ELSEVIER

Marine Micropaleontology 31 (1997) 97–133

MARINE MICROPALEONTOLOGY

The Cretaceous/Tertiary boundary event in Ecuador: reduced biotic effects due to eastern boundary current setting

Gerta Keller[a,*], Thierry Adatte[b], Chris Hollis[c], Martha Ordóñez[d], Italo Zambrano[d], Nelson Jiménez[d], Wolfgang Stinnesbeck[e], Antinor Aleman[f], Wendy Hale-Erlich[f]

[a] *Department of Geosciences, Princeton University, Princeton, NJ 08544, USA*
[b] *Institute de Géologie, 11 Rue Emile Argand, 2007 Neuchatel, Switzerland*
[c] *Institute of Geological and Nuclear Sciences, PO Box 30368, Lower Hutt, New Zealand*
[d] *Petroproduccion, Filial de Petroecuador, Km. 6 1/2 Via a Salinas, PO Box 10829, Guayaquil, Ecuador*
[e] *Geologisches Institut, Universität Karlsruhe, 76131 Karlsruhe, Germany*
[f] *Amoco Production Company, PO Box 3092, Houston, TX 77253, USA*

Received 27 July 1996; revised version received 22 October 1996; accepted 11 November 1996

Abstract

A multidisciplinary study of a new Cretaceous–Tertiary (K/T) boundary section near Guayaquil, Ecuador, reveals an unusually cool water, low diversity planktic foraminiferal fauna and a high diversity radiolarian fauna similar to those found in southern high-latitude K/T sequences despite the fact that this section was deposited near the Cretaceous equator. The K/T boundary is located by planktic foraminifera within a narrow interval bounded by last appearances of tropical Cretaceous species and first appearances of Tertiary species including *Parvularugoglobigerina eugubina*. As in southern high latitudes, there is no major mass extinction of either planktic foraminifera or radiolarians at this level. A major radiolarian faunal discontinuity occurs some 6 m higher in the section within foraminiferal Zone Plc, some 300–500 kyr after the K/T event.

$\delta^{13}C$ values from bulk carbonates show both high- and low-latitude characteristics. Similarly to low latitudes, there is a 3‰ negative $\delta^{13}C$ excursion at the K/T boundary which is generally interpreted as a major decrease in primary productivity. But unlike the low latitudes, recovery occurs within a few thousand years, as compared with 300–500 kyr, and suggests rapid nutrient influx from the Antarctic region via a current similar to the Humboldt current today. Similarly to high-latitude K/T sequences, a negative $\delta^{13}C$ shift occurs in the early Danian Zone Plb about 300 kyr after the K/T boundary. Sedimentologic and mineralogic data indicate a late Maastrichtian with relatively low biogenic quartz and high carbonate followed by increasing biogenic quartz (>50%) and decreasing carbonate (<5%) during the early Danian. This suggests intensified atmospheric and oceanic circulation and upwelling off Ecuador during the early Danian. The K/T transition is marked by increased volcanic activity, continental erosion and terrigenous influx, but this also occurs in the early Danian Zone at the P1a/P1b zonal transition and is thus not unique to the K/T boundary.

We suggest that the catastrophic biotic effects normally observed at the K/T boundary in low latitudes are greatly reduced or absent in the eastern equatorial Pacific because this region was dominated, then as now, by upwelling and

---

[*] Corresponding author. E-mail: keller@geo.princeton.edu.

PII S0377-8398(96)00061-8

current transport of nutrient-rich waters from the Antarctic Ocean. As a result, the biotic patterns are characteristic of southern high latitudes, whereas the $\delta^{13}C$ pattern combines ameliorated low-latitude effects with predominantly high-latitude trends.

Keywords: K/T; Ecuador; reduced biotic effects

1. Introduction

The Cretaceous/Tertiary (K/T) boundary mass extinction has been studied in marine sediments worldwide by numerous workers over the past 15 years. Despite the long-term research effort, the mass extinction record is still globally incomplete and the nature, tempo and ultimate cause of this biotic catastrophe remains enigmatic. This is in part because most known K/T complete sequences are located in the northern low-latitude Tethys region including Spain, Tunisia, Texas and Mexico. Few K/T sections have been studied from the Atlantic (mostly Walvis Ridge), Pacific (Hess Rise sites 577, 463), or Caribbean, and these are generally very condensed, incomplete or eroded through the critical interval (MacLeod and Keller, 1991a,b; Keller et al., 1993a; MacLeod, 1995). In addition, vast areas of the oceans either lack K/T boundary sediments due to subduction (e.g., Indian Ocean, North Pacific, East Pacific), or have never been drilled (South Pacific, Fig. 1). Thus, our understanding of the K/T mass extinction in the marine realm has largely been based on analyses of sequences within limited areas of the Tethys region, and the observed biotic effects have been erroneously generalized globally. This has become particularly evident with the examination of both northern and southern high-latitude sections.

For example, among planktic foraminifera, which are the most severely affected microfossil group by the K/T boundary catastrophe, about two-thirds of the species are extinct at or before the K/T boundary in the Tethys region (Keller, 1988, 1989; Brinkhuis and Zachariasse, 1988; Canudo et al., 1991; Keller and Perch-Nielsen von Salis, 1995; Keller et al., 1996). Though extinctions are not random, K/T extinct species include all tropical–subtropical, large, complex and highly ornamented morphologies. Smaller, less ornamented, morphologically simple and cosmopolitan taxa survived 100–300 kyr into the Tertiary (Keller, 1988; MacLeod and Keller, 1994; Keller and Perch-Nielsen von Salis, 1995). However, studies of high-latitude relatively complete K/T sections in the south (ODP Site 738, Keller, 1993, 1996; Keller and MacLeod, 1995; MacLeod, 1995) and north (Nye Klov, Denmark, Keller et al., 1993b; Koshak, Kazakhstan, Pardo, unpubl. data) have shown that this selective mass extinction pattern is not global. In fact, no significant species extinctions occurred across the K/T boundary in high latitudes. This is largely because tropical–subtropical taxa are absent in these areas, except for sporadic migrations during warm climate, and the indigenous fauna is largely similar to the cosmopolitan fauna at lower latitudes (Keller, 1996). However, this low–high-latitude dichotomy in species extinctions is also oversimplified as our investigation of the Ecuador section reveals.

Other fossil groups also reveal the absence of mass extinctions at the K/T boundary in high southern latitudes. For instance, radiolarians which so far are only known from southern high-latitude regions and primarily New Zealand in this stratigraphic interval, show a faunal turnover, but no significant extinctions (Hollis, 1993, 1996; Strong et al., 1995). Similarly, pollen and spores as well as plant fossils in New Zealand and Seymour Island, Antarctica, reveal no major changes, but suggest climatic and sea-level fluctuations (Askin, 1988, 1992; Askin and Jacobson, 1996). Invertebrate assemblages documented from Seymour Island, Antarctica, Chile and Brazil also show a long-term gradual faunal turnover, rather than a mass extinction at the K/T boundary (Zinsmeister et al., 1989; Stinnesbeck, 1996). These data reveal that the assumption of global mass extinctions as a result of a bolide impact was incorrect.

It is also generally assumed that the environmental effects of a major K/T bolide impact were devastating globally. Stable isotope studies now suggest that this was not the case. In the Tethys region, $\delta^{13}C$ values of surface waters decreased by 2–3‰ at the K/T boundary, suggesting a severe drop in primary

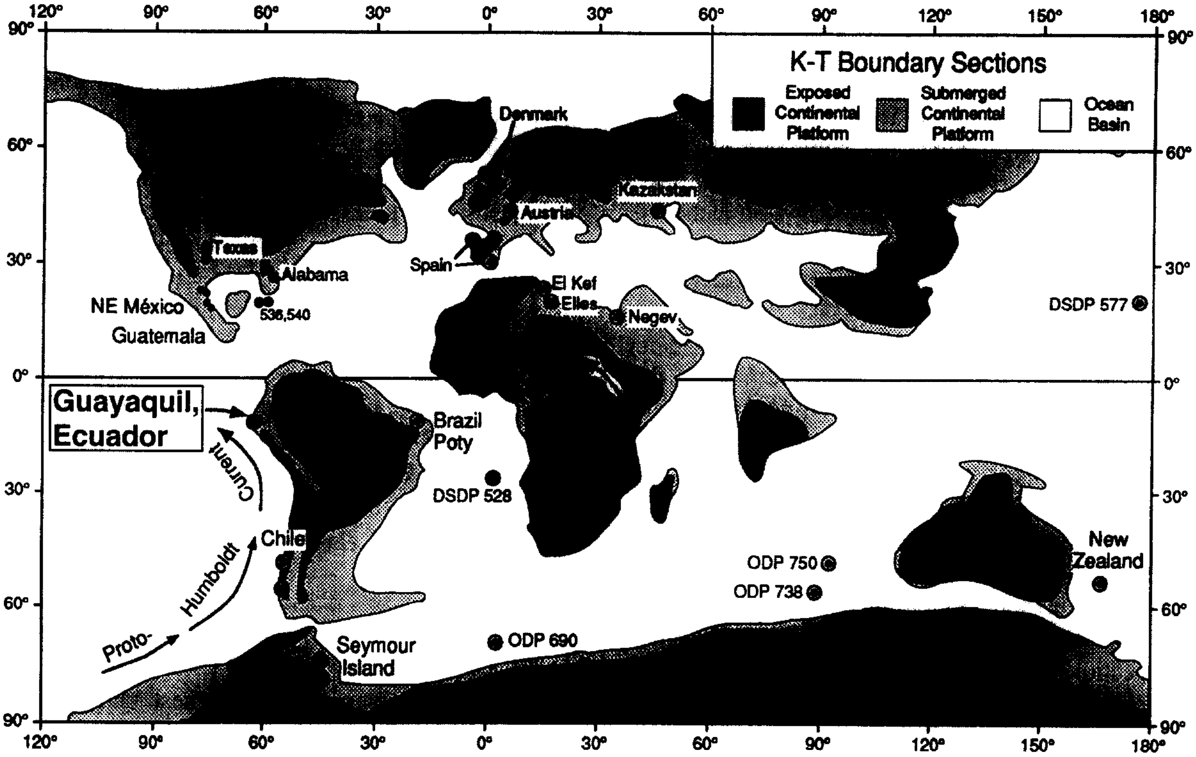


Fig. 1. Geographic location of near-complete Cretaceous–Tertiary boundary sections. Note that most sections known are concentrated in the Tethys region north of the equator. Few K/T sections are known from southern or northern high latitudes. To date, only New Zealand K/T sections have been studied in the South Pacific region between the equator and Antarctica. The Via Perimetral section of Guayaquil, Ecuador, is the first equatorial K/T section in the eastern South Pacific region.

productivity (Oberhänsli, 1986; Zachos and Arthur, 1986; Arthur et al., 1987; Zachos et al., 1989; Keller and Lindinger, 1989; Barrera and Keller, 1990). Until recently it was assumed that this productivity drop was global and possibly induced by a shutoff of photosynthesis due to a dust cloud generated by a bolide impact. However, in high-latitude sections $\delta^{13}C$ values decreased very little (0.5‰ at Nye Klov, Denmark, and Koshak, Kazakhstan, Keller et al., 1993b; Pardo et al., 1996), or even increased (ODP Site 738, Barrera and Keller, 1990), indicating that no significant change occurred in productivity at the K/T transition. But, at ODP sites 738, 750 and 690 a significant negative $\delta^{13}C$ shift occurred in Zone Plb, about 300 kyr after the K/T boundary (Barrera and Keller, 1994). Thereafter, in Zone Plc about 500 kyr after the K/T boundary, surface productivity began to return to latest Cretaceous levels in both low and high latitudes. In New Zealand, $\delta^{13}C$ evidence for an opportunistic plankton bloom directly above the K/T boundary (Hollander et al., 1993) appears to have been the first phase of a prolonged episode of very high productivity related to increased upwelling, as marked by siliceous plankton (Hollis et al., 1995). This high siliceous productivity is estimated to have peaked about 500 kyr after the K/T boundary.

These high–low-latitude differences reveal a K/T boundary event which apparently had varying biotic and environmental effects across latitudes which need to be fully explored, if we are to understand the adverse biotic effects of a major bolide impact. The major problem has been a lack of complete K/T sections in middle to high southern latitudes as well as in the equatorial region. Currently, the only good southern-hemisphere marine sections known are from ODP Site 738 (Fig. 1) and from New Zealand, though all of these sections are very condensed or have short hiatuses at the K/T boundary (Hollis, 1993; MacLeod, 1995; Keller, 1993, 1996). K/T sections known from Argentina, Peru and Chile were generally deposited in very shallow or subaerial environments and have major hiatuses (for a review see Stinnesbeck, 1996). Seymour Island sections generally lack Radiolaria or calcareous microfossils, although diatoms and palynomorphs show little change (Harwood, 1988; Askin, 1988; Askin and Jacobson, 1996). Only one K/T complete section (Poty Quarry, Recife, Brazil, Fig. 1) has been reported to date from the South American continent (Stinnesbeck, 1989; Albertão et al., 1994; Stinnesbeck and Keller, 1994, 1995, 1996). The Poty Quarry is similar to northeastern Mexico sections in that both contain typical Tethys planktic foraminiferal assemblages and an 'event' deposit (siliciclastic and breccia deposits) stratigraphically below the K/T boundary (Keller and Stinnesbeck, 1996b).

The need for southern-hemisphere sections that document biotic and environmental changes across the K/T transition has prompted this investigation of the Via Perimetral section in Guayaquil, Ecuador. The section was discovered by Amoco and Petroecuador geologists who located the K/T boundary within a 20 m interval of undifferentiated, rhythmically bedded siliceous limestones and cherts interbedded with thin layers of shales and volcanic ash. The location of this section was near the equator at K/T boundary time and provides the first record of the biotic and environmental response to the K/T boundary event in the east equatorial Pacific. Our multidisciplinary investigation concentrated on three major objectives.

(1) Stratigraphy and faunal turnover: Determine the completeness of the stratigraphic record across the K/T boundary based on siliceous and calcareous microfossils; document the K–T mass extinction and/or faunal turnover.

(2) Stable isotopes: Determine the magnitude of the $\delta^{13}C$ excursion at the K/T boundary and $\delta^{13}C$ trends within the Danian.

(3) Sedimentological and mineralogical analyses: Determine source, nature of deposition and environmental changes evident from whole rock mineralogical association.

2. Lithology, depositional setting and sampling

The Via Perimetral section is located along the Via Perimetral highway near the suburb of Ceibos northeast of central Guayaquil, Ecuador, at 2°10′47.5″S and 79°56′50.1″W. The exposure includes several hundred meters of the Maastrichtian to Paleocene Guayaquil Formation; the sediments generally strike 30°NW and dip 27°SW. The Guayaquil Formation is characterized by rhythmically bedded siliceous limestones, cherts and tuffaceous siltstones interbedded with thin layers of shale and volcanic ash (Fig. 2). Most beds average 5 to 15 cm in thickness, but a few reach 30 to 35 cm. The interbedded shale and ash layers are generally less than 1 cm thick and rarely reach a maximum of 5 cm. The lower and upper bedding surfaces of these thin layers are commonly wavy due to diagenetic compaction of the soft sediment by overlying strata, and a few layers show slumping features. Individual beds may swell or thin out, though in general they can be followed over distances of tens to hundreds of meters along the outcrop. Amalgamation of limestone and chert layers is common; some beds cut into underlying layers partially eroding them; other beds show weak gradation of sediments suggesting a distal turbidite origin. Fine scale laminations of alternating light–dark layers is common in cherts and siliceous limestones, whereas shale interlayers are generally fissile due to the pressure of the overlying sediments. No bioturbation was observed in the studied interval, suggesting unfavorable conditions with low oxygen content on the sea floor.

The rhythmically bedded siliceous limestones, cherts, tuffaceous siltstones and shales of the Guayaquil Formation were deposited in a bathyal slope environment. This is suggested by the rarity of benthic foraminifera and a faunal assemblage that consists of rare *Nuttalides truempyi*, *Dentalina*, *Nodosaria*, *Abyssamina* and other agglutinated forms. Planktic foraminifera are also relatively rare and preservation is poor which suggests deposition occurred at or below the lysocline. The rhythmic influx of terrigenous sediments (including volcanic sediments) suggests deposition occurred near a continental source and that terrigenous influx may have been related to seasonal increases in precipitation.

We measured, collected and studied a 20 m interval of the Guayaquil Formation which contains the K/T boundary. The section was sampled in detail for the first 15 m averaging 25 cm sample intervals. The top 5 m were sampled at 50 to 100 cm

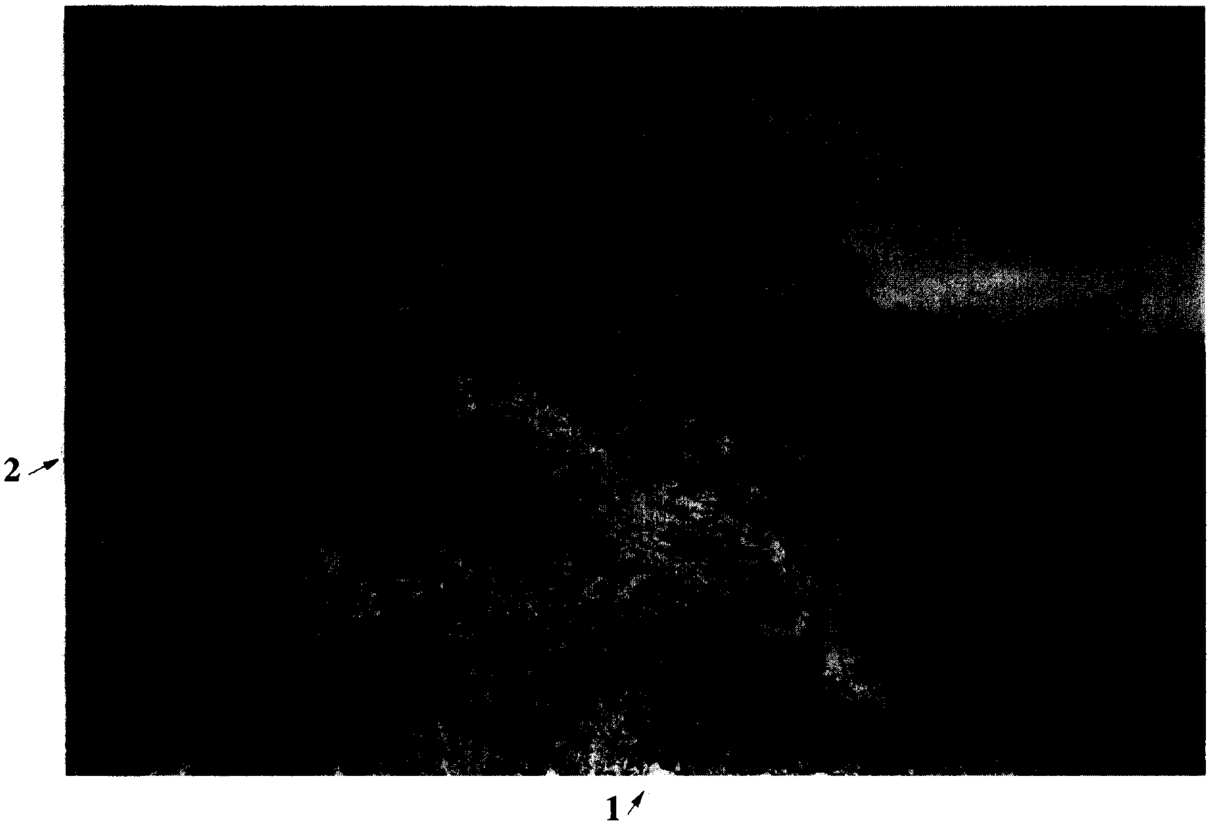


Fig. 2. Photo of the Via Perimetral K/T boundary exposure viewed from the Via Perimetral highway north of Guayaquil, Ecuador. Note the rhythmically bedded Guayaquil formation shows little variation between Maastrichtian and Tertiary sedimentation. The foraminiferal K/T boundary is marked with an arrow and the number *1*; the position of a radiolarian faunal turnover event that marks the K/T boundary in New Zealand sections is indicated by an arrow and the number *2*.

intervals and subsequently resampled at 10 to 20 cm intervals. Unlike K/T sections elsewhere, there is no sharp lithologic change that marks the K/T boundary within these rhythmically bedded sediments. However, there are two clues that suggest environmental changes. One is at 10.75 m from the base of the section (see arrow and #1 in Fig. 2) where a couplet of two thin shaly clay layers separated by a 1 cm thick grey limestone is sandwiched between siliceous limestone layers (Fig. 3b). This shaly clay interval marks the planktic foraminiferal K/T boundary and was sampled at cm intervals in two transects 50 m apart. The second clue is 16.75 m from the base of the section (see arrow and #2 in Fig. 2) and marks the onset of thick siliceous limestone layers (Fig. 3a). This latter interval marks a major radiolarian faunal change that in New Zealand sections is associated with the K/T boundary (Hollis, 1993, 1996). In this report we detail the upper 11 m of the collected interval spanning the latest Maastrichtian through early Danian.

3. Methods

Radiolaria were extracted using standard acid-leaching techniques (Hollis, 1993). Hydrochloric acid (HCL) digestion to remove carbonate was followed by brief immersion (1–2 hours) in 5% hydrofluoric acid. Most residues required repeated cleaning by boiling in a solution of 10% hydrogen peroxide (H_2O_2) and 5 *M* sodium hexametaphosphate [$(NaPO_3)_6$]. Sixty-six samples were processed and examined over the interval between 9 and 21 m. Thirty-two samples were prepared as strewn slides. Counts were made of nineteen samples and an additional six samples were searched for critical species

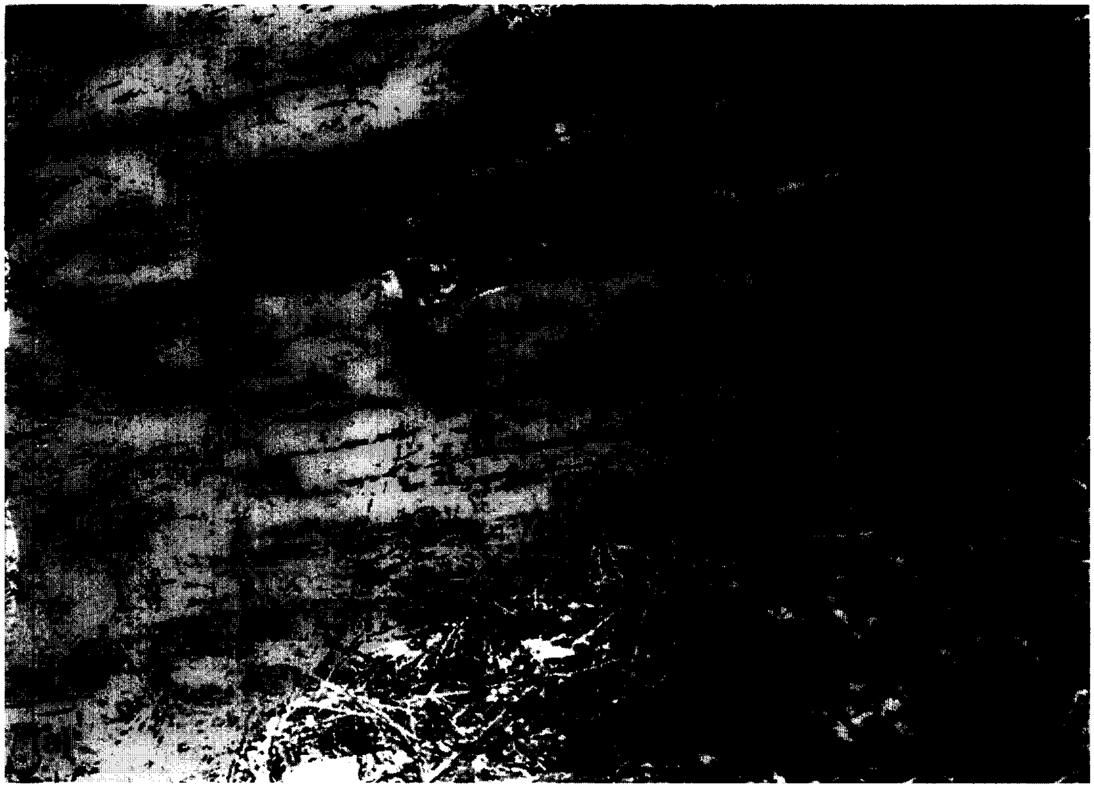


Fig. 3. (a) Photo of the interval encompassing the radiolarian faunal turnover event that marks the K/T boundary in New Zealand sections (for location see arrow and #2 in Fig. 2). Note the presence of thicker beds of siliceous limestones separated by very thin interlayers of shale.

(see Table 1). Although total counts of some samples with sparse fauna were low (<100), they are judged as adequate guides to trends within major groups, especially when tied to samples with larger counts.

Foraminifera were processed by first grinding the hard rocks with mortar and pestle, then cooking them for several hours with a strong detergent (Miramine), followed by standard washing through a 63 μm sieve. The residue was then dried in the oven and examined for foraminifera. This method provided good foraminiferal faunas in some isolated intervals, but many samples were barren and preservation is poor. Therefore, thin sections were prepared for all sample intervals to determine the presence or absence of foraminifera, examine lithologies, and search for exotic constituents (e.g., impact glass spherules and shocked minerals—none were found). Planktic foraminifera identified from thin sections were double checked with species present in washed residues to confirm their identifications whenever possible.

Samples were also processed for nannofossils and palynomorphs using standard laboratory techniques (Perch-Nielsen, 1979; Askin, 1988). Most samples are devoid of nannofossils (this report and Von Salis Perch-Nielsen, pers. commun., 1995) and palynomorphs are rare and only sporadically present.

Stable isotope analyses were conducted in the isotope laboratory of Princeton University. Bulk rocks of all lithologies sampled were measured including siliceous limestone, tuffaceous siltstone, shale, clay and ash layers. Samples were crushed with mortar and pestle and dried in the oven. The isotopic composition of the gas was measured with a VG Optima gas source mass spectrometer equipped with a common acid bath. The isotopic ratios are reported in delta notation as per mil deviation from the PDB standard with a standard error of 0.05‰ for $\delta^{13}C$ and 0.1‰ for $\delta^{18}O$. Only shale and clay layers provided reliable measurements, whereas other lithologies frequently lacked sufficient carbonate for gas measurements.

Fig. 3 (continued). (b) Photo of the foraminiferal K/T boundary interval showing the 10 cm thick couplet of two clay layers separated by a 1 cm thick limestone in turn sandwiched between siliceous limestone layers. For location see arrow and #1 in Fig. 2.

For this reason, only measurements from shales and clays containing more than 10–15% calcite may be reliable (Table 2). In the uppermost part of the section (top 5 m), even shale layers contain very little carbonate, except in some isolated samples, and gas measurements may not be reliable.

Whole rock and clay mineral analyses were conducted at the Geological Institute of the University of Neuchatel, Switzerland. Sample processing followed the procedure outlined by Kubler (1987). Whole rock mineralogy was determined from random powdered bulk samples. About 20 g per sample was ground with a 'jaw' crusher into small chips (1–5 mm). About 5 g was dried at 60°C and then ground again into a homogenous powder (particle size <40 μm). 800 mg of this powder was pressed (20 bar) in a powder holder covered with blotting paper and analyzed by XRD. Whole rock composition was determined by XRD (SCINTAG XRD 2000 Diffractometer) based on methods described by Klug and Alexander (1974), Kubler (1983) and Rolli (1990) and percent abundances are listed in Table 3. This method for semi-quantitative analysis of bulk rock mineralogy used external standards.

4. Stratigraphy

Radiolaria are the most common microfossils in the Guayaquil Via Perimetral section, whereas planktic foraminifera are intermittently present in carbonate-rich sediment layers and nannofossils, diatoms and palynomorphs are rare. Biostratigraphy of this section is therefore based on planktic foraminifera and Radiolaria. Planktic foraminifera are excellent biostratigraphic marker species in high- to low-latitude K/T boundary sections where they afford a high-resolution age zonation as shown in Fig. 4 with zonal index species marked in bold type. In this study, Keller's updated (1993) biozonation was used which includes the *Plummerita hantkeninoides* Zone that marks the last 170–200 kyr of the Maastrichtian (Pardo et al., 1996). The zonation of Berggren et al. (1995) is shown for comparison.

Although radiolarians are generally abundant in low latitudes, K/T boundary sections with radiolarians are extremely rare. The best K/T radiolarian records are known from New Zealand where Hollis (1993, 1996); Strong et al. (1995) detailed their ranges and developed an Early Paleocene biozona-

Table 1

Radiolarians in the Via Perimetral section, Guayaquil, Ecuador. Relative abundances shown as percentages of representative faunal counts

AGE	Late Cretaceous												Early Paleocene												
Radiolarian Zone	*Amphipyndax tylotus* Zone (= RK9)												RP1	RP2 (*A. kina* Zone)						RP3			RP3??		
SAMPLE	G18A	G19A	G21a	G21b	KT1	KT3	KT8	G23A	G26A	G27A	G30	G32	G33	G30R	G31R	G32R	G33R	G34	G37R	G44R	G45R	G50R	G35	G37	G39
Depth (m)	9.35	10.2	10.7	10.75	10.8	10.85	10.9	11.7	12.85	13.3	14.2	16.2	16.75	17	17.05	17.2	17.35	17.65	18	19.55	19.65	20.15	18.2	19.25	20.5
Abundance	com	abt	few	few	few	few	com	few	few	com	com	abt	few	com	com	com	com	com	abt	abt	abt	com	com	com	com
Radiolarians/gram	250	1500	50	10	10	10	>100	25	20	150	250	4000	25	>100	300	450	300	200	400	250	550	>100	>100	>100	>100
Preservation	mod	mod	gd	mod	gd	gd	mod	pr	mod	pr	pr	pr	v pr	pr	mod	mod	mod	pr	mod	mod	mod	pr	pr	pr	pr
SPUMELLARIA indet.	39.5	11.2	5.9		2.6	1.5	5.7	7.1	2.0	21.6	41.1	45.3	93.5	C	28.6	33.2	30.2	44.7	23.7	39.4	C	C	C	C	C
ACTINOMMIDAE indet.	10.7	23.1	1.7	2.0		0.5	0.7	1.2	2.0	10.1	17.3	15.1		C	36.7	25.5	24.9	19.6	25.5	30.5	C	C	C	C	C
Amphisphaera privus	x	4					0.7	2.4	1.0	1.0	x	2.2					x								
Amphisphaera n.sp. A	1	4					1.4	2.4	12.1	2.4	x	1.7													
Amphisphaera aotea													4.7	F	0.8	0.5		1.1		x	x				
Amphisphaera kina														C	30.6	20.4	21.0	22.9	20.1	12.5	C	C	C	C	C
Amphisphaera goruna																0.5	2.0								
Amphisphaera macrosphaera															0.8	1.5	1.0	0.6	2.9	3.6	x			F	F
Lithomespilus coronatus								2.4				0.9		F	0.8	5.1	5.9	x	2.6	3.9	x			x	x
Protoxiphotractus sp.						0.5																			
Prunocarpus sp.												0.9													
Saturnalis kennetti																	0.5		x	x	x				
Stylosphaera pusilla	2.8	1.7							1.0	1.0	0.4	0.4				0.5									
Stylosphaera spp.	0.5							2.4		1.0				x		0.5	1.5	0.6	2.2	1.1	x				
Stylosphaera minor																	x								
LITHELIIDAE indet.			7.6																						
Lithelius minor gp	1.4		16.1	11.2	19.5	10.7	?			1.0		x				1.0	x		0.4	x	x		x		x
SPONGURIDAE indet.	0.5	0.4				1.0		1.2	1.0	1.0		0.9			x	1.0	0.5	1.1	0.4	0.4					x
Amphymenium concentricum											x	x						x							
Amphymenium splendiarmatum												?				0.5	x	1.1	0.4	x	x	x	x		
Amphymenium aff. murrayanum																				x					
Phaseliforma laxa	x		3.4	12.2	14.3	11.7	4.3			0.5	x	?													
Spongurus spongiosus												x													
PATULIBRACCHIIDAE indet.																									
Crucella cf. *messinae*	0.5	1.7			1.3		0.7	2.4	1.0	x		x													
Paronaella cf. *venadoensis*		0.4			1.3				1.0			x							x						
SPONGODISCIDAE indet.	3.3	3.7	5.1	16.3	2.6	9.7	9.2	4.8	12.1	3.4	2.2	4.3		F		3.1	2.9	3.9	2.9	1.1				x	x
Spongodiscus sp.		1.2								0.5	0.4	x				0.5			0.4		x				x
Orbiculiforma sp.	0.5	x							1.0		0.4	x		x	0.4	1.5	3.4	1.1	1.5	2.9					

× = present, but not in count or assemblage not counted (NC). Abbreviations for siliceous fossil abundance and preservation: few; com = common; abt = abundant; vpr = very poor; pr = poor; mod = moderate; gd = good.

Table 1 (continued)

AGE	Late Cretaceous												Early Paleocene												
Radiolarian Zone	*Amphipyndax tylotus* Zone (= RK9)												RP1	RP2 (*A. kina* Zone)						RP3			RP3??		
SAMPLE	G18A	G19A	G21a	G21b	KT1	KT3	KT8	G23A	G26A	G27A	G30	G32	G33	G30R	G31R	G32R	G33R	G34	G37R	G44R	G45R	G50R	G35	G37	G39
PORODISCIDAE indet.	0.9	2.9	2.5							2.9	x	x			0.4	1.0	x	2.2				x			
Tholodiscus ocellatus																x		x	x						
NASSELLARIA indet.	12.6	4.1	5.9					2.4		9.6	11.7	4.3		x	0.4	0.5	x	0.6	0.7	0.7					
PLAGIACANTHIDAE indet.		0.8	0.8								0.4	1.3					1.0		0.4						
Lithomelissa amazon	x											x													
Lithomelissa heros	5.1	x	1.7						1.0	11.1	x	3.0					x		0.4	x					
Lithomelissa? hoplites												x													
Lophophaena? polycyrtis	x																								
Tetraphormis leia	x	0.4								0.5	x						x								
CANNOBOTRYIDAE indet.	x		x			x	x		x																
Rhopalosyringium magnificum	1.4	2.1	1.6	9.2	3.9	11.2	1.4		1.0	1.4	x	2.2							x						
Rhopalosyringium sparnon	x			3.1	11.7	5.6	17.0	4.8	4.0	0.5	2.2	0.9				x	x	x	x						
ARTOSTROBIIDAE indet.	0.9	1.2				0.5	0.7			2.9	0.4	0.4			x			x	x						
Artostrobus sp. Cr.		x									0.4			x	x	2.0	2.0	x	9.1	2.5	x	x			
Siphocampe altamontensis	1.9	0.4					0.7		1.0	0.5	x	0.9					0.5		0.7						
Siphocampe bassilis	3.3	6.6	0.8				0.7			2.9		1.3					0.5	x	x		x				
AMPHIPYNDACIDAE indet.											5.2	0.9				x		x	x		x				
Amphipyndax stocki	x	1.2		3.1		2.0	2.1	4.8	10.1		0.4	x													x
Amphipyndax tylotus	1.4	2.5	7.6	10.2	5.2	8.2	6.4	7.1	10.1	1.0	0.4	x													
Amphipternis alamedaensis														x			0.5								
ARCHAEODICTYOMITRIDAE indet.	1.4	0.8	2.5				0.7			2.9	6.1	1.3			x				x						
Archaedictyomitra lamellicostata	0.5	0.4	1.7		2.6	2.6				0.5	x	x													
Dictyomitra spp.						1.0						0.9													
Dictyomitra andersoni	0.9	2.5	10.2	14.3	3.9	7.7	14.9	8.3	4.0	1.0	1.3	1.7	0.9		0.4	0.5	x	x	x		x	x			
Dictyomitra crassispina			1.7		3.9		1.4	1.2	1.0		x	x						x							
Dictyomitra multicostata	0.9	0.8			3.9	2.0	0.7			0.5	x	0.4													
Mita regina	x									0.5		x													
'CRYPTOCEPHALIC' EUCYRTIDIIDAE indet.		0.8	3.4		1.3		2.1	1.2	2.0		0.4	0.9			x	0.5			0.4	x					
Myllocercion spp.	x	0.8				1.5	?			0.5		?													
Theocapsomma spp.				1.0		2.0	1.4	1.2																	
Theocapsomma amphora	2.8	7.4	11.0	8.2		8.7	16.3	31.0	21.2		7.4	2.6				x			0.4	x	x				
Theocapsomma aff. *comys*	0.9	0.8			2.6	1.5	0.7		1.0	1.0	x	0.4													
Theocapsomma erdnussa												0.4													

× = present, but not in count or assemblage not counted (NC). Abbreviations for siliceous fossil abundance and preservation: few; com = common; abt = abundant; vpr = very poor; pr = poor; mod = moderate; gd = good.

Table 1 (continued)

AGE	Late Cretaceous												Early Paleocene												
Radiolarian Zone	*Amphipyndax tylotus* Zone (= RK9)												RP1	RP2 (*A. kina* Zone)						RP3			RP3??		
SAMPLE	G18A	G19A	G21a	G21b	KT1	KT3	KT8	G23A	G26A	G27A	G30	G32	G33	G30R	G31R	G32R	G33R	G34	G37R	G44R	G45R	G50R	G35	G37	G39
OTHER EUCYRTIDIIDAE indet.		4.1							3.0	4.8	1.3	1.7		x		x	0.5		1.8	0.4		x			
Clathrocyclas hyronia		0.4								0.5															
Clathrocyclas lepta	2.3	x								1.0					x										
Clathrocyclas spp.																	0.5		1.8	x					
Clathrocyclas sp. A																	x								
Lithocampe sp. A	0.5	x																							
Stichomitra spp.	2.3	3.7	1.7		2.6	2.0	3.5	6.0	6.1	4.8		0.9	0.9	x	x		x	x	1.1	x		x			
Stichomitra compsa	x	0.4	2.5	7.1	5.2	7.7	3.5	6.0	0.0	3.4	0.4	0.9					x				x				
Stichomitra livermorensis		0.4										x													
Stichomitra asymmetra	x	7.4	4.2	2.0						1.9		1.3				x	x	0.6	x						
Stichomitra wero																				?					
Stichomitra granulata																				0.7	x	x			
Bathropyramis sanjoaquinensis	x																								
Cornutella californica												x					1.0		0.4	0.4	x				
TOTAL COUNT	215	242	118	98	77	196	141	84	99	208	231	232	107	NC	245	196	205	179	274	279	NC	NC	NC	NC	NC
% Spumellaria	61	50	42	42	42	36	23	26	34	46	62	72	92		40	49	46	55	30	34					
% Plagiacanthids	5.1	0.8	2.5	0.0	0.0	0.0	0.0	0.0	1.0	11.1	0.4	4.3	0.0		0.0	0.0	1.0	0.0	0.7	0.0					
% Cannobotryids	1.4	2.1	1.7	12.2	15.6	16.8	21.3	4.8	5.1	1.9	2.2	3.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0					
% Artostrobiids	6.0	8.3	0.8	0.0	0.0	0.5	2.1	0.0	1.0	6.3	0.9	2.6	0.0		0.0	2.0	2.9	0.0	9.9	2.5					
% Amphipyndacids	1.4	3.7	7.6	13.3	5.2	10.2	8.5	11.9	20.2	1.0	6.1	0.9	0.0		0.0	0.0	0.5	0.0	0.0	0.0					
% Archaeodictyomitrids	3.7	4.5	16.1	14.3	14.3	13.3	17.7	9.5	5.1	5.8	7.4	4.3	0.9		0.4	0.5	0.0	0.0	0.0	0.0					
% 'Cryptocephalic' eucyrtidiids	3.7	9.9	14.4	9.2	15.6	13.8	20.6	33.3	24.2	1.4	7.8	4.3	0.0		0.0	0.5	0.0	0.0	0.7	0.0					
% Other eucyrtidiids	5.1	16.5	8.5	9.2	7.8	9.7	7.1	11.9	9.1	16.3	1.7	4.7	0.9		0.0	0.0	2.0	0.6	5.1	1.4					
DIATOMS														few	rare	rare	rare	rare	few	rare	rare	rare	rare	rare	rare
SPICULES - long	abt	abt	com	com	abt	com	com	com	com	com	abt	com	com	com	com	abt	abt	com	abt	abt	abt	com	com	com	com
SPICULES - round	com	com	com	com	abt	com	com	com	com	com	abt	com	com	com	com	com	com	abt	com	com	com	few	com	com	com
SPICULES - other	few	few	few	few	few	few	few	few	few	few	rare	rare	rare	few	few	few	few	rare	few	few	few	rare	few	few	few

× = present, but not in count or assemblage not counted (NC). Abbreviations for siliceous fossil abundance and preservation: few; com = common; abt = abundant; vpr = very poor; pr = poor; mod = moderate; gd = good.

Table 2
Oxygen and carbon isotope data of bulk carbonate across the K/T boundary at the Via Perimentral section, Guayaquil, Ecuador. Samples labelled GQ and K mark two 20 cm transects across the K/T clay couplet at locations 50 m apart

Sample No.	Depth (m)	$\delta^{13}C$	$\delta^{18}O$
17	9.15	−0.69	−2.61
18	9.40	−1.03	−3.67
19	10.24	−1.75	−3.83
19C	10.26	−1.66	−3.71
20	10.50	−1.46	−3.47
20A	10.55	−0.87	−4.02
21	10.80	−1.08	−3.58
GQ1	10.81	−1.27	−3.85
GQ2	10.84	−0.91	−3.98
GQ3	10.86	−4.25	−3.46
GQ4	10.87	−2.25	−3.53
GQ5	10.88	−1.32	−3.63
GQ8	10.92	−1.08	−3.79
GQ9	10.93	−12.21	−2.52
K-1	10.86	−3.39	−3.55
K-2	10.87	−1.88	−4.06
K-3	10.88	−1.40	−3.81
K-4	10.90	−2.31	−3.84
K-5	10.92	−1.83	−3.94
K-6	10.93	−2.64	−3.87
K-7	10.94	−3.09	−4.00
K-8	10.95	−1.83	−4.16
22A	11.45	−2.12	−4.48
23	11.57	−1.92	−4.89
24	11.65	−2.11	−4.46
25	12.70	−2.18	−3.96
26	12.80	−2.55	−3.76
26A	12.85	−2.63	−4.50
27	13.45	−1.82	−4.86
28	13.66	−2.24	−4.69
29	13.82	−1.62	−4.24
30A	14.15	−5.81	−2.84
31	14.80	−3.22	−3.61
32	16.25	−2.34	−4.14
33	16.80	−2.35	−3.69
34	17.45	−4.24	−3.40
35	18.20	−1.79	−3.14
36	18.68	−0.75	−2.26
37	19.31	0.61	−1.47
30[a]		2.75	0.06
34[a]		2.24	−0.32

[a] Second sample collection, see Fig. 10.

tion. This biozonation was correlated with planktic foraminiferal datums based on the Flaxbourne River section which is the most complete K/T section known from New Zealand (Strong et al., 1987; Strong, 1994). Recent work on this section shows that the basal Paleocene radiolarian Zone RP1 can be correlated with the interval corresponding to foraminiferal Zones Pla to Plc(1) of Keller (1993) as shown in Fig. 4. The first appearance of the RP1 index species *Amphisphaera aotea* coincides with the first appearance of tiny Paleocene *Eoglobigerina* spp. (including *E. simplicissima*) directly above an iridium-rich boundary clay and 7 cm below the first appearance of *P. eugubina*. In a total of five sections examined for Radiolaria in New Zealand, the first appearance of the RP1 Zone index *A. aotea* is marked by a switch from nassellarian to spumellarian dominance, a significant increase in the diatom/radiolarian ratio and in whole rock silica content (Hollis et al., 1995). At the Flaxbourne River section, the base of the succeeding Zone RP2 is defined by the first appearance of *Amphisphaera kina* which coincides with the first appearance of *Morozovella inconstans* at the base of Zone Plc(2) of Keller (1993). Fig. 4 shows the planktic foraminiferal and radiolarian calibration for the K/T boundary transition based on the Flaxbourne River section along with the stratigraphic positions of zones identified in the Guayaquil Via Perimetral section of Ecuador (this study). Note that many of the radiolarian faunal changes associated with the K/T boundary in Marlborough coincide with a local radiolarian extinction event in lower foraminiferal Zone Plc in Ecuador, about 300 kyr after the K/T event.

4.1. Planktic foraminifera

Planktic foraminifera identified in the Via Perimetral section are shown in Fig. 5. Foraminifera are generally more common in Maastrichtian samples than in the early Danian and relative species abundances and preservation decrease upsection with the top 3 m being nearly barren. Maastrichtian assemblages identified between samples 17 and 21 contain only fifteen species, an unusually low species richness for an equatorial location which normally has between 50 and 60 species. This low species richness is comparable to high-latitude assemblages (e.g., ODP Site 738, Nye Klov, Koshak, Fig. 1; Keller, 1993; Keller et al., 1993b; Pardo et al., 1996) as also suggested by the very rare and sporadic occurrence of globotruncanids and other tropical species

Table 3
Whole rock mineralogical analysis (percent) across the K/T transition at the Via Perimetral, Guayaquil, section of Ecuador

Sample No.	Depth (m)	Phyllos.	Quartz	Fsp-55K	Plagio	Calcite	Gypsum	Other
17	9.15	23.30	25.63		0.96	17.36		32.75
17A	9.20	9.80	31.91			2.69		55.6
18	9.40	18.90	26.42			19.68		35.01
18A	9.38		9.73			2.84		87.43
18B	9.60	8.29	27.25			28.47		35.99
18C	9.80	7.29	8.32			84.39		
18D	9.82	6.08	4.47			48.30		41.15
19	10.24	10.72	14.50			4.03		70.75
19A	10.18	9.91	41.38			17.61		31.10
19B	10.20	9.69	12.26			65.89		12.15
19C	10.26	12.61	13.66			45.01		28.73
20	10.50	22.28	16.88			35.33		25.51
20A	10.55	9.65	28.11			41.28		20.96
21	10.80	14.78	15.80			19.26		50.15
21A	10.82	13.74	19.84			18.61		47.80
22	11.42	26.68	18.69			7.65		46.98
22A	11.45	10.95	42.91			10.99		35.15
23	11.57	14.86	28.64			31.36		24.14
23A	11.58		16.96			4.63		78.42
24	11.65	18.57	27.39		1.30	22.51		30.24
25	12.70	16.79	22.99			28.49		31.74
25A	12.75	7.93	38.43			23.69		29.95
26	12.80	20.20	22.72			28.68		28.40
26A	12.85	8.85	43.00			16.78		31.37
27	13.45	8.44	48.02	0.63				42.91
27A	13.50		41.13			3.81		55.06
28	13.66	14.73	48.64	0.63	0.53	4.85		30.63
28A	13.69	9.45	38.83			26.21		25.51
29	13.82	20.30	33.55	1.11	1.10			43.94
29A	13.84	8.98	44.10			19.32		27.60
30	14.14	28.82	11.90	1.20	0.82	24.04		33.21
30A	14.15	17.57	41.51					40.91
31	14.80	21.46	36.07		0.86	3.03		38.59
32	16.25	17.55	42.98			5.93		33.54
33	16.80	9.24	48.74					42.02
34	17.45	19.38	22.41	1.03	1.25			55.93
GQ1	10.81	13.56	27.75			41.84		16.85
GQ2A	10.84	13.77	28.77			39.71		17.76
GQ2B	10.85	12.48	31.10			38.04		18.38
GQ3	10.86	11.44	10.62		2.41	14.52		61.01
GQ5	10.88	15.66	16.93		3.11	19.02		45.28
GQ6	10.89	13.40	2.00		9.30		8.26	67.00
GQ7	10.90	19.76	7.33		3.47	16.86		55.59
GQ8	10.92	15.95	20.36		1.90	19.39		42.40
GQ9A	10.93	14.01	27.96			32.02		26.02
GQ9B	10.94	15.11	29.66			31.38		23.85
GQ10	10.95	15.20	21.09			45.75		17.96
GQ11A	10.96	10.93	31.36			36.91		30.81
GQ11B	10.97	11.30	32.41	1.22		27.63		27.44

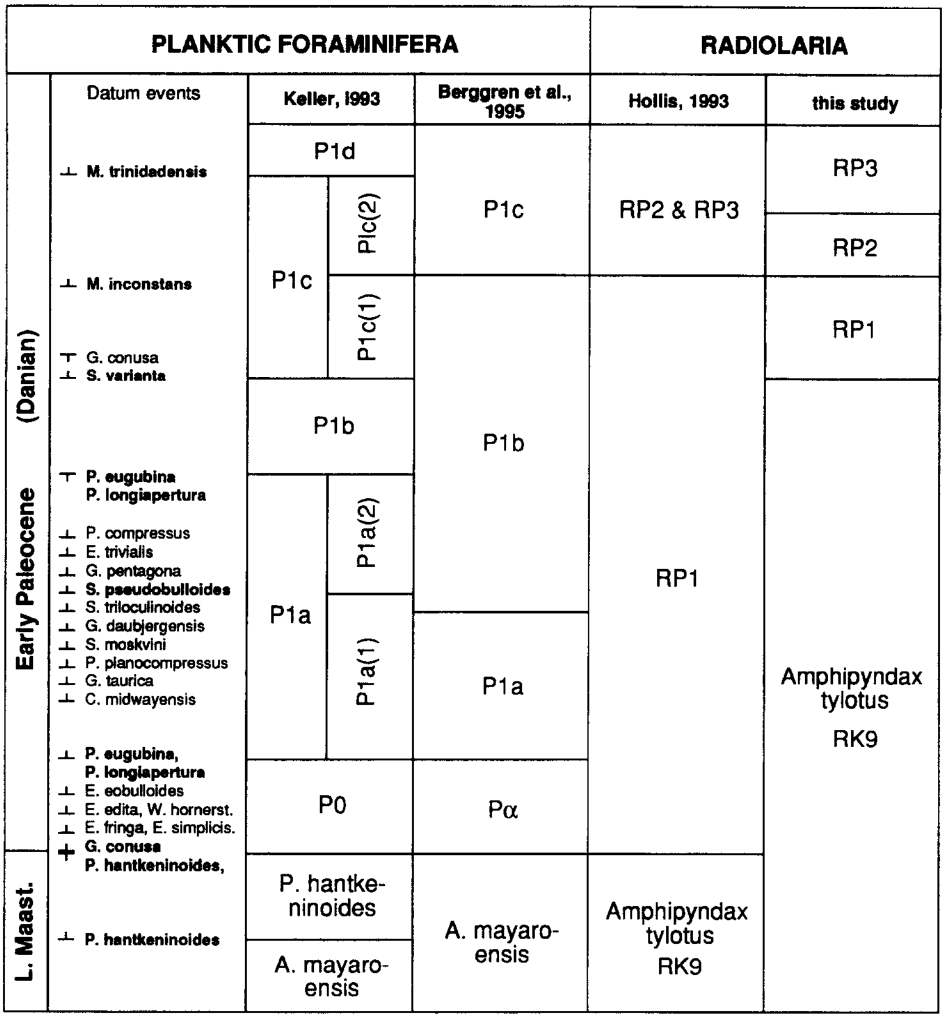
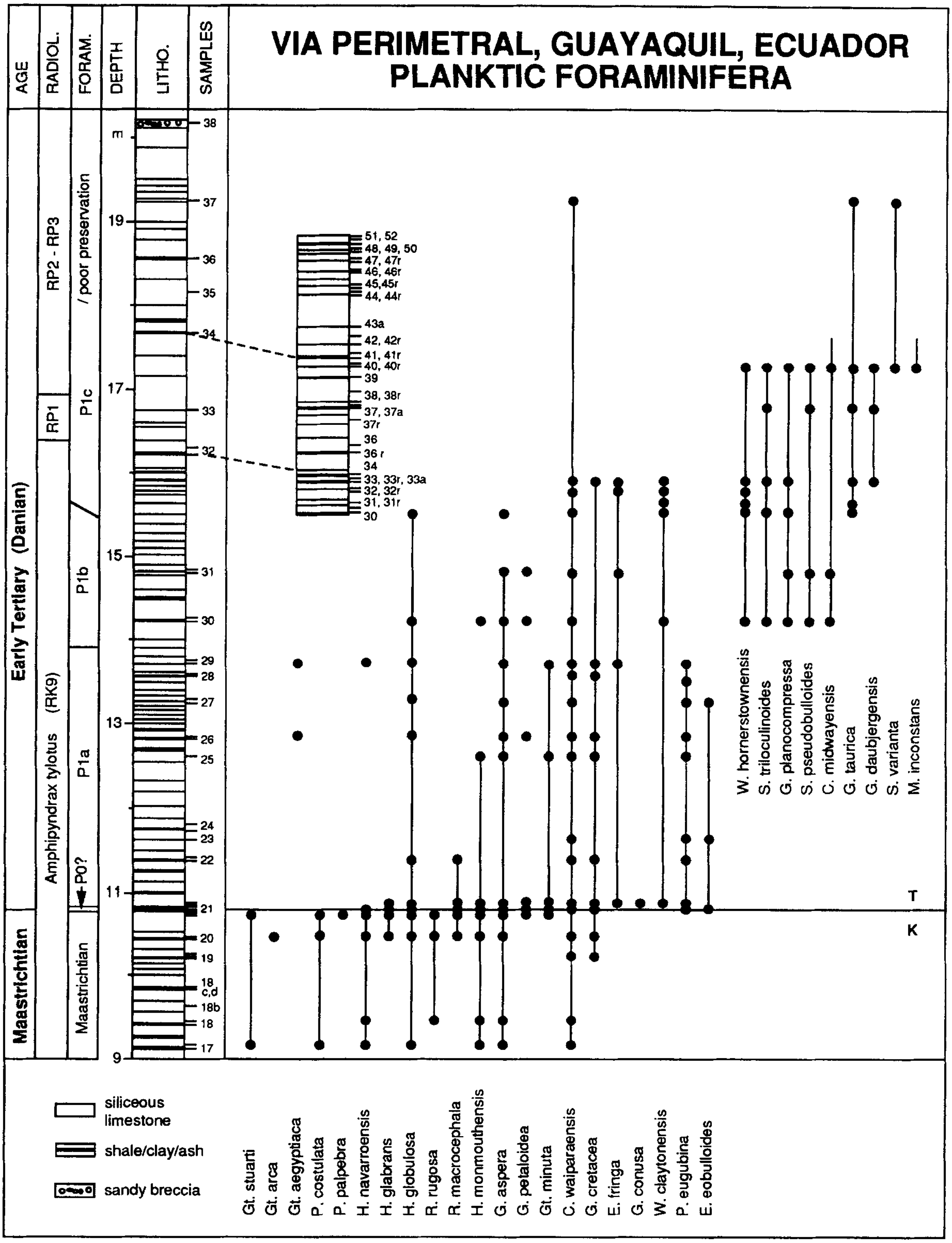


Fig. 4. Foraminiferal and radiolarian biozonations of Keller (1993) and Hollis (1993) applied to the Via Perimetral section of Guayaquil, Ecuador, K/T transition. Foraminiferal zonal marker species are identified in bold type. The biozonation of Berggren et al. (1995) is shown for comparison. Note that in the Via Perimetral section the first Tertiary radiolarian Zone RP1 is not recognized until foraminiferal Zone Plc. Cretaceous radiolarian assemblages characterize the earliest Danian. This difference between New Zealand and Ecuador may be due to a delay imposed by oceanographic conditions in the eastern South Pacific Ocean.

(Figs. 5 and 6). (Note that the two occurrences of *Globotruncana aegyptiaca* in Danian samples may be reworked.) Most of the Maastrichtian assemblage consists of small hedbergellids, heterohelicids, globogerinellids, guembelitrids, globotruncanellids and a few rugoglobigerinids as shown in Fig. 7a for sample 20. This assemblage, together with the common presence of *Chiloguembelina waiparaensis*, is typical of high latitudes (Keller, 1993; Keller and MacLeod, 1995). It suggests an unusually cool-water equatorial environment off Ecuador at K/T boundary time, probably influenced by a proto-Humboldt current (Fig. 1) and upwelling similar to the present.

A major faunal change occurs at sample 21 (Fig. 5), an interval marked by two thin clay layers separated by a thin limestone and sandwiched between siliceous limestone layers (Figs. 3b and 6). About half of the Maastrichtian foraminiferal assemblages disappeared during this interval (e.g., globotruncanids, rugoglobigerinids, pseudotextularids and some heterohelicids), whereas cosmopolitan


VIA PERIMETRAL, GUAYAQUIL, ECUADOR
PLANKTIC FORAMINIFERA
AGE
RADIOL.
FORAM.
DEPTH
LITHO.
SAMPLES
Early Tertiary (Danian)
Maastrichtian
RP2 - RP3
RP1
Amphipyndrax tylotus (RK9)
/ poor preservation
P1c
P1b
P1a
P0?
Maastrichtian
m
19
17
15
13
11
9
38
37
36
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18 c,d
18b
18
17
51, 52
48, 49, 50
47, 47r
46, 46r
45,45r
44, 44r
43a
42, 42r
41, 41r
40, 40r
39
38, 38r
37, 37a
37r
36
36 r
34
33, 33r, 33a
32, 32r
31, 31r
30
T
K
W. hornerstownensis
S. triloculinoides
G. planocompressa
S. pseudobulloides
C. midwayensis
G. taurica
G. daubjergensis
S. varianta
M. inconstans
siliceous limestone
shale/clay/ash
sandy breccia
Gt. stuarti
Gt. arca
Gt. aegyptiaca
P. costulata
P. palpebra
H. navarroensis
H. glabrans
H. globulosa
R. rugosa
R. macrocephala
H. monmouthensis
G. aspera
G. petaloidea
Gt. minuta
C. waiparaensis
G. cretacea
E. fringa
G. conusa
W. claytonensis
P. eugubina
E. eobulloides

species seem to have survived (Fig. 5). Two 20 cm transects 50 m apart were sampled at cm intervals across this faunal transition as shown in Fig. 6. In both transects, the foraminiferal turnover is the same, although several samples are barren. Beginning from 5 cm below the clay layer (sample GQ-2) and continuing upward through the clay couplet (Fig. 6), the faunal assemblage consists of morphologically significantly smaller hedbergellids, globigerinellids and heterohelicids than 50 cm below the clay couplet (compare Fig. 7a and b). This type of dwarfing is commonly observed beginning just below the K/T boundary in high- and low-latitude sections (e.g., ODP Site 738, Brazos River, Texas, Nye Klov, Denmark and Koshak, Kazakhstan; Keller, 1989, 1993; Keller et al., 1993b; MacLeod, 1993).

The first Tertiary species, including *Parvularugoglobigerina eugubina* and *Eoglobigerina eobulloides* are present in the marly limestone 1 cm above the clay layer couplet and *E. fringa* and *Woodringina claytonensis* first appear in the limestone 3 cm above (Fig. 6). These tiny globigerine morphologies are readily seen in thin sections (Fig. 7c). Based on planktic foraminifera, the K/T boundary transition, or Zone P0, thus encompasses the clay layer couplet. However, because no Danian species are present within the clay layer couplet, this interval is identified as P0? Zone Pla, which is defined by the range of *P. eugubina*, begins just above the clay layer couplet. Fifty cm above the base of Pla, planktic foraminifera are rare, except for biserial, low-oxygen-tolerant taxa (e.g., *C. waiparaensis*) and guembelitrids, whereas Radiolaria are increasingly abundant (Fig. 7d, sample 23). This may indicate cooler temperatures, intensified upwelling (radiolarians) and a well-developed oxygen minimum zone.

Zone P1a spans nearly 3 m and indicates comparable sediment accumulation rates to El Kef (Tunisia), Brazos River (Texas) and El Mimbral (Mexico). In addition to generally common *C. waiparaensis* and *Guembelitria cretacea*, various other Cretaceous survivor species are present (Fig. 5) along with new Tertiary species. This is a typical, though low diversity Zone P1a assemblage. Other characteristic Zone P1a taxa (e.g., *Woodringina hornerstownensis*, *Subbotina triloculinoides*, *Globanomalina planocompressa*, *G. taurica*, *S. pseudobulloides*, *Chiloguembelina midwayensis* and *Globoconusa daubjergensis*, Figs. 4 and 5) appear upsection in Zone P1b–c in the Via Perimetral section. Their absence in Zone P1a may be due to poor preservation.

The first typical Zone P1c assemblage is present in sample 32 of the original section and in samples 33 and 34 of the second sample collection (see insert in Fig. 5). The Zone P1b/P1c boundary is tentatively placed here because *Subbotina varianta*, which marks the base of Zone P1c, is not present until higher upsection. This is suggested by the co-appearance of this species with *M. inconstans* which marks the P1c(1)/P1c(2) boundary (Fig. 4). Most samples in the top 3 m of the section are barren.

4.2. *Radiolaria*

Radiolaria were studied by two groups independently (C. Hollis and M. Ordóñez) and both came up with equivalent faunal successions. Radiolaria are common although generally not well preserved. The best preservation is found in shale samples near the radiolarian K/T boundary and in siliceous limestones of the second sample collection (samples 31r–45r, see insert in Fig. 8). The harder lithologies usually yielded richer and better preserved radiolarian faunas. However, there are no obvious differences between adjacent soft and hard layers (mudstone and siliceous mudstone/chert) in overall composition of the faunas. Sponge spicules are abundant throughout the section and are usually slightly more abundant than radiolarians. Elongate megaloscleres are usually more common than globular microscleres. Abundance of the latter relative to the less robust megaloscleres appears to increase as preservation decreases. Diatoms are rare and restricted to samples above 32, including the interval between 30r and 50r. Note that in the discussion on population trends, Hollis' data (Table 1) are utilized. Common radiolarian taxa are illustrated in Plates I–III.

Fig. 5. Range chart of planktic foraminifera in the Via Perimetral section, Guayaquil, Ecuador. Note that because of poor sample control and poor preservation, the Zone Plb/Plc interval was only tentatively identified. Insert of the stratigraphic interval with samples 30 to 52 is at the same meter scale and represents a second sample collection at more closely spaced intervals.

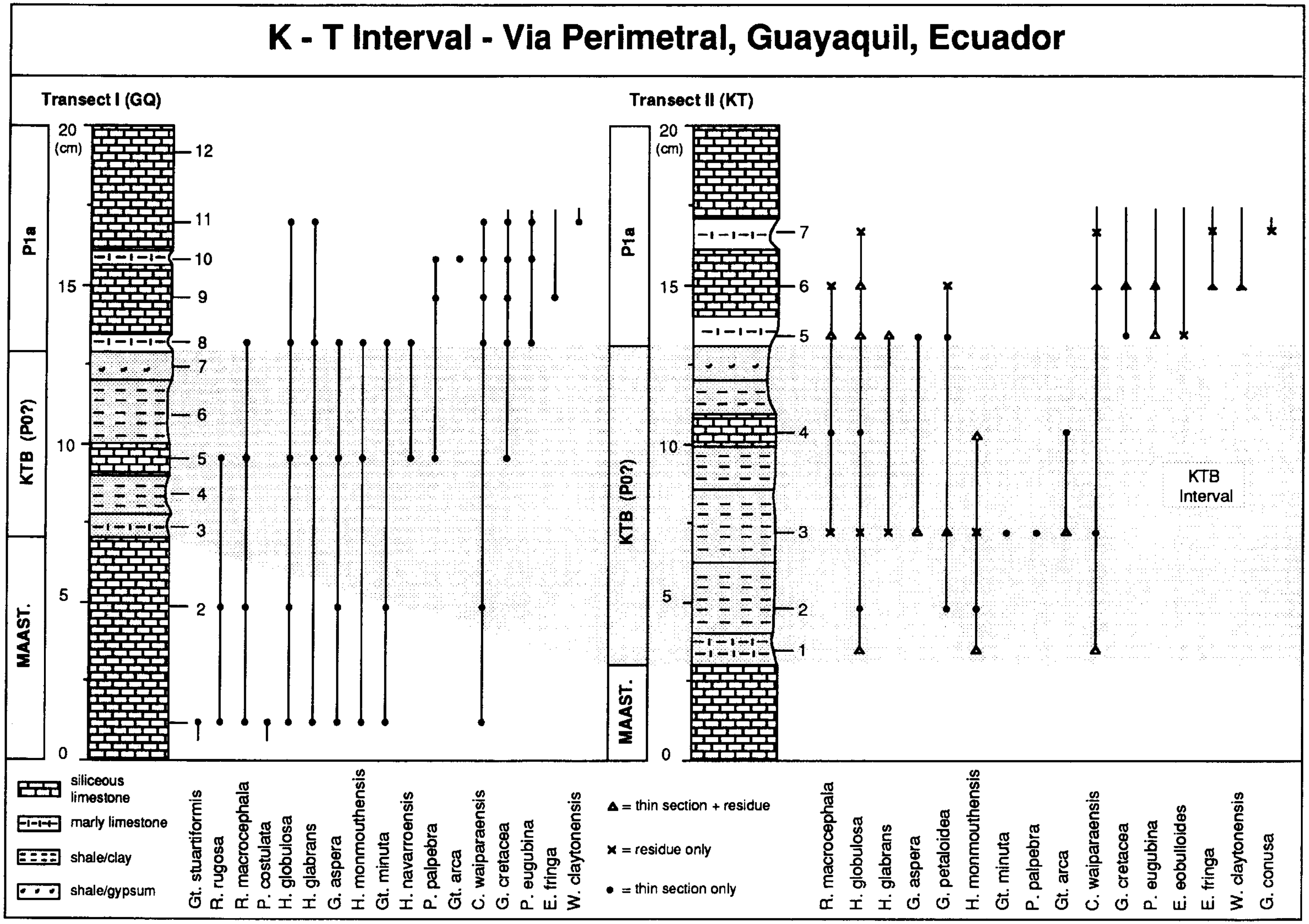


Fig. 6. Lithologic variations and planktic foraminiferal ranges across of the K/T boundary (*KTB*) transition in two transects 50 m apart in the Via Perimetral section, Guayaquil, Ecuador. The shaded interval marks the clay couplet that represents the foraminiferal K/T boundary. Note that the first Tertiary planktic foraminifera, including *P. eugubina*, appear in the marly limestone layer above this clay couplet.

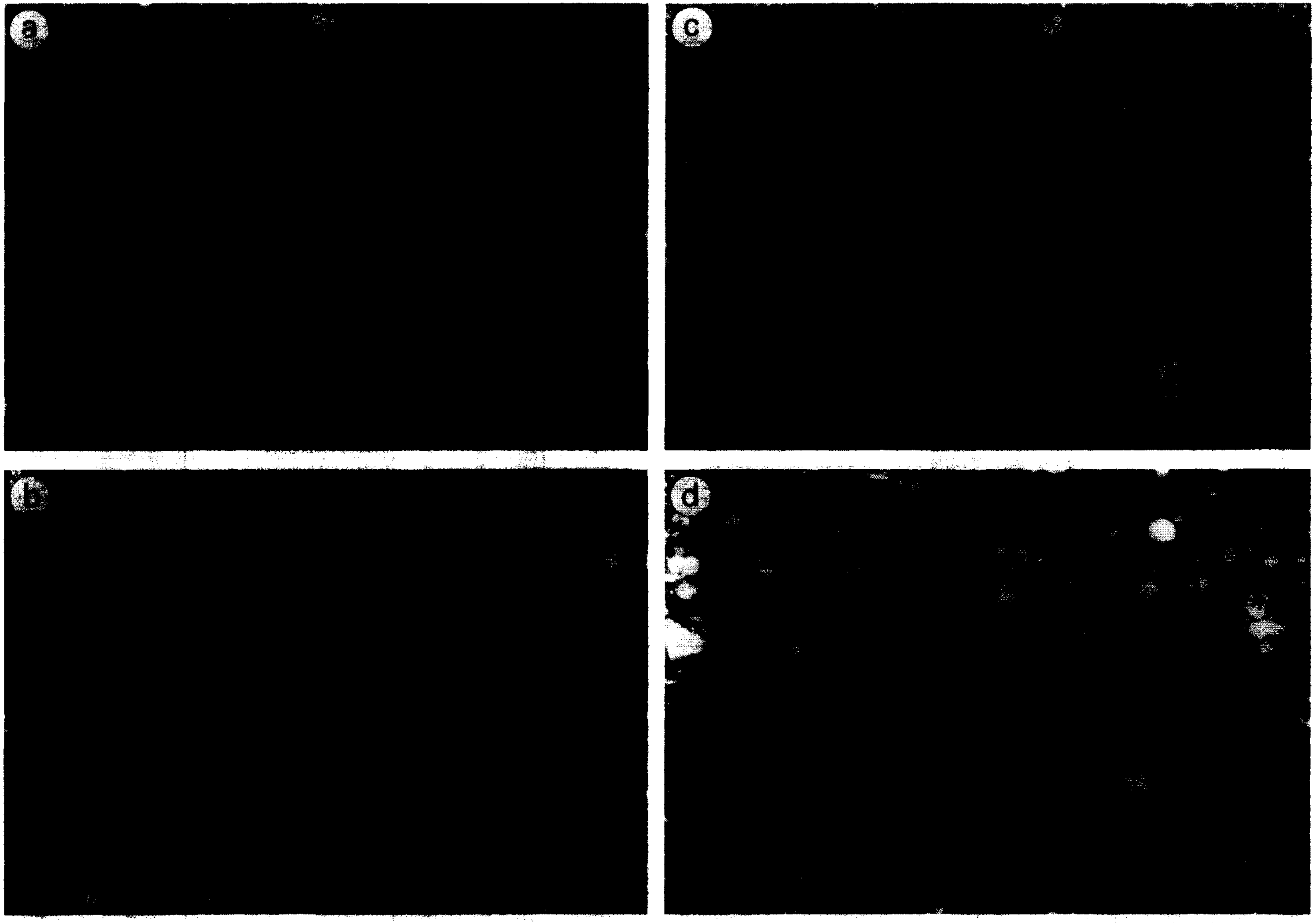


Fig. 7. (a) Thin section photo of a typical sample of the limestone 25–30 cm below the K/T boundary clay (sample 20 of Fig. 5). Note that planktic foraminifera are common, but only very small and mostly cosmopolitan species (hedbergellids, globigerinellids, globotruncanellids, heterohelicids, guembelitrids and few ruglobigerinids) are present despite the equatorial location of this section. Typical low-latitudes species, such as globotruncanids are nearly absent. Species richness is also unusually low (15 species). All of these characteristics are typical of high-latitude assemblages and suggest unusually cool temperatures off Ecuador during latest Maastrichtian time. (b) Thin section photo of planktic foraminifera in a limestone sample 5 cm below the K/T boundary clay couplet (sample 2 of Transect I in Fig. 6). Note that species are significantly smaller and dwarfed in this interval. Hedbergellids, globigerinellids, guembelitrids and heterohelicids (primarily *Chiloguembelina waiparaensis*) dominate. Dwarfing of the planktic foraminiferal fauna in this interval indicates stressed conditions prior to the K/T boundary event. (c) Thin section photo of the shale layer containing the first Tertiary planktic foraminifera, including *Parvularugoglobigerina eugubina* (sample 8 of Transect I in Fig. 6) in the Via Perimetral section, Guayaquil, Ecuador. Note that small Cretaceous taxa are still present along with rare Tertiary species. (d) Thin section photo of a typical siliceous limestone layer 80 cm above the K/T boundary (sample 23 in Fig. 5). Note the high radiolarian abundance. Tiny biserial (*C. waiparaensis*) and triserial (*G. cretacea*) taxa are common in this interval.

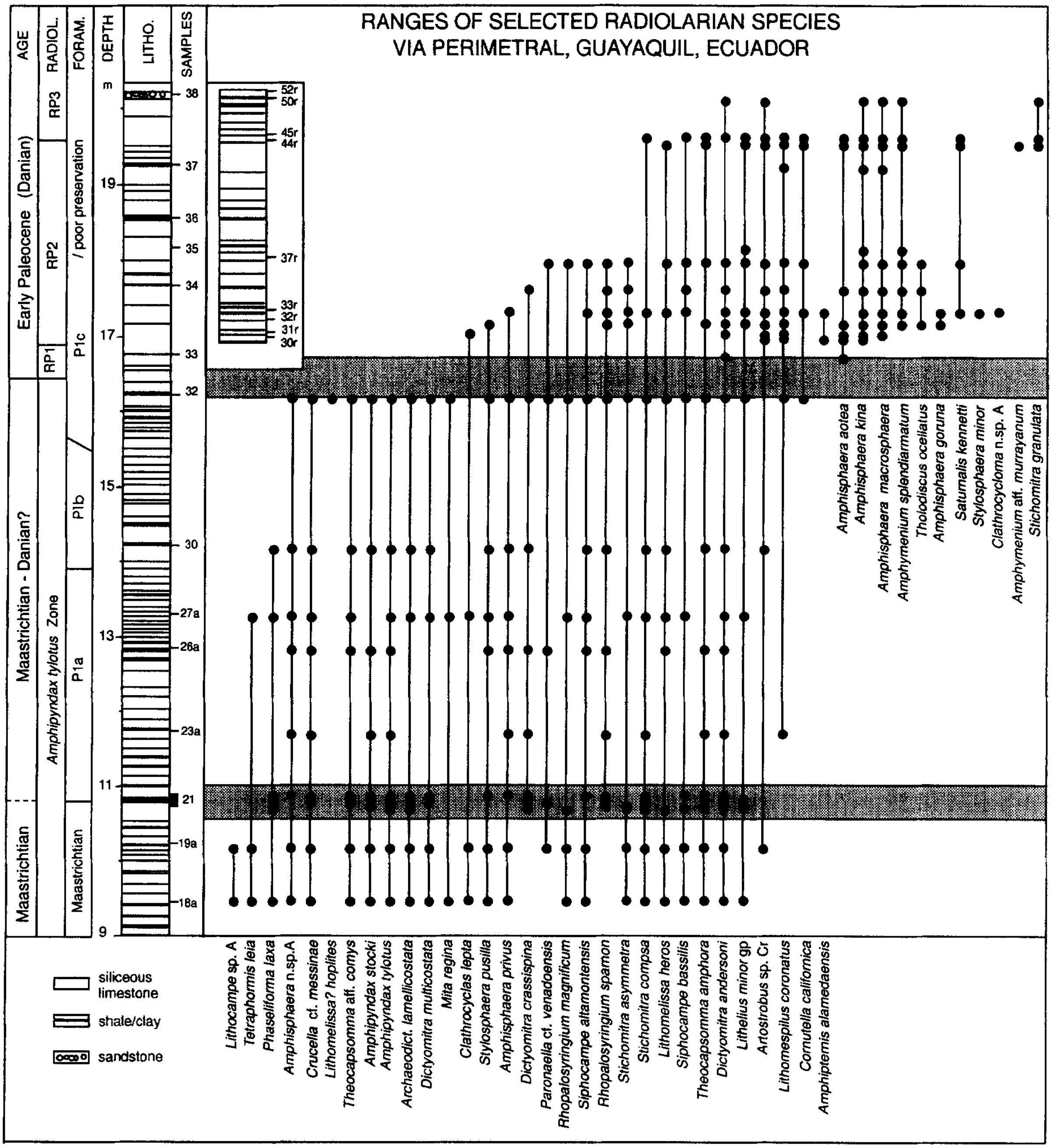


Fig. 8. Ranges of radiolarians within the Via Perimetral section, Guayaquil, Ecuador. Intervals in which the K/T boundary location is inferred based on planktic foraminifera and radiolarians are stippled. Virtually all species cross the foraminiferal K/T boundary. However, the radiolarian K/T boundary marks a major discontinuity in which 9 species last appear and 10 Cretaceous species are restricted to isolated occurrences in the overlying Paleocene.

The interval between samples 18A to 32 (Figs. 8 and 9) is correlated with the late Campanian–Maastrichtian *Amphipyndax tylotus* (RK9) radiolarian Zone (Foreman, 1977; Sanfilippo and Riedel, 1985; Hollis, 1993). Faunas are characterized by abundant nassellarians, particularly *Rhopalosy-*

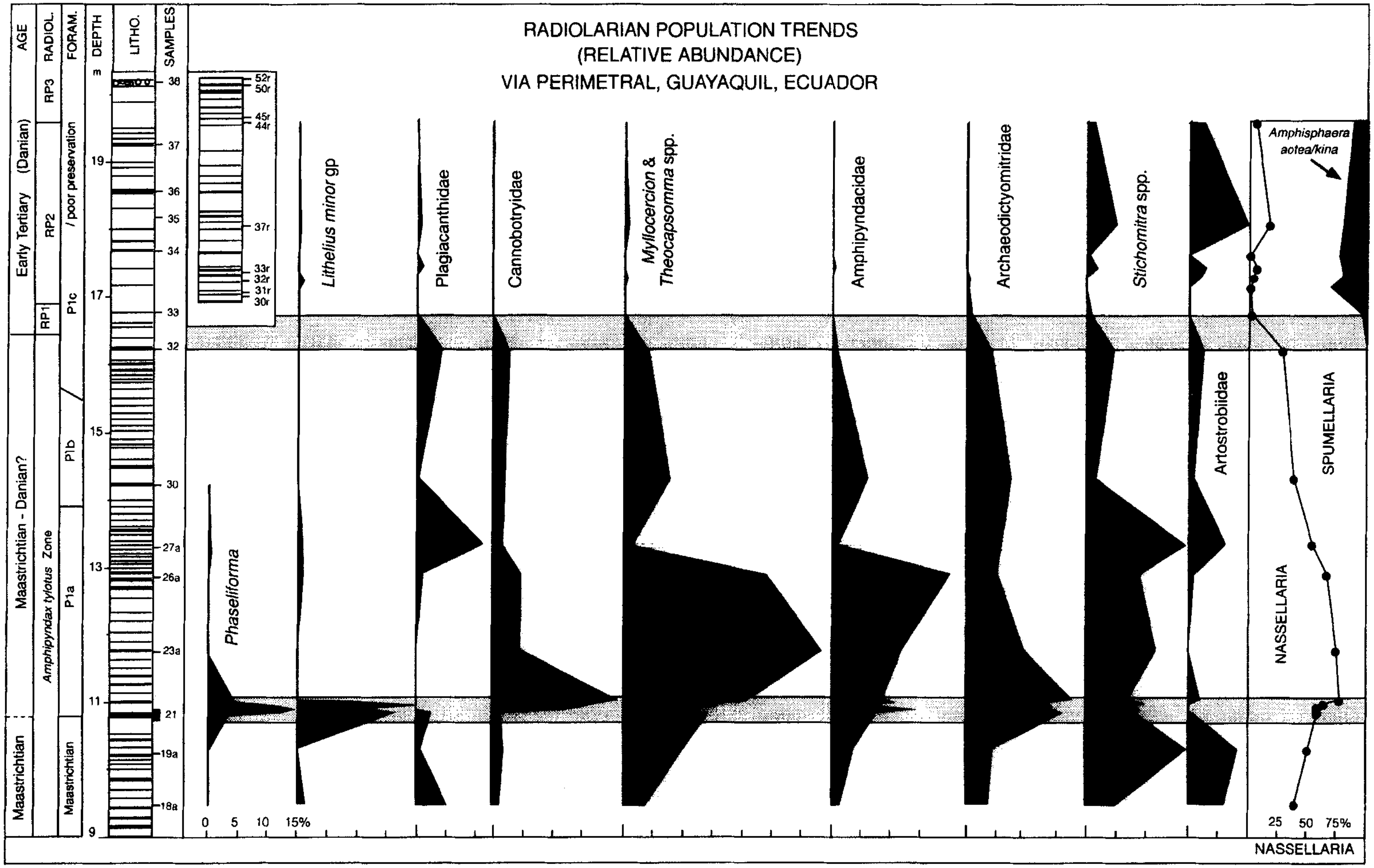
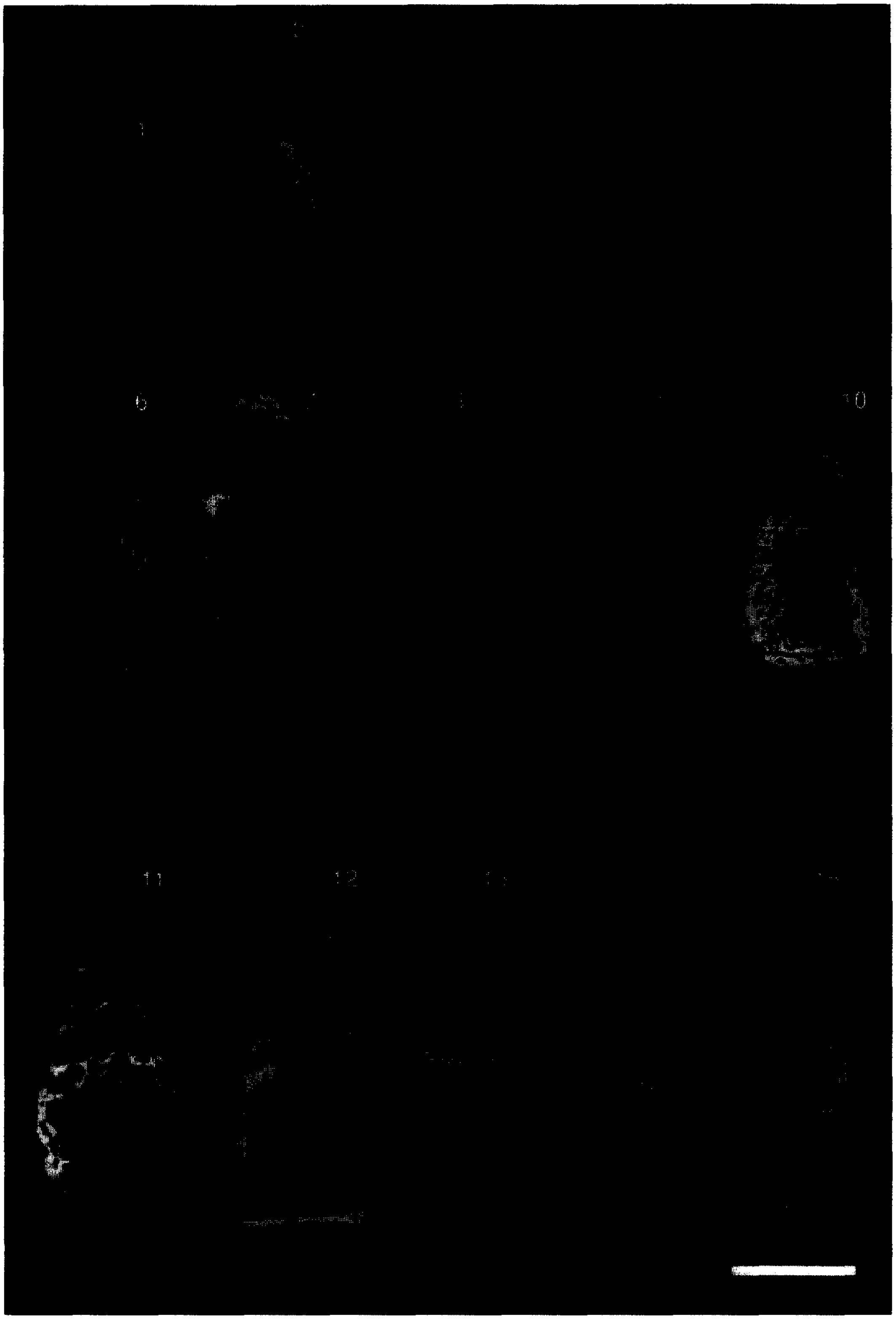


Fig. 9. Radiolarian population trends in the Via Perimetral section, Guayaquil, Ecuador. Only minor changes in relative abundance of some radiolarian taxa occur at the foraminiferal K/T boundary. However, the radiolarian K/T boundary marks a major decline in the dominant taxa of the underlying interval and a rise in undifferentiated spumellarians, the index species *Amphisphaera aotea* and *A. kina*, and the nassellarian genus *Artostrobus*.


1
6
10
11
12

ringium spp., *Theocapsomma* spp., *Lithomelissa heros*, *Amphypyndax tylotus*, *Dictyomitra andersoni*, *Stichomitra compsa* and *S. asymmetra*. Common spumellarians include *Amphisphaera* n.sp., *A. privus*, *Phaseliforma laxa* and *Lithelius minor*. A major faunal discontinuity occurs between samples 32 and 33 (Figs. 8 and 9). Without the contrary evidence from foraminifera, radiolarian evidence would indicate that this is the most obvious location for the K/T boundary. At least nine species last appear in sample 32 and a further ten species have only isolated occurrences in one or two overlying samples. Although such a discontinuity is not evident in the Marlborough New Zealand section, an accompanying switch from nassellarian to spumellarian dominance and the first appearance of the earliest Tertiary index taxon in sample 33 are the two primary features of the boundary in this section (Hollis, 1993). Faunal discontinuities have been noted across less well documented K/T boundaries in California (Foreman, 1968) and the south Atlantic Ocean (DSDP Site 327A).

Sample 33 is correlated with the *Amphisphaera aotea* (RP1) Zone based on the presence of the index species. The overlying 2–3 m (samples 34–40, and 30r–37r) is correlated with the succeeding *A. kina* (RP2) Zone based on the presence of the index species and other taxa which first appear in RP2 in New Zealand (e.g., *A. goruna*, *A. macrosphaera*, *Saturnalis kennetti*, *Amphymenium spendiarmatum* and *Clathrocyclas* sp., Hollis, 1993). Faunas are dominated by *A. kina*, but with a moderately diverse spumellarian assemblage and significant numbers of nassellarians (4–16%, notably *Artostrobus* sp.). The uppermost part of the second sample collection (44r–52r) is correlated with the *Stichomitra granulata* (RP3) Zone based on the presence of rare specimens of the index species. In other respects assemblages of this interval are similar to the RP2 interval. The RP2/PR3 boundary may be diachronous as it occurs within the Plc(2)–Pld interval at Flaxbourne River, but within Plc(1) at ODP Site 752B (Hollis, in prep.). Alternatively, the foraminiferal index *Morozovella inconstans* which marks the Plc(1)/Plc(2) boundary may be diachronous.

5. Discrepancy in placement of K/T boundary

Both Radiolaria and planktic foraminifera show relatively straight-forward trans-K/T faunal sequences that can be correlated with sections in New Zealand and globally. Nevertheless, the placement of the K/T boundary based on these two faunal groups are 6 m apart in the Guayaquil Via Perimetral section. Possible reasons for this discrepancy include: (A) criteria used for defining the K/T boundary in Ecuador differ from those adopted in the El Kef stratotype; (B) misidentification of small foraminiferal species in the poorly preserved faunas; (C) current calibration between Radiolaria and foraminifera based on only one region (Marlborough, New Zealand), may not be representative globally; (D) different oceanographic conditions between Ecuador and New Zealand. Each of these possible explanations are examined below.

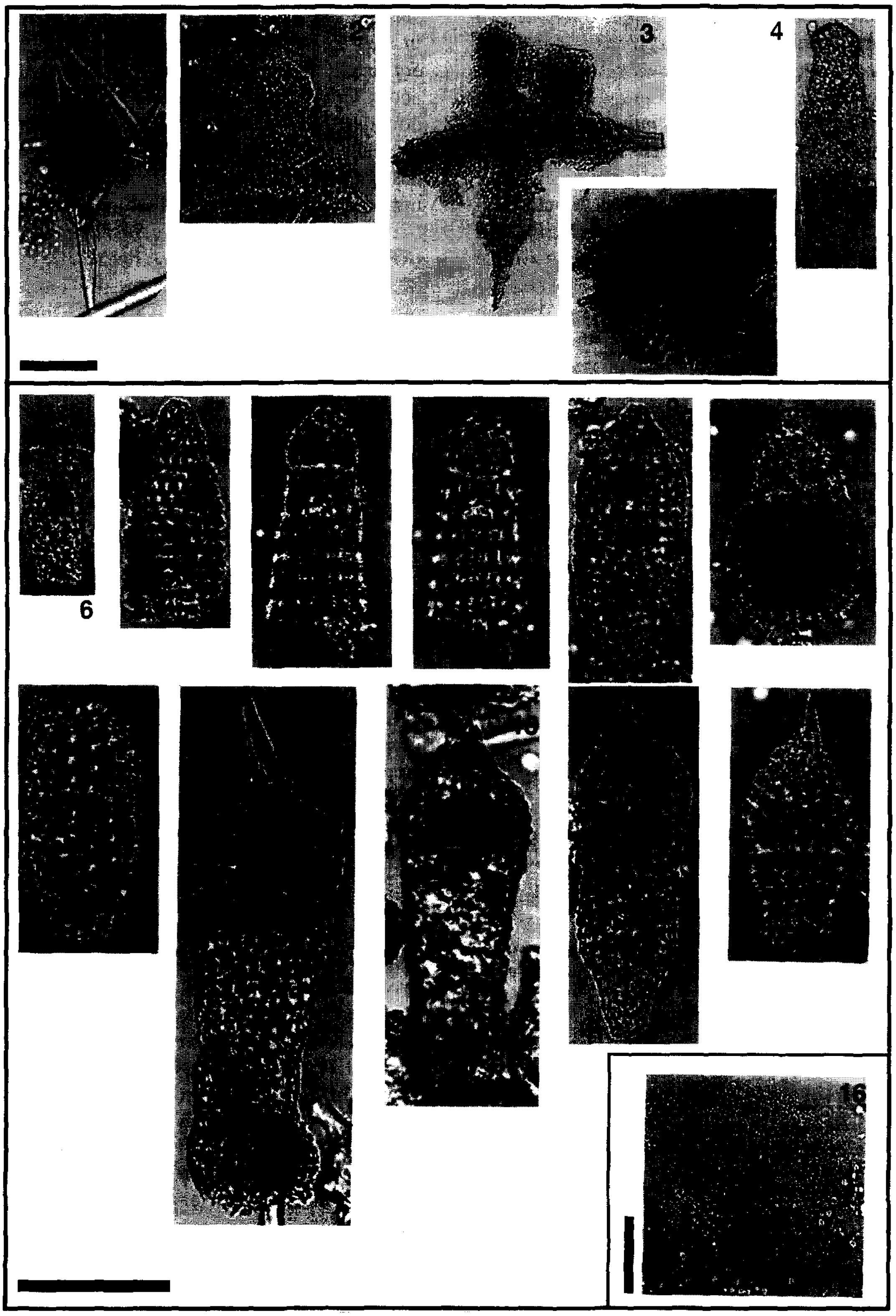
(A) The K/T boundary is globally identified based on a set of criteria observed at the stratotype section at El Kef, Tunisia: (1) A lithological change from marl to clay marks the K/T boundary with a 2–4 mm thick oxidized red layer at the base of the clay. (2) Peak iridium values coincide with the base of the clay layer and peak concentrations of Ni-rich spinels are present in the red layer. (3) A negative $\delta^{13}C$ shift of nearly 3‰ in fine fraction carbonate occurs at the base of the clay layer. (4) The

---

Plate I

Cretaceous and Cretaceous–Paleocene radiolarians, Via Perimetral section of Guayaquil, Ecuador. Digital images from SEM originals (by MO) rescaled to a single magnification (by CH) as indicated by the 100 micron scale bar.

1. *Lithomespilus coronatus* Squinabol, sample 39, Paleocene.
2. *Amphisphaera* n.sp., sample 30, Paleocene?
3. *Rhopalosyringium sparnon* Foreman, sample 17, Cretaceous.
4. *Rhopalosyringium sparnon* Foreman, sample 13, Cretaceous.
5. *Rhopalosyringium* sp. sample 15, Cretaceous.
6. *Theocapsomma* aff. *comys* Foreman, sample 32, Paleocene?
7. *Theocapsomma* aff. *comys* Foreman, sample 13, Cretaceous.
8. *Amphipyndax stocki* (Campbell and Clark), sample 14, Cretaceous.
9. *Amphipyndax tylotus* Foreman, sample 32, Paleocene?
10. *Amphipyndax tylotus* Foreman, sample 13, Cretaceous.
11. *Dictyomitra crassispina* (Squinabol), sample 32, Paleocene?
12. *Dictyomitra multicostata* Zittel, sample 13, Cretaceous.
13. *Dictyomitra andersoni* (Campbell and Clark), sample 28, Paleocene?
14. *Stichomitra compsa* Foreman, sample 22, Paleocene?
15. *Stichomitra* sp., sample 17, Cretaceous.
16. *Stichomitra asymmetra* Foreman, sample 15, Cretaceous.


2
3
4
6
16

first Tertiary planktic foraminifera appear within a few centimeters of the clay layer. (5) The extinction of all tropical and subtropical Cretaceous planktic foraminifera occurs at or below the iridium anomaly and clay layer (Keller et al., 1996). The K/T section in Guayaquil is unusual in that there is no major lithological change between Tertiary and Paleocene sediments, thus criterion 1 is absent. Although thin clay/shale layers are present at both foraminiferal and radiolarian K/T boundaries, neither is marked by anomalous iridium concentrations or Ni-rich spinels (Rocchia and Robin, written commun., 1995), and thus criterion 2 is also absent (though the interval between samples 32 and 33 has not been sampled in detail). Criterion 3, a 3‰ $\delta^{13}C$ negative shift is present in the foraminiferal K/T boundary clay, but a 2.5‰ $\delta^{13}C$ negative shift is also present 1 m below the radiolarian K/T boundary and is therefore not unique in the Guayaquil section. The K/T boundary in the Guayaquil section is therefore identified primarily based on criterion 4, the microfossils. Although this significantly increases the uncertainty factor, the planktic foraminiferal turnover at the K/T boundary has been shown to be a very reliable marker globally.

It is significant that the presence of a pronounced $\delta^{13}C$ negative shift in surface waters at the foraminiferal K/T boundary in the Guayaquil section supports the placement of this boundary, but is not definitive. This shift is present in all low-latitude K/T boundary sequences, but is generally much reduced or absent in high latitudes (Keller, 1993; Keller et al., 1993b; Barrera and Keller, 1994). Moreover, high-latitude sections show a major $\delta^{13}C$ negative shift near the early Danian Plb/Plc interval (Barrera and Keller, 1994), which may correlate with the second $\delta^{13}C$ shift in the Guayaquil section as discussed below.

(B) Small foraminiferal species are difficult to identify in poorly preserved assemblages such as the Guayaquil section. Nevertheless, morphologies of small Danian species are distinctly different from small Maastrichtian species. Even if we assume that some Danian index species (i.e., *P. eugubina*) may have been misidentified, this still leaves many other Danian species present within the 6 m interval below the radiolarian K/T boundary (Fig. 5). Thus, the discrepancy between the two K/T boundary placements can not be explained solely on the basis of misidentification of some foraminiferal species.

(C) Whether the zonal calibration between Radiolaria and foraminifera based on New Zealand can be applied globally still has to be examined in other sections. An explanation for possible diachroneity between radiolarian turnover in New Zealand and Ecuador requires consideration of oceanographic conditions through the K/T transition in the Paleo-Pacific.

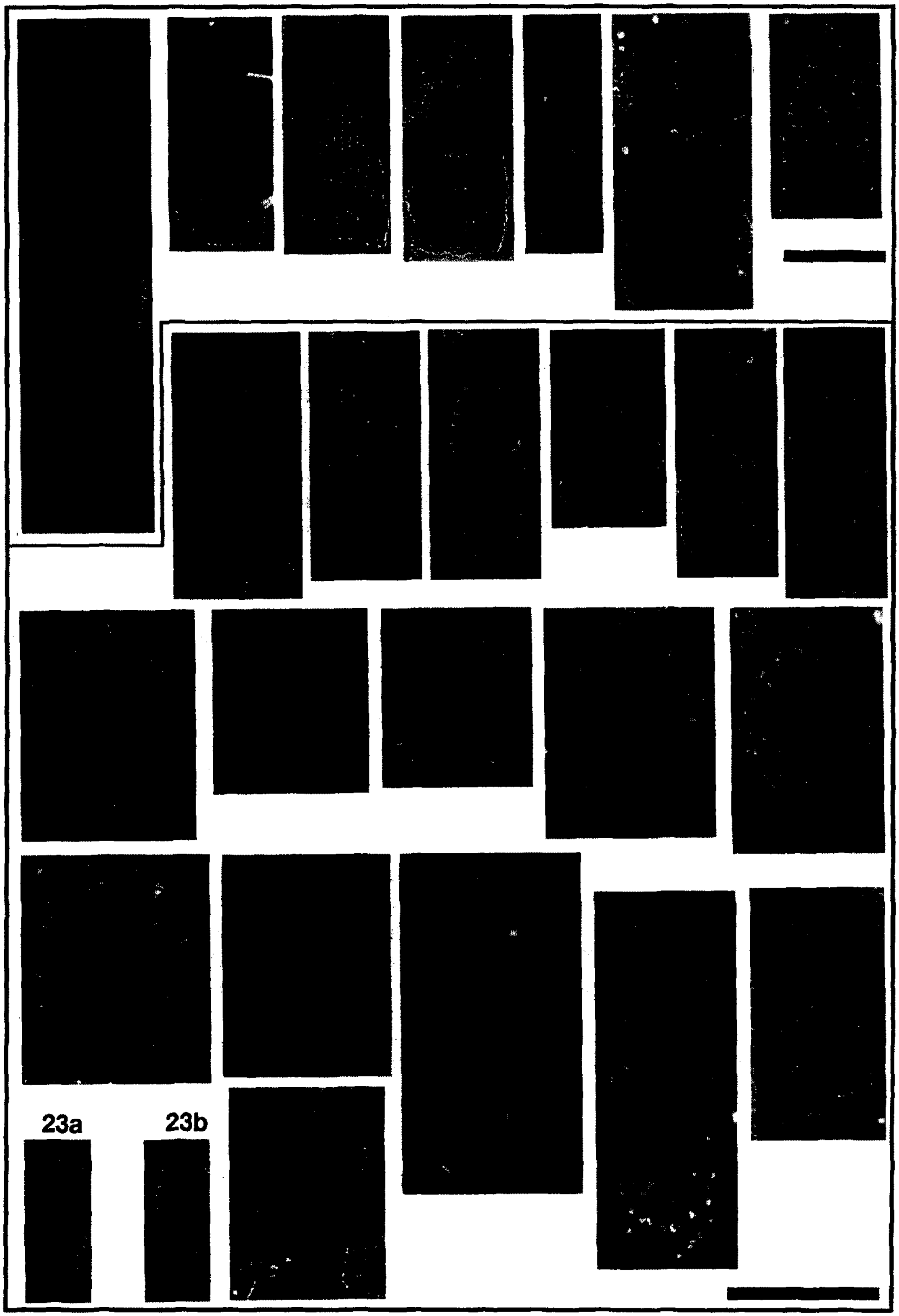
(E) As noted earlier, Maastrichtian planktic foraminiferal assemblages of Ecuador are of very low diversity similar to high latitudes and the K/T faunal turnover is equivalent to that in high-latitude sections (Keller, 1993; Keller et al., 1993b). Radiolaria show no faunal discontinuity at the foraminiferal K/T boundary. However, relative abundance changes suggest a minor perturbation such as a fall in sea level between samples 19 and 11A (Fig. 9). These faunal changes include: (1) A decrease in radiolarian abundance although preservation improves; (2) a 10–20% decrease in the relative abundance of spumellarians; (3) a short-lived disappearance of several spumellarian species, including *Amphisphaera* and *Stylosphaera* spp.; (4) an increase in two spumel-

---

Plate II

Cretaceous and Cretaceous–Paleocene radiolarians, Via Perimetral section of Guayaquil, Ecuador. Digital images from transmitted light microscope. Scale bar represents 100 microns.

1. *Amphisphaera* n.sp., sample 18a, Cretaceous.
2. *Paronaella* cf. *venadoensis* Pessagno, sample 19a, Cretaceous.
3. *Crucella* cf. *messinae* Pessagno, sample 27a, Paleocene?
4. *Spongurus spongiosus* (Lipman), sample 32, Paleocene?
5. *Orbiculiforma* sp., sample 18a, Cretaceous.
6. *Lithomelissa heros* Campbell and Clark, sample 37r, Paleocene.
7. *Siphocampe altamontensis* (Campbell and Clark), sample 27a, Paleocene?
8. *Siphocampe bassilis* (Foreman), sample 45r, Paleocene.
9. *Eastonerius* sp., sample 19a, Cretaceous.
10. *Theocapsomma amphora* (Campbell and Clark), sample 45r, Paleocene.
11. *Theocapsomma* aff. *comys* Foreman, sample 32, Paleocene?
12. *Rhopalosyringium magnificum* Campbell and Clark, sample 37r, Paleocene.
13. *Rhopalosyringium magnificum* Campbell and Clark, sample 32, Paleocene?
14. *Rhopalosyringium sparnon* Foreman, sample 32, Paleocene?
15. *Rhopalosyringium sparnon* Foreman, sample 37r, Paleocene.
16. *Tetraphormis leia* Foreman, sample 30, Cretaceous.


23a
23b

larian groups, *Phaseliforma* sp. and *Lithelius minor* sp., from <2% to a peak of 10%; (5) several nassellarian groups increase in abundance (i.e., cannobotryids,*Theocapsomma* spp., *Amphipyndax tylotus*, *Dictyomitra* spp., *Stichomitra compsa*; (6) other nassellarians decrease (i.e., *Lithomelissa*, *Siphocampe*). All of these changes are relatively short-lived and a return to faunas similar to those found below the foraminiferal K/T boundary occurs over a 2 m interval between samples 11 and 27A (Fig. 9). Sea level changes may explain this trend. For instance, *Amphipyndax* and *Dictyomitra* tend to increase in abundance in shallow neritic to upper bathyal waters (Hollis, 1996), which suggests that faunal changes above sample 19A may have been in response to the latest Maastrichtian sea level fall (Keller et al., 1993b; Pardo et al., 1996; Keller and Stinnesbeck, 1996a). Subsequent saltational transgression across the foraminiferal K/T boundary and through the earliest Danian may explain the progressive return of radiolarian faunas equivalent to those of the late Maastrichtian. If we assume that the foraminiferal K/T boundary is equivalent to this boundary worldwide, then the radiolarian faunas responded primarily to ongoing oceanographic changes and the K/T event had little effect upon them.

A much greater change in radiolarian populations occurs 6 m higher in the section (samples 32–33, Figs. 8 and 9). At this interval there is: (1) a 20–30% increase in spumellarians and corresponding decrease in nassellarians to <5% in all but two of the overlying assemblages; (2) the first appearance of Paleocene index species (samples 33 and 34), including abundant *Amphisphaera kina*; (3) the disappearance of nine Cretaceous species and last consistent occurrence of ten Cretaceous species (Fig. 8). These faunal changes, together with the first occurrence of diatoms in sample 35, are very similar to those observed at the K/T boundary in New Zealand (Hollis, 1993, 1996), where increased actinommids and the appearance of diatoms has been interpreted to imply upwelling (Hollis et al., 1995). There would be little reason to doubt that this was also the location of the K/T boundary in the Guayaquil section, were it not for the evidence from planktic foraminifera that the boundary lies some 6 m lower in the sequence. However, because little is known of radiolarian faunal changes through the K/T transition outside the New Zealand region, it is conceivable that this faunal event occurred some 300 kyr later in Ecuador than a remarkably similar event in New Zealand. The climatic/oceanographic agents that have been inferred to be responsible for enhanced surface productivity in the earliest Paleocene seas of Marlborough may have had similar, but less pronounced effects on seas off Ecuador some 300 kyr later at a time when siliceous productivity peaked in Marlborough. It is notable that the disappearance and sharp decline of many Cretaceous survivor species at this horizon in the Guayaquil section also occur well above the K/T boundary in foraminiferal zones Plb–Plc in the New Zealand sections (Hollis, 1996). To examine the nature of climatic and oceanographic conditions off Ecuador further, we have analyzed sediments for stable isotopes and mineralogical variations.

Plate III

Cretaceous, Cretaceous–Paleocene and Paleocene (15–22, 24) radiolarians, Via Perimetral section of Guayaquil, Ecuador. Digital images from transmitted light microscope. Scale bar represents 100 microns.

1. *Dictyomitra crassispina* (Squinabol), sample 32, Paleocene?
2. *Dictyomitra andersoni* (Campbell and Clark), sample 45r. Paleocene.
3. *Dictyomitra multicostata* Zittel, sample 18a, Cretaceous.
4. *Dictyomitra multicostata* Zittel, sample 18a, Cretaceous.
5. *Mita regina* (Campbell and Clark), sample 32, Paleocene?
6. *Amphipyndax tylotus* Foreman, sample 32, Paleocene?
7. *Stichomitra compsa* Foreman, sample 33r, Paleocene.
8. *Stichomitra livermorensis* (Campbell and Clark), sample 32, Paleocene?
9. *Stichomitra asymmetra* Foreman, sample 18a, Cretaceous.
10. *Stichomitra asymmetra* Foreman, sample 18a, Cretaceous.
11. *Stichomitra asymmetra* Foreman, sample 19a, Cretaceous.
12. *Stichomitra asymmetra* Foreman, sample 32, Paleocene?
13. *Lithomespilus coronatus* Squinabol, sample 34, Paleocene.
14. *Amphisphaera aotea* Hollis, sample 34, Paleocene.
15. *Amphisphaera aotea* Hollis, sample 34, Paleocene.
16. *Amphisphaera kina* Hollis, sample 34, Paleocene.
17. *Amphisphaera kina* Hollis, sample 34, Paleocene.
18. *Amphisphaera kina* Hollis, sample 45r, Paleocene.
19. *Amphisphaera macrosphaera* (Nishimura), sample 34, Paleocene.
20. *Saturnalis kennetti* Dumitrica, sample 44r, Paleocene.
21. *Amphymenium splendiarmatum* Clark and Campbell, sample 34, Paleocene.
22. *Stichomitra granulata* (Petrushevskaya), sample 45r, Paleocene.
23. *Artostrobus* sp. Cr. Petrushevskaya, sample 37r, Paleocene.
24. *Clathrocyclas* n.sp. A. sample 33R, Paleocene.

6. Stable isotopes

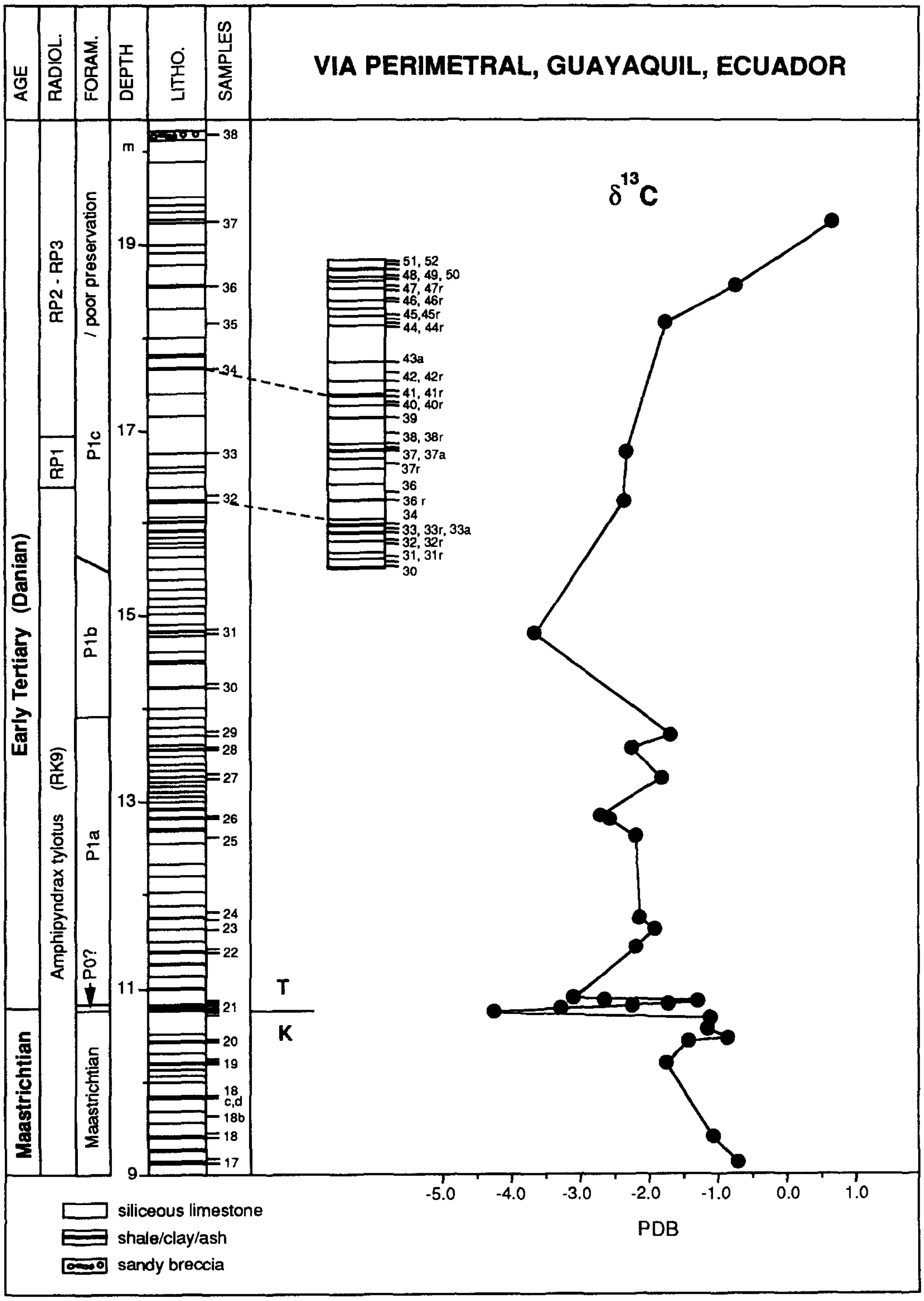
Bulk rock samples were analyzed for all lithologies including siliceous limestones, tuffaceous siltstones, ashes and thin shaly or clayey interlayers. Among these lithologies, shaly and clayey interlayers were generally most carbonate-rich and yielded good $\delta^{13}C$ isotopic data. Insufficient carbonate was available for reliable gas measurements in most samples from other lithologies. The $\delta^{13}C$ curve in Fig. 10 is therefore based primarily on the thin shaly or clayey interlayers of this rhythmically bedded section. Stable isotopes were also measured across the foraminiferal K/T boundary clay couplet (GQ in Table 2, see Fig. 6 for sample location) as shown in Fig. 11 along with mineralogical data. $\delta^{13}C$ and $\delta^{18}O$ data are given in Table 2, though only the $\delta^{13}C$ data will be discussed because diagenetic alteration of biogenic carbonate in these samples altered the original oxygen isotope values. $\delta^{13}C$ values are little affected by calcite replacement because the largest carbon reservoir is in the biogenic carbonate (Scholle and Arthur, 1980).

The Via Perimetral $\delta^{13}C$ record has significant features in common with both low- and high-latitude K/T boundary sequences, including: (1) a 3‰ negative $\delta^{13}C$ shift at the K/T boundary that is characteristic of low latitudes (Zachos and Arthur, 1986; Arthur et al., 1987; Zachos et al., 1989; Keller and Lindinger, 1989; Barrera and Keller, 1994); (2) the presence of a negative $\delta^{13}C$ shift in the Danian foraminiferal Zone P1b which is characteristic of high latitudes, but has not been previously observed in low latitudes (Barrera and Keller, 1994); and (3) a major positive increase in $\delta^{13}C$ values in foraminiferal Zone P1c that is characteristic of both high and low latitudes.

During the latest Maastrichtian, $\delta^{13}C$ values decreased by about 1‰ and increased again 1‰ in the 50 cm below the K/T boundary (Fig. 10). At the base of the foraminiferal K/T boundary clay couplet, $\delta^{13}C$ values drop by 3‰, but return to near pre-shift values by the top of the first clay layer as shown in the expanded interval of Fig. 11. From the thin limestone through the upper clay layer up to the first appearance of Tertiary species, $\delta^{13}C$ values remain relatively high followed by a short-term decrease of 2‰ near the base of Zone Pla (Fig. 11). The 3‰ magnitude of the $\delta^{13}C$ shift at the base of the boundary clay is similar to that observed at El Kef and Brazos River, two of the most complete K/T boundary sequences known today (Keller and Lindinger, 1989; Barrera and Keller, 1990). Unlike in these latter sections, however, $\delta^{13}C$ values recover very quickly in the Guayaquil Via Perimetral section. For instance, at El Kef and Brazos River $\delta^{13}C$ values do not recover until foraminiferal Zone P1c, an estimated 300–500 kyr after the K/T boundary (Keller and Lindinger, 1989). The rapid recovery within the clay layer in the Ecuador section may be due to upwelling and the high nutrient influx from the Antarctic Ocean via a proto-Humboldt current. This is suggested by the fact that Antarctic sections show no $\delta^{13}C$ shift at the K/T boundary (Barrera and Keller, 1994) and cool high-latitude faunal assemblages dominate in the Guayaquil section.

Mean $\delta^{13}C$ values through Zone Pla are relatively high and only about 1‰ lower than in the latest Maastrichtian as compared to 3‰ lower at El Kef. In Zone P1b, sample resolution is low though a negative $\delta^{13}C$ shift of 2‰ is indicated. This $\delta^{13}C$ shift seems to correlate with a major shift observed in Zone Plb in Antarctic Ocean ODP sites 690 and 738 (Barrera and Keller, 1994). Since no Zone Plb $\delta^{13}C$ shift has been observed in other low-latitude sections, this event again links this equatorial location to the southern high latitudes. Barrera and Keller (1994) interpreted this $\delta^{13}C$ shift as the first major decrease in surface productivity in southern high latitudes since the Cretaceous. In the Guayaquil section this $\delta^{13}C$ event occurs about 1 m below the major

Fig. 10. Bulk rock $\delta^{13}C$ isotope record across the K/T boundary and lower Danian in the Via Perimetral section, Guayaquil, Ecuador. The $\delta^{13}C$ record is based on shale and clay interlayers. Siliceous limestones and tuffaceous siltstones and ashes provided unreliable amounts of gas for analysis. Data points in Zone Plc which have less than 5% calcite, are based on very small gas amounts and may be less reliable. Note that the foraminiferal K/T boundary is marked by the 3‰ negative $\delta^{13}C$ excursion that is characteristic of this boundary at low latitudes; recovery appears to have been faster than in other low-latitude sections. A second $\delta^{13}C$ excursion occurs in Zone Plb and is characteristic of southern high latitudes (Barrera and Keller, 1994).


VIA PERIMETRAL, GUAYAQUIL, ECUADOR
AGE
RADIOL.
FORAM.
DEPTH
LITHO.
SAMPLES
Early Tertiary (Danian)
Maastrichtian
RP2 - RP3
RP1
Amphipyndrax tylotus (RK9)
/ poor preservation
P1c
P1b
P1a
P0?
Maastrichtian
m
19
17
15
13
11
9
38
37
36
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18 c,d
18b
18
17
51, 52
48, 49, 50
47, 47r
46, 46r
45,45r
44, 44r
43a
42, 42r
41, 41r
40, 40r
39
38, 38r
37, 37a
37r
36
36 r
34
33, 33r, 33a
32, 32r
31, 31r
30
δ13C
T
K
-5.0
-4.0
-3.0
-2.0
-1.0
0.0
1.0
PDB
siliceous limestone
shale/clay/ash
sandy breccia

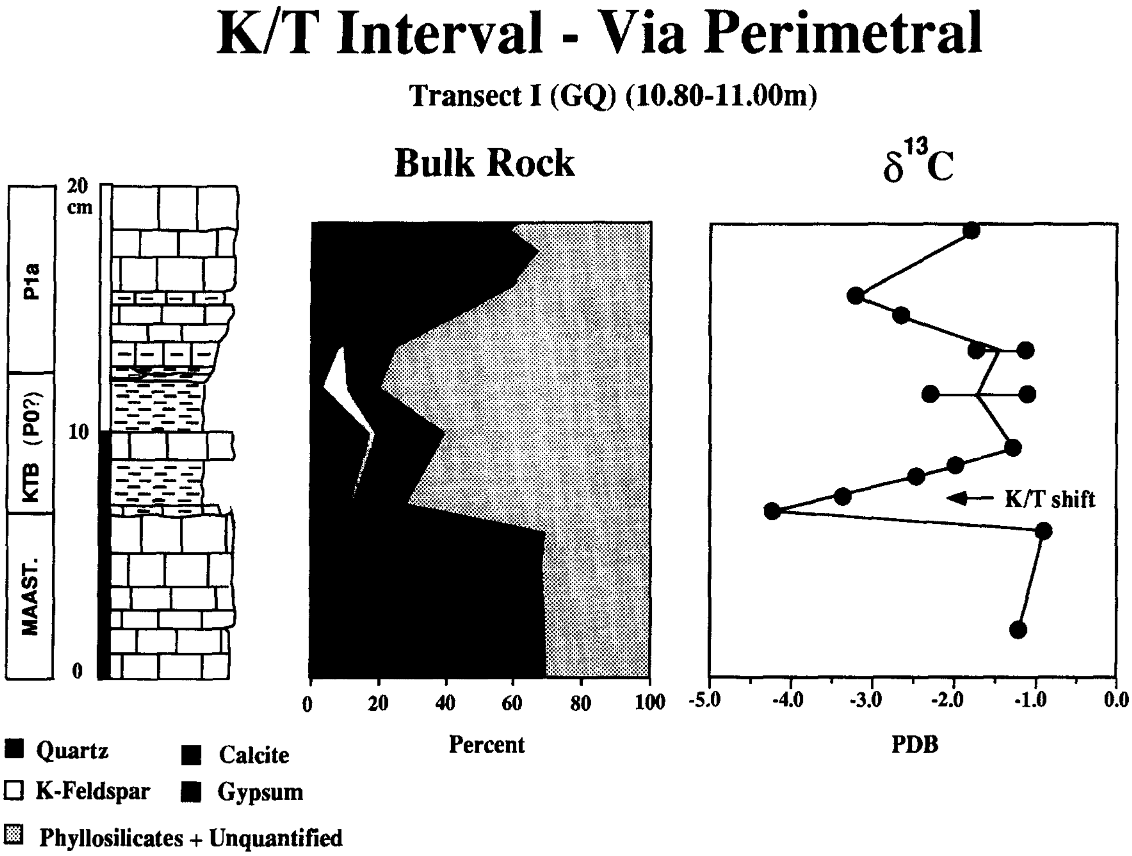


Fig. 11. Details of bulk rock mineralogy and bulk $\delta^{13}C$ values across the K/T boundary clay couplet in the Via Perimetral section, Guayaquil, Ecuador. Note that the 3‰ negative $\delta^{13}C$ excursion occurs at the base of the lower shaly clay layer and that the recovery of $\delta^{13}C$ to pre-K/T levels occurs within this clay layer within a few thousand years. This is a much shorter recovery time than observed at other low-latitude K/T boundary localities where recovery does not occur until Zone Plc, or about 300 kyr after the K/T boundary. A second 2‰ negative $\delta^{13}C$ excursion occurs above the second clay layer near the base of Zone Pla. See text for discussion.

radiolarian faunal turnover and the disappearance of most Cretaceous species.

Very little calcite is present in bulk samples of Zone Plc and as a result $\delta^{13}C$ values may not be reliable. However, values obtained show the characteristic increase in $\delta^{13}C$ that is observed in both low and high latitudes (Fig. 10; Oberhänsli, 1986; Zachos et al., 1989; Keller and Lindinger, 1989; Barrera and Keller, 1994). Danian Zone Plc marks the post-K/T recovery of oceanic $\delta^{13}C$ values to pre-K/T conditions, and hence the return to normal high surface productivity (Zachos and Arthur, 1986; Oberhänsli, 1986; Arthur et al., 1987; Keller and Lindinger, 1989; Barrera and Keller, 1994). Off Ecuador, this return to high surface productivity is marked by increasingly high siliceous productivity probably as a result of climate cooling and increased thermal gradients leading to intensified atmospheric and oceanic circulation and upwelling.

7. Mineralogy

Whole rock analyses show that the dominant sedimentary components are quartz (10–48%), calcite (0–84%) and phyllosilicates (0–29%, Table 3). Unquantified phases probably correspond to phyllosilicates in shales, and quartz in siliceous limestones (the latter is predominantly biogenic silica from Radiolaria and diatoms). A significant amount of (biogenic) quartz is present throughout the section, but generally increases through the Danian from an average of 20% in the late Maastrichtian (Fig. 12)

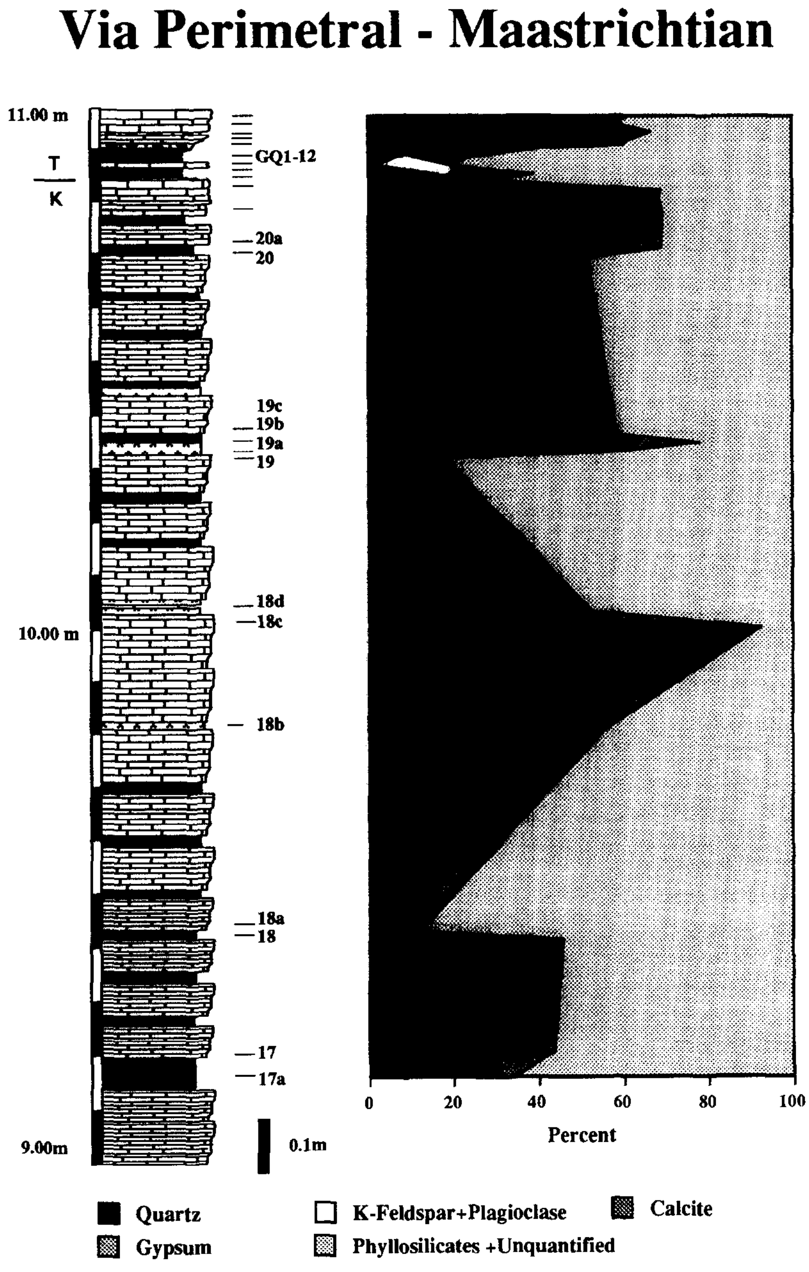


Fig. 12. Major mineralogical components of the latest Maastrichtian to K/T boundary interval in the Via Perimetral section, Guayaquil, Ecuador. Note that quartz (predominantly of biogenic origin) averages less than 20%, as compared with its increasingly high abundance in lower Danian sediments, and that calcite decreases from an average 40% in the Maastrichtian to less than 5% in the early Danian Zone Plb.

to 48% at the major radiolarian faunal turnover (Zone RP1) and in foraminiferal Zone Plc (Fig. 13). Quartz abundance is generally highest in siliceous limestones and lowest in shale or bentonite-ash layers. During the Maastrichtian, quartz averages less than 10% in shaly interlayers and more than 20% in siliceous limestones (Fig. 13). An opposite trend is observed in calcite content. Calcite generally de-

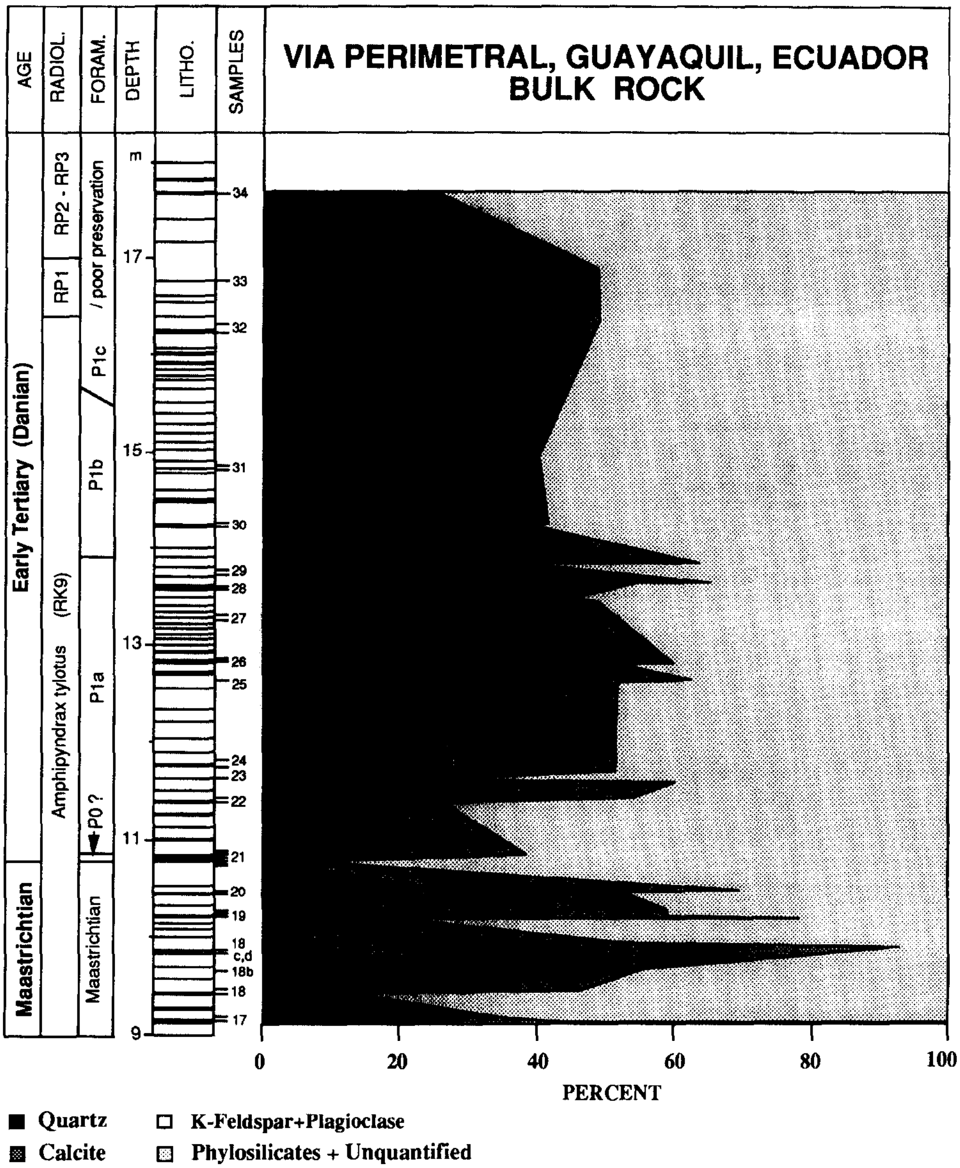


Fig. 13. Major mineralogical components from the Maastrichtian to Danian interval in the Via Perimetral section, Guayaquil, Ecuador. Note the increase in quartz of biogenic origin (former opaline silica) and concurrent decrease in calcite through the early Danian.

creases from the Maastrichtian into the Danian and averages less than 5% in radiolarian zones RP1 to RP2–RP3. Though, calcite content is highly variable averaging between 50 and 60% in siliceous limestone layers.

There is no evidence of a significant detrital influx during the latest Maastrichtian. But a major change is observed at the foraminiferal K/T boundary as shown in Figs. 11 and 14. In the clay couplet, both quartz and calcite decrease dramatically beginning at the base of the clay couplet coincident with a 3‰ negative $\delta^{13}C$ excursion (Fig. 11). In the upper part of the clay couplet, quartz and calcite are nearly absent although $\delta^{13}C$ values have nearly recovered as shown in Fig. 14 based on individual mineralogical components. The decrease in quartz and calcite

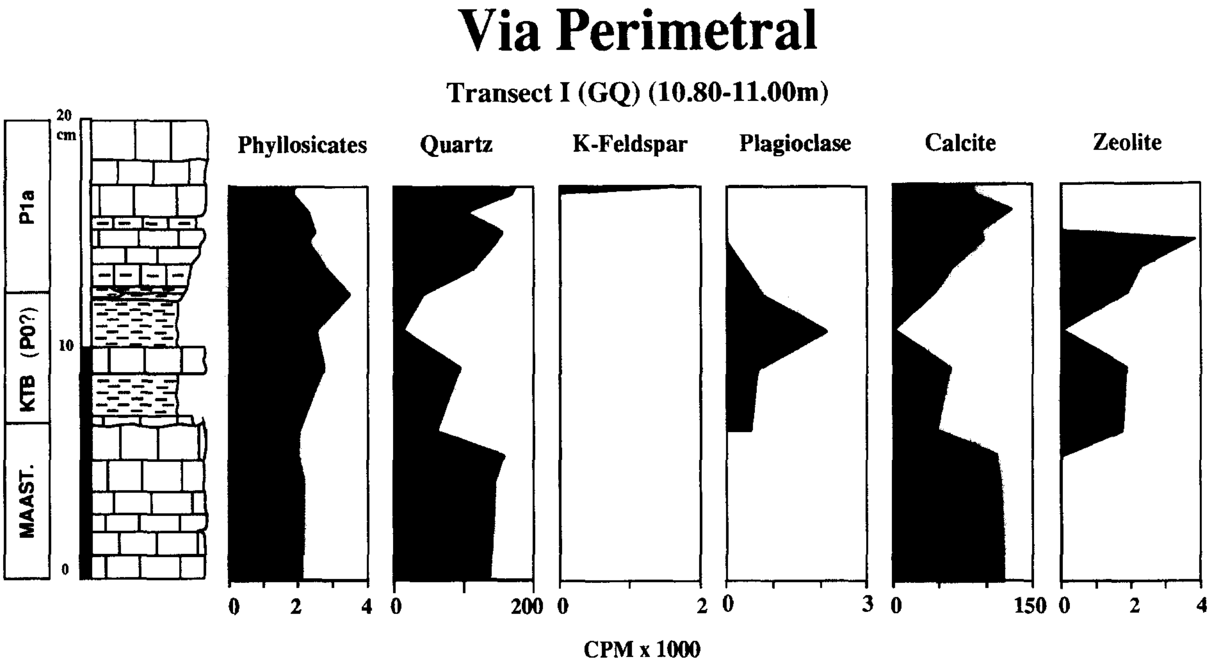


Fig. 14. Major mineralogical components shown individually across the foraminiferal K/T boundary interval in the Via Perimetral section, Guayaquil, Ecuador. Note the decrease in quartz and calcite and concurrent increase in plagioclase and zeolites during this period. This trend suggests that quartz is predominantly biogenic and decreased in relative abundance as a function of dilution due to increased terrigenous influx. The increased abundance of zeolites suggests increased volcanic activity during this time.

within the clay couplet suggests dissolution as well as a drop in surface productivity. This is also implied by the rarity of foraminifera and Radiolaria within this interval. In contrast, plagioclase increases which may suggest either concentration due to dissolution, or increased detrital influx. The general absence of plagioclase in the rest of the analyzed section suggests increased detrital influx. Zeolites are abundant through this interval and imply increased transport and diagenesis, or increased volcanic activity. Bulk rock and preliminary clay-mineral analyses indicate that these zeolites belong to the Heulandite–Clinoptilolite group. These zeolites are particularly abundant in volcanoclastic sediments and reflect the progressive alteration of volcanic glass. But in the absence of glass, dissolution of siliceous microfossils may provide a source of silica to form clinoptilolite. In the present case, both origins are possible. Nevertheless, the presence of numerous ash layers with high smectite and zeolite contents indicate increased volcanic activity through the K/T transition. These mineralogical data, coupled with the $\delta^{13}C$ and microfossil data, indicate a foraminiferal K/T transition marked by temporarily decreased primary productivity, increased volcanism and erosion.

Relative abundances (counts per minute, CPM) of individual mineralogical components through the early Danian are shown in Fig. 15. Calcite generally decreases from the late Maastrichtian through the early Danian Zone Pla and nearly disappears in zones Plb and Plc coincident with the second $\delta^{13}C$ shift and just below the radiolarian faunal turnover. This decrease in biogenic calcite is apparent in thin sections as well as washed residues where foraminifera become increasingly rare upsection and are generally absent in Zone Plc, except in some isolated samples. This suggests an increasingly silica-rich environment accompanied by carbonate dissolution.

Isolated occurrences of K-Feldspar, generally associated with plagioclase, are present near the base of Pla, at the Pla/Plb boundary and within Zone Plc (radiolarian zones RP2–RP3, Fig. 15). These co-occurrences of alkaline and plagioclase feldspars suggest increased detrital influx at times of lower sea levels. Short hiatuses associated with sea level falls at the P0/Pla and Pla/Plb boundaries are documented

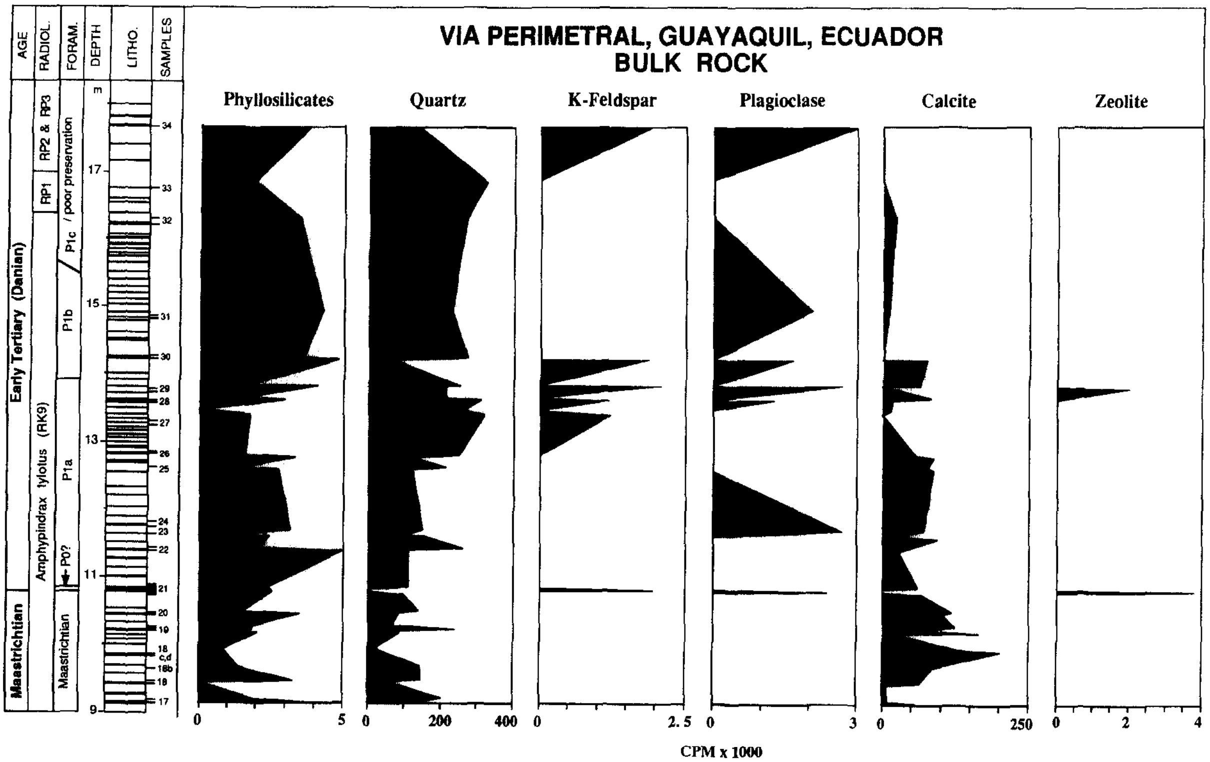


Fig. 15. Variations of major mineralogical components shown in uppermost Maastrichtian through lower Danian sediments. Note the increase in quartz and concurrent decrease in calcite with the latter reaching a permanent low in Zone Plb coincident with the $\delta^{13}C$ excursion. Terrigenous components such as K-feldspar and plagioclase present at select intervals, including the foraminiferal K/T boundary, lower Zone Pla, near the Pla/Plb boundary and within Zone Plc, suggest terrigenous influx and erosion at these times. Increased zeolite abundance at the K/T and Pla/Plb boundaries suggest increased volcanic activity.

from K/T sections worldwide (for a summary see MacLeod and Keller, 1991a,b).

As noted earlier, quartz increases from the Maastrichtian into the Danian, with the major increase beginning in the upper part of Zone Pla and continuing into Zone Plc (Fig. 15). Within this increasing trend, the lowest quartz values coincide with the $\delta^{13}C$ shifts at the foraminiferal K/T boundary and in Zone Plb as well as one sample (18) in the latest Maastrichtian. The association of low quartz with major reductions in primary productivity ($\delta^{13}C$ shifts) in an environment where siliceous microfossils (Radiolaria and diatoms) predominate, suggests a primary biogenic origin (opaline silica transformed by diagenesis to alpha quartz) for part or even the majority of the quartz. This is indicated by a diffraction pattern characterized by broader diffraction peaks (Moore and Reynolds, 1989; Jones and Segnit, 1971), as is common for detrital quartz. A biogenic origin for at least part of the quartz is also indicated by the lack of a correlation between the feldspar-phyllosilicate assemblage and quartz distribution. Since the former is primarily of detrital origin, the dissociation of quartz implies a biogenic origin. This is also indicated by the increase of unquantified parts in phyllosilicates, which in limestones corresponds to a poorly crystallized biogenic silica phase. The latter is probably related to the high abundance of Radiolaria observed in thin sections (Fig. 7d). In general, increased quartz content of primarily biogenic origin suggests increased productivity and upwelling.

8. Discussion and conclusions

The Via Perimetral K/T boundary section in Guayaquil, Ecuador, is a rare find not only because it is the only known deep-water K/T section in the eastern equatorial Pacific, but also because of its unusual sedimentologic, faunal and isotopic records. These records reveal (1) an equatorial location dominated by an eastern boundary current which originated in the Antarctic region similar to the modern Humboldt (Peru–Chile) current, and (2) evidence of upwelling that ameliorated or dominated equatorial climatic and environmental marine conditions. As the catastrophic effects of the K/T boundary event were largely limited to low latitudes (Keller, 1993, 1996; Keller et al., 1993b; Barrera and Keller, 1994; MacLeod and Keller, 1994), the Via Perimetral section provides a critical link between low- and high-latitude effects not only for the K/T event, but also for the periods before and after this event. Moreover, this section provides further constraints on the biotic and environmental effects of the K/T event and confirms that global catastrophic effects of a bolide impact have been overestimated and may have been limited to low latitudes.

8.1. Biotic record

The biotic record within the Via Perimetral section of Ecuador is unlike at any other known low-latitude K/T sections in that calcareous and siliceous microfossil assemblages are similar to New Zealand and other Antarctic region sites. Planktic foraminifera are of very low diversity (15 species) as compared with other low-latitude assemblages (50–60 species) and largely consist of cool temperate and cosmopolitan taxa, similar to ODP sites 738, 690 and 750 (Keller, 1993; Keller and MacLeod, 1995). Cosmopolitan species survived well into the Danian as observed at all K/T complete sections worldwide (MacLeod and Keller, 1994) and only rare warm water taxa disappeared. Thus, for foraminiferal faunas off Ecuador, the K/T event was not as catastrophic as for low-latitude faunas in general, but rather was significantly reduced similar to the trend observed in high-latitude K/T sequences.

Radiolaria show no major faunal turnover across the K/T boundary, instead the major faunal change coincides with the lower part of foraminiferal Zone Plc and near a second $\delta^{13}C$ shift. These faunal changes closely resemble those that occur at the K/T boundary in New Zealand. We suggest that this 300 kyr diachroneity may be due to the delayed influence of oceanographic events in the eastern central Pacific which caused enhanced siliceous productivity and a spumellarian bloom in parts of the southwest Pacific during the earliest Tertiary.

8.2. Stable Isotopes

The stable isotopic record at the Guayaquil Via Perimetral section shows a dynamic interaction of both low- and high-latitude characteristics. At the foraminiferal K/T boundary, the 3‰ negative $\delta^{13}C$ excursion which is generally interpreted as a drop in primary productivity (Oberhänsli, 1986; Arthur et al., 1987), is of the same magnitude as in other low-latitude sections. However, recovery occurred within several thousand years (within the 3–4 cm thick clay layer), whereas in other low-latitude sections recovery occurred some 300–500 kyr later (Oberhänsli, 1986; Zachos et al., 1989; Keller and Lindinger, 1989; Barrera and Keller, 1994). Why low-latitude recovery was delayed for so long is still a mystery. In high-latitude sections examined in the Southern Ocean as well as in Denmark and Kazakhstan there is no major $\delta^{13}C$ shift or significantly decreased productivity at the K/T boundary. Barrera and Keller (1994) argued that from the late Maastrichtian through the Early Paleocene, the Antarctic was the most significant source of deep water in the oceans. This would suggest that recovery of low-latitude productivity was largely dependent on upwelling of nutrient-rich deep water originating from the Antarctic Ocean. At the Via Perimetral section, the quick recovery may have been driven by both wind-driven upwelling and equatorial advection of nutrient-rich Antarctic waters north along the coast of South America via an eastern boundary current equivalent to the modern Humboldt current. Because the tip of South America and Antarctica were still close together at K/T time preventing circum-Antarctic circulation, northward flow of Antarctic waters may have been significantly stronger than within the modern Humboldt current.

In the Antarctic region, Barrera and Keller (1994) identified a $\delta^{13}C$ excursion within foraminiferal Zone Plb about 300 kyr after the K/T boundary. This $\delta^{13}C$ excursion is also present in the Via Perimetral section, but is not observed in any other low-latitude section, and is thus further evidence for Antarctic water influence. Full recovery of surface water productivity in both high and low latitudes occurs within Zone Plc (Oberhänsli, 1986; Arthur et al., 1987; Keller and Lindinger, 1989; Barrera and Keller, 1994).

8.3. Mineralogy

Sedimentologically, the Maastrichtian through Paleocene Via Perimetral section is unusual for a tropical location in that it consists of rhythmically bedded radiolarian-rich siliceous limestones interlayered with thin beds of ash and shale, very similar to sections in New Zealand (Hollis, 1993, 1996; Strong et al., 1995). The increasing quartz (biogenic) and decreasing carbonate content through the early Danian suggest that atmospheric and oceanic circulation and associated upwelling intensified during this time, likely triggered by climate cooling that reached a maximum in foraminiferal Zone Plc (radiolarian Zone RP1 to RP2–RP3), about 300–500 kyr after the foraminiferal K/T event. This record is similar to that observed in New Zealand (Hollis, 1993, 1996) and Antarctic Ocean ODP sites 738, 690 and 750 in the Antarctic region (Stott and Kennet, 1990; Keller, 1993; Barrera and Keller, 1994), but is unlike that observed in other low-latitude sections.

Sedimentological data indicate two intervals of low calcite and low quartz within this long-term environmental trend, but with high K-feldspar and plagioclase and zeolites: One of these intervals occurs just above the foraminiferal K/T boundary, whereas the other is present at the Zone Pla/Plb boundary (Fig. 15). Both of these mineralogical peaks suggest increased terrigenous influx and volcanic activity during short sea level lows. Thus, sedimentologically, there appears to be nothing unique or unusual at either the foraminiferal or radiolarian K/T boundaries. The absence of major mineralogical and sedimentological anomalies at the K/T boundary is not unusual and was also observed by Chamley and Robert (1979) and Chamley et al. (1984); Robert and Chamley (1990) in clay mineral associations at various K/T sections.

The mineralogical and faunal trends observed in the Via Perimetral section across the K/T transition may be largely related to climatic changes. Climatic influences on plankton productivity and deposition of siliceous sediments include: modification of ocean dynamics and especially the intensity and geographic distribution of upwelling, and the variation of silica input into the oceans through continental weathering and river run-off. The main driving force of ocean currents and upwelling are climate-related thermal gradients. During cooler climates, steep latitudinal gradients result in more intensive atmospheric and oceanic circulation (Janecek and Rea, 1984; Rea et al., 1985). During cooler climates of the Cenozoic, stronger atmospheric circulation lead to higher upwelling related silica productivity in the equatorial zone and to an expansion of this productive zone. In the case of the K/T transition, cooler temperatures are known to have prevailed through the Danian, associated with a generally rising eustatic sea level, interrupted by short-term sea level lows and short hiatuses at the P0/Pla, Pla/Plb boundaries and in Zone Plc (MacLeod and Keller, 1991a,b; Keller et al., 1993a,b; Keller and Stinnesbeck, 1996a,b). In the offshore Ecuador region, climate induced intensified atmospheric and oceanic circulation and upwelling related to a generally rising, though fluctuating, sea level may account for the increased rate of siliceous productivity through the Danian as well as the absence of mass extinctions at the K/T boundary.

Acknowledgements

We are grateful to the reviewers, W. Riedel, A. Sanfilippo and J.C. Ingle for many helpful comments and suggestions that greatly improved this report. We thank Robin Rocchia at CEA-CNRS, Gif Sur Yvette, France, for analyzing samples for iridium, Dan Schrag at Princeton University for stable isotope analysis and insights on diagenesis, Katharina von Salis Perch-Nielsen for examining samples for nannofossils and Dave Pocknall and C.P. Strong for valuable comments and making unpublished material available. We thank Amoco for providing a small travel grant for field work and Petroecuador for logistical help as well as the enthusiastic support of this study by Walter Zumba Erazo, Galo Montenegro and Stalin Benitez Acosta. This study was supported in part by NSF OCE-9021338 to GK, the New Zealand Science and Technology Fellowship HLS301 to CH and the Swiss National Fund No. 8220-028367 to TH.

References

Albertão, G.A., Koutsoukos, E.A.M., Regali, M.P.S., Attrep Jr., M. and Martins Jr., P.P., 1994. The Cretaceous–Tertiary boundary in southern low-latitude regions: preliminary study in Pernambuco, northeastern Brazil. Terra Nova, 6: 366–375.

Arthur, M.A., Zachos, J.C. and Jones, D.S., 1987. Primary productivity and the Cretaceous/Tertiary boundary event in the oceans. Cretaceous Res., 8: 43–54.

Askin, R.A., 1988. The palynological record across the Cretaceous/Tertiary transition on Seymour Island, Antarctica. In: R.M. Feldmann and M.O. Woodburne (Editors), Geology and Paleontology of Seymour Island, Antarctic Peninsula. GSA Mem., 169: 155–162.

Askin, R.A., 1992. Preliminary palynology and stratigraphic interpretations from a new Cretaceous/Tertiary boundary section from Seymour Island. Antarct. J. U.S., 25: 42–44.

Askin, R.A. and Jacobson, S.R., 1996. Palynological change across the Cretaceous/Teritiary boundary on Seymour Island, Antarctica: Environmental and depositional factors. In: N. MacLeod and G. Keller (Editors), Cretaceous–Tertiary Mass Extinctions: Biotic and Environmental Changes. Norton, New York, NY, pp. 20–39.

Barrera, E. and Keller, G., 1990. Stable isotope evidence for gradual environmental changes and species survivorship across the Cretaceous/Tertiary Boundary. Paleoceanography, 5: 867–890.

Barrera, E. and Keller, G., 1994. Productivity across the Cretaceous/Tertiary boundary in high latitudes. Geol. Soc. Am. Bull., 106: 1254–1266.

Berggren, W.A., Kent, D.V., Swisher III, C.C. and Aubry, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In: W.A. Berggren, D.V. Kent, M.-P. Aubry and J. Hardenbol (Editors), Geochronology, Time Scales and Global Stratigraphic Correlation. SEPM Spec. Publ., 54: 129–212.

Brinkhuis, H. and Zachariasse, W.J., 1988. Dinoflagellate cysts, sea level changes and planktonic foraminifera across the Cretaceous/Tertiary boundary at El Haria, northwest Tunisia. Mar. Micropaleontol., 13: 153–190.

Canudo, I., Keller, G. and Molina, E., 1991. K/T boundary extinction pattern and faunal turnover at Agost and Caravaca, SE Spain. Mar. Micropaleontol., 17: 319–341.

Chamley, R. and Robert, C., 1979. Late Cretaceous to early Paleogene environmental evolution expressed by the Atlantic clay sedimentation. In: W.K. Christensen and T. Birkelund (Editors), Cretaceous–Tertiary Boundary Events Symposium, Copenhagen, Proc., 2: 71–77.

Chamley, R., Maillot, H., Dué, G. and Robert, C., 1984. Paleoenvironmental history of the Walvis Ridge at the Cretaceous–Tertiary transition from mineralogical and geochemical investigations (Sites 585). Init. Rep. SDSP, 74: 414–419.

Foreman, H.P., 1968. Upper Maastrichtian Radiolaria of California. Paleontol. Assoc. London, Spec. Pap. Palaeontol. 3, 82 pp.

Foreman, H.P., 1977. Mesozoic Radiolaria from the Atlantic basin and its borderlands. In: F.M. Swain (Editor), Stratigraphic Micropaleontology of Atlantic Basin and Borderlands. (Developments in Paleontology and Stratigraphy, 6.) Elsevier, Amsterdam, pp. 305–320.

Harwood, D.M., 1988. Upper Cretaceous and Lower Paleocene diatom and silicoflagellate biostratigraphy of Seymour Island, eastern Antarctic Peninsula. Geol. Soc. Am. Mem., 169: 55–129.

Hollander, D.J., MacKenzie, J.A. and Hsu, K.J., 1993. Carbon isotope evidence for unusual plankton blooms and fluctuations of surface water CO_2 in 'Strangelove Ocean' after terminal Cretaceous event. Paleogeogr., Paleoclimatol., Paleoecol., 104: 229–237.

Hollis, C.J., 1993. Latest Cretaceous to Late Paleocene radiolarian biostratigraphy: A new zonation from the New Zealand region. Mar. Micropaleontol., 21: 295–327.

Hollis, C.J., 1996. Radiolarian faunal change through the Cretaceous–Tertiary transition of eastern Marlborough, New Zealand. In: N. MacLeod and G. Keller (Editors), Cretaceous/Tertiary Mass Extinction: Biotic and Environmental Changes. Norton, New York, NY, pp. 173–203.

Hollis, C.J., Rodgers, K.A. and Parker, R.J., 1995. Siliceous plankton bloom in the earliest Tertiary of Marlborough, New Zealand. Geology, 23: 835–838.

Janecek, T.R. and Rea, D.K., 1984. Pleistocene fluctuations in northern hemisphere tradewinds and westerlies. In: A. Berger, J. Imbrie, J. Hays, G. Kukla and B. Saltzman (Editors), Milankovitch and Climate. NATO ASI, Ser. C, 126: 331–348.

Jones, J.B. and Segnit, E.R., 1971. The nature of opale I. Nomenclature and constituent phases. J. Geol. Soc. Aust., 18: 57–68.

Keller, G., 1988. Extinction, survivorship and evolution of planktic foraminifers across the Cretaceous/Tertiary boundary at El Kef, Tunisia. Mar. Micropaleontol., 13: 239–263.

Keller, G., 1989. Extended Cretaceous/Tertiary boundary extinctions and delayed population changes in planktic foraminifera from Brazos River, Texas. Paleoceanography, 4(3): 287–332.

Keller, G., 1993. The Cretaceous/Tertiary boundary transition in the Antarctic Ocean and its global implications. Mar. Micropaleontol., 21: 1–45.

Keller, G., 1996. The Cretaceous/Tertiary Mass extinction in planktonic foraminifera: Biotic constraints for catastrophy theories. In: N. MacLeod and G. Keller (Editors), Cretaceous/Tertiary Mass Extinction: Biotic and Environmental Changes. Norton, New York, NY, pp. 63–100.

Keller, G. and Lindinger, M., 1989. Stable isotope, TOC and CaCO3 records across the Cretaceous/Tertiary boundary at El Kef, Tunisia. Paleogeogr., Paleoclimatol., Paleoecol., 73: 243–265.

Keller, G. and MacLeod, N., 1995. Reply to comment on "The Cretaceous–Tertiary boundary transition in the Antarctic Ocean and its global implications". Mar. Micropaleontol., 24: 101–118.

Keller, G. and Perch-Nielsen von Salis, K., 1995. K/T mass extinction: Effects of global change on calcareous nannoplankton. In: S. Stanley (Editor), The Effects of Post-global Change on Life. Natl. Acad. Sci./Natl. Res. Counc., Natl. Acad. Press, Washington, DC, pp. 72–93.

Keller, G. and Stinnesbeck, W., 1996a. Sea-level changes, clastic deposits and megatsunamis across the Cretaceous–Tertiary boundary. In: N. MacLeod. and G. Keller (Editors), The Cretaceous/Tertiary Boundary Mass Extinction: Biotic and Environmental Changes. Norton, New York, NY, pp. 443–478.

Keller, G. and Stinnesbeck, W., 1996b. Near-K/T age of clastic deposits from Texas to Brazil: Impact, volcanism and/or sea level lostand? Terra Nova, 8: 277–285.

Keller, G., MacLeod, N., Lyons, J.B. and Officer, C.B., 1993a. Is there evidence for Cretaceous–Tertiary boundary-age deepwater deposits in the Caribbean and Gulf of Mexico? Geology, 21: 776–780.

Keller, G., Barrera, E., Schmitz, B. and Mattson, E., 1993b. Gradual mass extinction, species survivorship and long-term environmental changes across the Cretaceous/Tertiary boundary in high latitudes. Geol. Soc. Am. Bull., 105: 979–997.

Keller, G., Li, L. and MacLeod, N., 1996. The Cretaceous/Tertiary boundary stratotype section at El Kef, Tunisia: How catastrophic was the mass extinction? Paleogeogr., Paleoclimatol., Paleoecol., 119: 221–254.

Klug, H.P. and Alexander, L., 1974. X-ray Diffraction Procedures for Polycrystalline and Amorphous Materials. Wiley, New York, NY, 996 pp.

Kubler, B., 1983. Dosage quantitatif des mineraux majeurs des roches sedimentaires par diffraction X. Cah. Inst. Geol. Neuchatel, Ser. ADX, 1.

Kubler, B., 1987. Cristallinite de l'illite, methodes normalisees de preparations, methodes normalisees de mesures. Cah. Inst. Geol. Neuchatel, Ser. ADX.

MacLeod, N., 1993. The Maastrichtian–Danian radiation of triserial and biserial planktic foraminifera: Testing phylogenetic and adaptational hypothesis in the (micro) fossil record. Mar. Micropaleontol., 21: 47–100.

MacLeod, N., 1995. Graphic correlation of high-latitude Cretaceous–Tertiary (K/T) boundary sequences from Denmark, the Weddell Sea and Kerguelen Plateau: Comparison with the El Kef (Tunisia) boundary stratotype. Mod. Geol., 20: 109–147.

MacLeod, N. and Keller, G., 1991a. Hiatus distribution and mass extinction at the Cretaceous/Tertiary boundary. Geology, 19: 497–501.

MacLeod, N. and Keller, G., 1991b. How complete are Cretaceous/Tertiary boundary sections? A chronostratigraphic estimate based on graphic correlation. Geol. Soc. Am. Bull., 103: 1439–1457.

MacLeod, N. and Keller, G., 1994. Comparative biogeographic analysis of planktic foraminiferal survivorship across the Cretaceous/Tertiary (K/T) boundary. Paleobiology, 20(2): 143–177.

Moore, D. and Reynolds, R., 1989. X-ray Diffraction and the Identification and Analysis of Clay-minerals. Oxford Univ. Press, 332 pp.

Oberhänsli, H., 1986. Latest Cretaceous–early Neogene oxygen and carbon isotopic record at DSDP sites in the Indian Ocean. Mar. Micropaleontol., 10: 91–115.

Pardo, A., Ortiz, N. and Keller, G., 1996. Latest Maastrichtian and K/T boundary foraminiferal turnover and environmental changes at Agost, Spain. In: N. MacLeod and G. Keller (Editors), Cretaceous–Tertiary Mass Extinction: Biotic and Environmental Changes. Norton, New York, NY, pp. 157–190.

Perch-Nielsen, K., 1979. Calcareous nannofossils at the K/T boundary in Tunisia. In: W.A. Christensen and R.G. Bromley (Editors), K/T boundary Events. Univ. Copenhagen, pp. 238–243.

Rea, D.K., Leinen, M. and Janecek, T.R., 1985. Geologic approach to long-term history of atmospheric circulation. Science, 227: 721–725.

Robert, C. and Chamley, H., 1990. Paleoenvironmental significance of clay mineral associations at the Cretaceous–Tertiary passage. Paleogeogr., Paleoclimatol., Paleoecol., 79: 205–219.

Rolli, M., 1990. Dosage semi-quantitatif RX sur Scintag. Cah. Inst. Geol. Neuchatel, Ser. ADX 10, 41 pp.

Sanfilippo, A. and Riedel, W.R., 1985. Cretaceous Radiolaria. In: H.M. Bolli, J.G. Saunders and K. Perch-Nielsen (Editors), Plankton Stratigraphy. Cambridge Univ. Press, London, pp. 573–630.

Scholle, P.A. and Arthur, M.A., 1980. Carbon isotope fluctuations in Cretaceous pelagic limestones: potential stratigraphic and petroleum exploration tool. Am. Assoc. Pet. Geol. Bull., 64: 67–87.

Stinnesbeck, W., 1989. Fauna y microflora de Pernambuco, Noreste de Brasil. Contrib. Simp. Cretacio de America Latina, Parte A: Eventos y Registro Sediment, pp. 215–230.

Stinnesbeck, W., 1996. Ammonite extinctions and environmental changes across the Cretaceous/Teritiary boundary in central Chile. In: N. MacLeod and G. Keller (Editors), Cretaceous–Tertiary Mass Extinction: Biotic and Environmental Changes. Norton, New York, NY, pp. 289–302.

Stinnesbeck, W. and Keller, G., 1994. Field Guide to the Cretaceous–Tertiary boundary section at Poty, north of Recife, northeastern Brazil: 14th Int. Sedimentol. Congr., IAS, Recife, Field Guide, pp. 1–18.

Stinnesbeck, W. and Keller, G., 1995. The Cretaceous–Tertiary boundary in southern low latitude regions: Preliminary study in Pernambuco, northeastern Brazil—Comments and Reply. Terra Nova, 7: 375–382.

Stinnesbeck, W. and Keller, G., 1996. Environmental changes across the Cretaceous–Tertiary boundary in northeastern Brazil. In: N. MacLeod and G. Keller (Editors), Cretaceous–Tertiary Mass Extinction: Biotic and Environmental Changes. Norton, New York, NY, pp. 481–500.

Stott, L.D. and Kennet, J.P., 1990. The paleoceanographic and climatic signature of the Cretaceous/Paleogene boundary in the Antarctic: Stable isotopic results from ODP Leg 113. Proc. ODP, Sci. Results, 113: 829–848.

Strong, C.P., 1994. Foraminiferal sequence at the Cretaceous–Tertiary boundary, Flaxbourne River, Marlborough, NZ. Geol. Soc. N. Z., Misc. Publ., 80A: 174 (abstract).

Strong, C.P., Brooks, R.R., Wilson, S.M., Reeves, R.D., Orth, C.J., Mao, Y.-Y., Quintana, L.R. and Anders, E., 1987. A new Cretaceous–Tertiary boundary site at Flaxbourne River, New Zealand: biostratigraphy and geochemistry. Geochim. Cosmochim. Acta, 51: 2769–2777.

Strong, C.P., Hollis, C.J. and Wilson, G.J., 1995. Foraminiferal, radiolarian and dinoflagellate biostratigraphy of Late Cretaceous to Middle Eocene pelagic sediments (Muzzle Group), Mead Stream, Marlborough, New Zealand. N. Z. J. Geol. Geophys., 38: 171–209.

Zachos, J.C. and Arthur, M.A., 1986. Paleoceanography of the Cretaceous–Tertiary boundary event: Inferences from stable isotopic and other data. Paleoceanography, 1: 5–26.

Zachos, J.C., Arthur, M.A. and Dean, W.E., 1989. Geochemical evidence for suppression of pelagic marine productivity at the Cretaceous/Tertiary boundary. Nature, 337: 61–64.

Zinsmeister, W.J., Feldmann, R.M., Woodburne, M.O. and Elliot, D.H., 1989. Latest Cretaceous/earliest Tertiary transition on Seymour Island, Antarctica. J. Paleontol., 63: 731–738.