite. **b** An altered spherule from the same breccia layer

oval or elongate forms, and rimmed by smectite. Many spherules are infilled with sparry calcite or micritic sediments that suggest diagenetic alteration of originally glassy spherules and/or post-depositional infilling of glass bubbles. In some spherules, part of the original glassy matrix is still present and surrounded by diagenetically altered glass (Fig. 19).

The Guatemalan spherules are similar in shape to spherules from Beloc, Haiti. They differ from the spherules in the northeastern Mexico siliciclastic deposits in that the latter are predominantly rounded and often consist of large composite spherules containing within them smaller sparry calcite-infilled spherules. Similar composite spherules were observed in Paleocene flood basalts from western Greenland by Robin et al. (1996) who attributed them to a volcanic origin. Such composite spherules were not observed in the Guatemala breccias but are common in the near-K/T siliciclastic deposits of northeastern Mexico (Stinnesbeck et al. 1993, 1996; Keller et al. 1994a). The stratigraphic position of the spherules at or near the K/T boundary in Haiti, Mimbral and Guatemala suggests a common origin. A common origin is also strongly supported by preliminary electron microprobe analyses of Guatemalan glass spherules which indicate chemical compositions similar to black and yellow glasses from Beloc in Haiti, Mimbral in northeastern Mexico (Tables 1 and 2) and glass within andesitic rocks in the Chicxulub breccia (e.g. Jéhanno et al. 1992; Smit et al. 1992; Swisher et al. 1992; Blum and

Table 1 Chemical composition of three El Caribe glasses and comparison with dark glasses from Beloc, Haiti, and Mimbral, Mexico. Beloc glass analysis from Koeberl (1993). Mimbral glass values from Stinnesbeck et al. (1993). Number in parenthesis corresponds to the number of electron microprobe analyses

	#1(5)	#2(3)	#3(1)	Haitian	Mexican
Na_2O	0.06	0.08	0.13	3.72	3.00
MgO	7.35	5.71	6.95	2.55	2.67
Al_2O_3	16.08	18.10	19.39	15.33	14.70
SiO_2	53.36	57.11	60.19	63.29	57.70
P_2O_5	0.12	0.19	0.24	0.07	–
K_2O	4.87	2.69	0.11	1.62	1.07
CaO	1.43	2.25	2.57	7.21	5.23
TiO_2	0.31	2.63	0.01	0.68	0.73
FeO	7.6	3.68	0.96	5.27	5.73
Total (%)	91.21	92.49	90.56	99.74	90.83

Table 2 Chemical composition of one El Caribe glass and comparison with yellow glasses from Beloc, Haiti, and Mimbral, Mexico. Beloc glass analysis from Koeberl (1993). Mimbral glass values from Smit et al. (1992). Number in parenthesis corresponds to the number of electron microprobe analyses. #4* values of El Caribe spherule are recalculated to 100%

	#4(1)	#4*	Haitian	Mexican
Na_2O	0.15	0.18	2.54	2.02
MgO	5.53	6.60	4.02	3.9
Al_2O_3	12.72	15.19	13.25	12.4
SiO_2	40.92	48.86	48.73	52.2
P_2O_5	0.63	0.75	0.06	–
K_2O	0.07	0.08	0.65	0.58
CaO	23.43	27.98	24.71	22.96
TiO_2	0.10	0.12	0.64	0.56
FeO	0.17	0.20	4.98	4.73
Total (%)	83.72	99.96	99.58	99.35

Chamberlain 1992; Stinnesbeck et al. 1993; Koeberl et al. 1994; Leroux et al. 1995).

Nevertheless, questions still remain as to the origin, precise age and stratigraphic position of this glass and spherule-producing event. In the Guatemala breccias, spherules have so far been detected only in the top layers of the breccia unit at El Caribe, and their precise stratigraphic position is difficult to estimate due to a hiatus at the K/T boundary (Fig. 18). The timing of the Chicxulub glass is also poorly constrained; there is some evidence that the breccia unit containing the glass is overlain by approximately 18 m of uppermost Maastrichtian marls (Ward et al. 1995). At Beloc, Haiti, a layer of Maastrichtian carbonate-rich sediments also stratigraphically separates the spherule layer from the overlying iridium anomaly (Jéhanno et al. 1992; Leroux et al. 1995). In northeastern Mexico the spherule and glass-producing event is at the base of a several metres thick siliciclastic deposit which contains several discrete horizons of bioturbation with truncated burrows that indicate long-term episodic deposition (Ekdale and Stinnesbeck, in press). In addition, a Maastrichtian-age marl layer commonly overlies the siliciclastic unit and underlies earliest Danian sediments (Lopez-Oliva and Keller 1996). The spherules and glass in northeastern Mexico are therefore stratigraphically below the K/T boundary and suggest a pre-K/T event, close to the end but still within the uppermost Maastrichtian.

Other origins

We found evidence for a short-term impact or volcanic event only near the top of the Guatemala breccia. Except for these uppermost layers, no glass spherules or altered glass shards appear to be present within the breccia. In addition, no basement rocks or other exotic lithologies were detected, and the carbonate clasts are not mechanically fragmented or altered. The breccia deposit consists of polymictic fragments of older, lithified carbonates embedded in a matrix of either lime mud or sparry calcite cement. Furthermore, the breccia deposit was probably not caused by a single event, as suggested by upward fining, the fair to poor sorting, roundness of clasts and bedding features. Multi-event breccia deposition is indicated by alternate layers with different clast sizes and degree of roundness, colour changes and micro-layering (ca. 1–2 cm thick) towards the top of the unit.

Based on these observations we suggest that the limestone breccia units of Caribe, Aserradero, Chisec and Actela are multi-event deposits. With the exception of the topmost spherule-bearing breccia layers, their relationship to the K/T boundary impact on northern Yucatan is unclear at present. Therefore, other origins for breccia deposition should also be considered such as collapse, penecontemporaneous disturbance or rip-up, tectonic or fault-related breccias:

1. Collapse breccias generally result from dissolution of dolostone, limestone and sulphates (anhydrite and/or gypsum). Such solution-collapse breccias are common worldwide (Friedman 1996; Stanton 1966). However, Guatemala breccias do not conform to collapse-breccia environments because the Campur formation generally lacks evaporites and the lithologies recognized in the breccia represent external, rather than internal, platform environments.
2. Penecontemporaneous disturbance or rip-up breccias usually form thin deposits and do not contain a variety of lithologies. Both thickness and the polymictic nature of the Guatemala breccias argue against such an origin. However, impact scenarios which call for a series of giant tsunami and seiche waves may partly account for the Guatemalan breccia characteristics such as mixed lithologies and variable thickness of deposits. Although this hypothesis unlikely accounts for the entire breccia deposits because of the absence of impact evidence (except in the top layer) and basement lithologies, the unaltered character of the sediments and the multi-event character of the deposit.
3. Tectonic breccias occur in the vicinity of major fault zones and do not persist along the strike of the bedding. Although these breccias are regionally known in the South Petén basin immediately north of the Polochic-Matagua fault zone (e.g. Blount and Moore 1969), they are not as widespread as the breccia unit examined here. In addition, tectonic breccia clasts are usually angular with matching boundaries, whereas the breccia deposits studied in Guatemala show no matching clast boundaries other than by stylolithic pressure dissolution.
4. Widespread faulting can supply sufficient detritus for the observed polymict breccias and seems a likely source for the extensive breccia deposits of central Guatemala. An extensive fault system developed during the late Campanian–Maastrichtian when the Yucatan and Chortis blocks collided subfrontally and caused pervasive compression of the southern Yucatan block (Rosenfeld 1981; Dengo 1982; Donelly et al. 1990; Pindell and Barrett 1990; Michaud et al. 1992; Fourcade et al. 1994). The collision ended the deposition of shallow-water limestones in the region and caused the drowning of the carbonate platform (Campur formation) during the late Campanian *G. calcarata* zone as evidenced at Chemal. Subsequently, a deep basin with siliciclastic sedimentation (the Sepur formation) developed along the southern margin of the Yucatan block during the Maastrichtian and early Tertiary, whereas local fault blocks and areas further to the south were uplifted and emerged. Debris flows of shallow-water limestone breccias and their deposition into deeper-water basins occurred from areas principally near the suture zone where serpentinites were obducted at the same time (Donelly et al. 1990;

Fourcade et al. 1994). The expression of this tectonic event is seen in the abrupt lithological change from stable carbonate platform (Campur formation) to flysch deposition (Sepur formation) throughout central Guatemala and Chiapas (Bochil, Chilil; Quezada Muñeton 1990; Stinnesbeck et al. 1994). The breccia deposits between the Campur and Sepur formations could be part of this tectonic event. The beginning of tectonic instability is often marked by sheet-like debris flows with little internal organization that result from episodic collapse triggered by major earthquakes, or overloading of the slope (e.g. along fault ridges).

The onset of platform drowning and tectonic instability varies in the region. At Chisec, Aserradero, Caribe and Actela a disconformity between the platform limestone and overlying breccia prevents determination of platform drowning (Fig. 18). However, at Chemal, and Chilil in Chiapas, the transition is present. At Chilil, a thin pelagic limestone unit conformably overlies the shallow-water limestones of the Angostura formation (equivalent to Campur formation in Guatemala) and contains a planktic foraminiferal assemblage indicative of the early late Maastrichtian *G. gansseri* zone (Fig. 18; Stinnesbeck et al. 1994). At Chemal, this unit of pelagic limestones is of late Campanian *G. calcarata* zone age. It conformably overlies the shallow-water carbonates and underlies siliciclastic flysch deposits of late Maastrichtian age (Fig. 18).

The flysch sequence at Chemal is characterized by numerous distal sandstone turbidites, olistolithic limestone blocks of shallow-water origin and a 1-m-thick bed of polymictic limestone breccia. The depositional sequence at Chemal is thus similar to Bochil, Chiapas, where a shale–sandstone flysch of Campanian to Eocene age also contains interbedded olistolithic blocks of shallow-water carbonates and several thick layers of a polymictic limestone breccia (Quezada Muñeton 1990; Stinnesbeck et al. 1994). One of these repeated breccia deposits occurs 1 m below the K/T boundary as suggested by elevated iridium values (Montanari et al. 1994). Taking into account the palaeogeographic setting and sedimentological sequence of the Bochil section, it seems unlikely that this particular breccia deposit could have resulted from “breakage of reefal sediments” triggered by the Chicxulub impact as suggested by Montanari et al. (1994, p. 85).

Conclusion

The following conclusions were reached as a result of our study:

1. Our investigation of five K/T sequences in Guatemala provides evidence in support of a major short-term regional impact or volcanic event by the presence of abundant spherules within the top layer of the breccia at El Caribe. Spherules and glass of similar geochemical compositions which have previously been reported from K/T sections in northeastern Mexico, Haiti and Chicxulub suggest a common origin. However, data from northeastern Mexico, Haiti and possibly Chicxulub suggest that this spherule event may have preceded the K/T event, which is marked by an anomaly and the extinction of tropical planktic foraminifera.
2. The presence of unconformities, differently coloured beds and fair sorting into layers of smaller and bigger clasts suggests a multi-event and possibly long-term component in the deposition of the Guatemala breccia. The subrounded outline of many clasts additionally indicates transport by water, particularly in the upper 3 or 4 m of the breccia at Chisec and Caribe where bedding in centimetre-thick layers is conspicuous and the clasts are rounded grains only a few millimetres in diameter. At Chisec early Danian (P1a Zone) planktic foraminifera are present in the top 10 cm of the breccia and suggest contemporaneous erosion and reworking with deposition of Zone P1a.

Our observations suggest a multi-event scenario for deposition of the Guatemala breccias, with a long-term origin, related to regional tectonics, and a short-term impact or volcanic event. Long-term breccia deposition may be related to compressive tectonic movements during the collision between the Yucatan and Chortis blocks near the end of the Cretaceous. In this multi-event scenario, the spherule and glass-producing event occurred near the end of the Maastrichtian and was superimposed over long-term regional tectonic events.

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