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Palynology and sequence stratigraphy of the Cretaceous of eastern Venezuela

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From Jurassic to Tertiary times, northeastern Venezuela represented the continental shelf of a tectonically passive margin. A dominantly marine Cretaceous sedimentary section, within an overthrusted allochthonous block and with a maximum thickness of 3658 m, is found in the subsurface in this area. Palynomorph recovery from these strata, together with planktonic foraminifera and calcareous nannofossils, indicate an age-range from at least Aptian to Maastrichtian. The palynological assemblages observed exhibit changes with time and environments, which are here related to the sedimentary evolution. Integrated analyses of palynology, lithology, and well logs are the basis for the reconstruction of the sedimentary evolution in the area. The oldest marine sediments in this section correspond to the uppermost part of the Lower Zuni Megacycle and contain a maximum flooding surface correlative with that dated at 111 Ma. The rest of the sequence represents a major transgressive-regressive cycle (Upper Zuni) and contains seven sequences correlative with global eustatic cycles. The Turonian transgression dated at 91.5 Ma is the most important marine transgression in the entire section and is recognizable in all sections studied, while the Maastrichtian-Paleocene boundary dated at 68 Ma is not always clearly recognizable.

Key Words: Cretaceous; Aptian-Maastrichtian; dinoflagellates; biostratigraphy; paleoenvironments; sequence stratigraphy; passive margin; eastern Venezuela.

1. Introduction

1.1. Objectives

This paper reports on the stratigraphy and palynological content, particularly dinoflagellates, of Cretaceous strata drilled in an allochthonous thrust block from the Eastern Basin of Venezuela (Figure 1). The objectives of the paper are to expand our knowledge on the stratigraphic distribution of Cretaceous dinoflagellate assemblages in tropical, shallow marine environments, and to present a chronostratigraphic model for the evolution of the Cretaceous in Venezuela's Eastern Basin. The model proposed is based on a sequence stratigraphic analysis and correlation with global eustatic cycles (Haq *et al*., 1988) and serves to correlate the strata studied with other Cretaceous sections in the region. The data on palynomorphs will help to refine the known biostratigraphic ranges of the species included and to improve our paleoenvironmental interpretations of Tethyan palynomorph assemblages.

1.2. General setting

Global eustatic cycles for the Mesozoic and Cenozoic were first proposed by Vail *et al*. (1977). These cycles were then correlated with published biostratigraphic zonations and calibrated with a paleomagnetic scale and radiomagnetic ages by Haq *et al*. (1988). In the stratigraphic record of a continental margin, the cycles are recognized by transgressions and regressions, which can be linked to the rise and fall of the global (or local) sea level.

The amount of sediments reaching a basin and the space available to accommodate them are controlled by changes in the volume of the world's oceans, changes in the amount of water filling them and continental uplift or subsidence (Vail *et al*., 1991). This uplift or subsidence can be caused by tectonic events or by lithostatic reactions to the loading and unloading of the continental margins.

Tectonic processes can obscure the relation of transgressive-regressive sedimentary successions to global eustatic cycles. A tectonically passive, continental margin such as the Cretaceous of eastern

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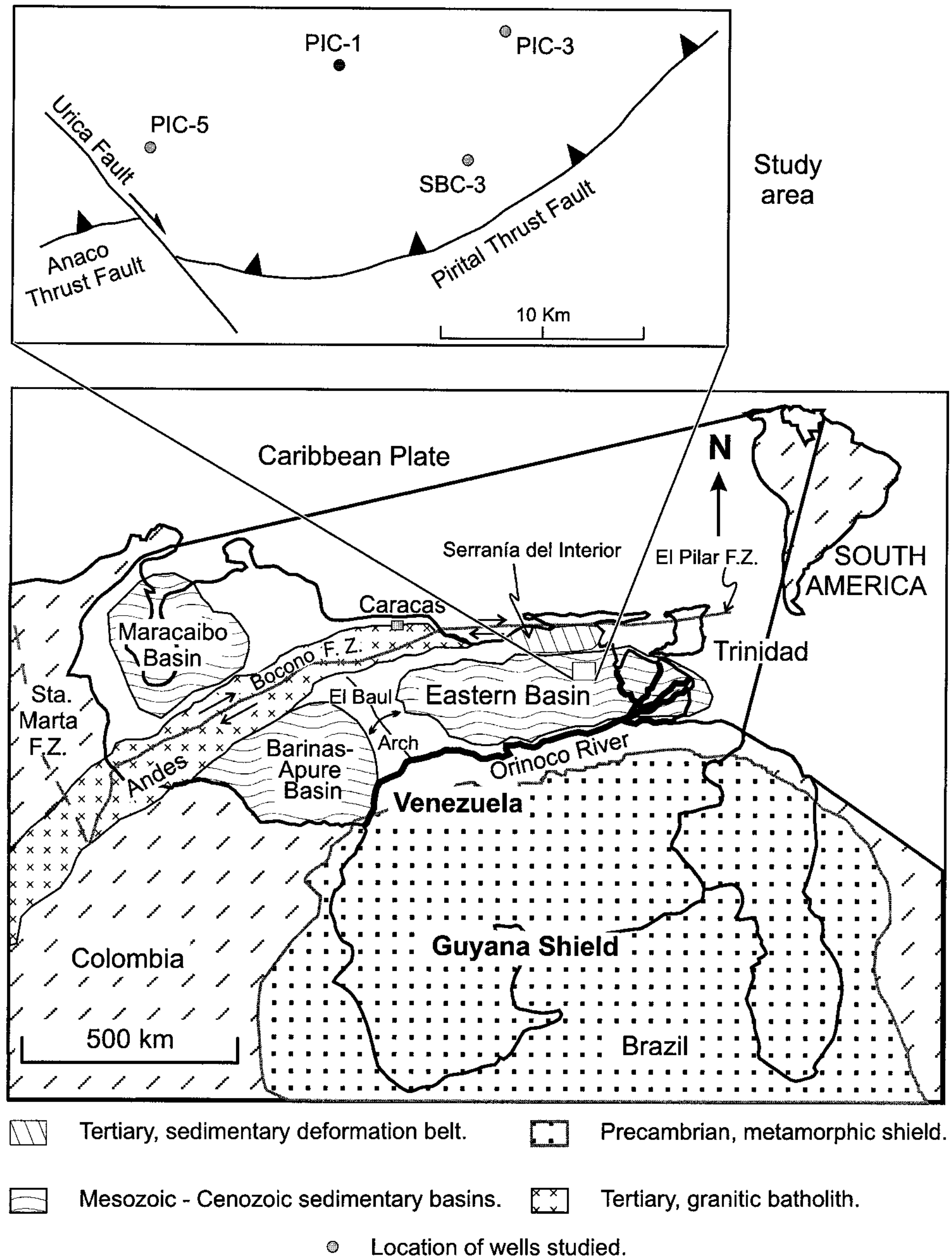


Figure 1. Main tectonic and geologic elements in Venezuela and location of wells studied.

Venezuela, could be a good place to try and separate eustatic from tectonic cycles. In addition, shallow marine environments represented in continental margin settings, usually exhibit lithologic and micropaleontological changes that are obvious. Therefore in passive margin, marine-dominated sedimentary successions, transgressive-regressive cycles are normally recognizable and could be related to eustatic cycles.

Cretaceous strata in eastern Venezuela have been extensively studied from outcrops in the Serranía del Interior and areas to the north (González de Juana *et al.*, 1980; Morris *et al.*, 1990; Bellizzia & Dengo, 1990; Erikson, 1994; Stephan *et al.*, 1994). Depositional environments represented in these strata range from continental and nearshore in the south and west, to deep-water marine paleoenvironments in the north and northeast.

The known stratigraphic record from the subsurface in eastern Venezuela indicates that mostly shallow marine sediments were deposited during the

Cretaceous Period (González de Juana *et al.*, 1980). During most of this time, the northern margin of South America was passive, particularly in the area now occupied by eastern Venezuela. Therefore the Cretaceous sequences in eastern Venezuela provide an excellent opportunity to compare paleoenvironmental changes in the sedimentary record to global eustatic changes, without important tectonic components. An analysis of the micropaleontological record of these sequences, as the one undertaken in this study, should provide evidence to relate all these changes.

1.3. Tectonic setting

Prior to the Jurassic, the Caribbean did not exist and the North and South American continental plates were united. During the Jurassic, plate separation occurred and by Campanian-Maastrichtian times the proto-Caribbean plate appeared, extending from the west (Pindell & Barrett, 1990; Pindell & Erikson, 1993). Today the northern edge of the South American continent is extensively deformed by right-lateral, strike-slip faulting, and an oblique subduction area is present to the north (Molnar & Sykes, 1969; Burke *et al.*, 1984; Pindell & Barrett, 1990).

As a result of this evolution, the Caribbean region is tectonically complex and consists of a mixed oceanic and continental North American plate; a mostly oceanic Caribbean plate; the mixed oceanic and continental South American plate; and the oceanic Pacific and Nazca plates.

In Venezuela (Figure 1), the main geological elements (González de Juana *et al.*, 1980) are the stable Guyana Shield to the south, the Miocene or younger Andes mountains to the northwest, and the Miocene or younger right-lateral, strike-slip fault along the Andes and to the east, known as the Bocono-Moron-El Pilar Fault System (Schubert, 1984), labeled as Bocono F. Z. and El Pilar F. Z. on Figure 1.

The Eastern Basin of Venezuela (Figure 1) is located north of the Guyana Shield and south of the Serranía del Interior, which was formed by late Tertiary compression of the Caribbean and the South American plates. In the subsurface, a complex structural regime is dominated by the late Miocene Pirital Thrust Fault which dips to the north. In this paper we present data on the sedimentary sequences drilled in an allochthonous block overlying the Pirital Fault, and located east of the Urica Fault (see inset on Figure 1).

1.4. Stratigraphy

The oil-producing Tertiary strata of the Eastern Basin of Venezuela have been drilled and studied for a long time (González de Juana *et al.*, 1980). However, the basin also contains Cretaceous strata with an age-range from Barremian to Maastrichtian (Paredes *et al.*, 1994). These Cretaceous rocks represent almost continuous marine sedimentation from at least Aptian to Maastrichtian times. Presumed Barremian strata represent mainly continental to paralic paleoenvironments.

In the allochthonous block, the Cretaceous sequence is unconformably overlain by Tertiary strata and overlies thrusted Miocene strata (Figure 2). The Cretaceous units drilled have been correlated with stratigraphic units cropping out in the Serranía del Interior (Figure 2), and the same stratigraphic nomenclature is applied to the subsurface sections. In general, the stratigraphic units in the subsurface represent shallower facies than those present in the Serranía del Interior; but deeper than those present to the south (González de Juana, *et al.* 1980).

Cretaceous Units. The oldest drilled unit is the Barranquín Formation, which is composed mainly of coarse to medium grained clastics. Conformably overlying this unit is the calcareous El Cantil Formation, which includes a basal shaly member known as the Miembro García. Conformably overlying the El Cantil limestones rest the black, thin-bedded, calcareous shales of the Querecual Formation. Conformably overlying the black shales, the San Antonio Formation consists of alternating sandstones and shales. The uppermost unit of the Cretaceous sequence is the San Juan Formation, which consists of thick-bedded, medium to coarse grained sands.

The San Juan Formation is conformably overlain by alternating siltstones and dark gray shales assigned to the Vidoño Formation (Paleocene), and/or by glauconitic sandstones and siltstones of the Caratas Formation (Eocene). Unconformably overlying these units, are the coarse clastics of the Morichito Formation (Pliocene) in the western part of the study area, and the medium to coarse clastics of the Merecure Group (Oligocene to Miocene) in the eastern part.

2. Material and methods

2.1. Data

The material used includes core and cuttings samples from four exploratory wells drilled by CORPOVEN (a Venezuelan oil company, now part of PDVSA) in Venezuela's Eastern Basin. The palynological results are based mainly on the analysis of samples from the following wells.

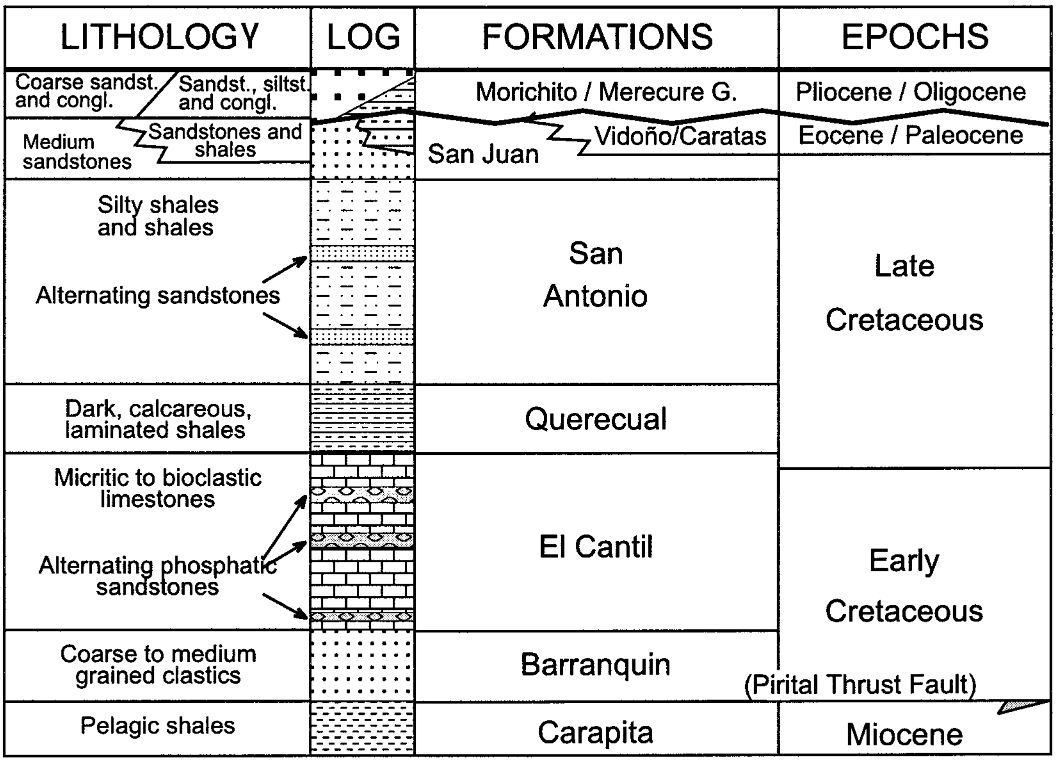


Figure 2. Cretaceous stratigraphy of the Serranía del Interior, as applied to the allochthonous block.

Well	Cretaceous drilled m (ft)	Cuttings samples analyzed	Core samples analyzed
PIC-1E	3,600 (11,630)	134	
PIC-3E	3,674 (11,870)	19	
PIC-3E	2,400 (7,803)	84	
SBC-3	900 (2,800)	43	6

Lithological interpretations are based on the gamma ray well logs and the cuttings samples. Microfossil content was used to construct a biostratigraphic and paleoenvironmental framework for the sequences analyzed. Age assignments of the sections studied are based mainly on the stratigraphic ranges of the palynomorphs contained in cuttings and core samples. When assigning ages based on fossils contained in cuttings samples, mainly uppermost appearances of taxa were considered.

2.2. Sample preparation

Samples for palynological analyses were prepared following the normal treatment with HCl, HF and ZnBr2 (Wood *et al.*, 1996). The residue was then sieved through 100 μm and 20 μm mesh sieves, and strew mounts were prepared with the residue retained on the 20 μm. One slide per sample was analyzed under the microscope, and numerical abundances of marine and terrestrial palynomorphs were recorded.

2.3. Palynological Marine Index

Since the recovery from all samples was low to moderate, a precise statistical analysis was not undertaken. Instead, to help in the interpretation of the depositional environments, a Palynological Marine Index (PMI) was calculated for all samples analyzed. This PMI was calculated using the formula: $PMI=(Rm/Rt+1)\ 100$, where Rm = Richness of marine palynomorphs (dinoflagellates, acritarchs and chitinous internal molds of foraminifera), counted as the number of taxa per sample; and Rt = Richness of terrestrial palynomorphs (pollen and spores), also counted as the number of taxa per sample.

Null values of PMI indicate samples without marine palynomorphs, and are interpreted to represent terrestrial or freshwater environments. Low values of PMI are interpreted as indicative of brackish water influence, and higher values are interpreted as indicative of marine conditions of deposition. When compared to a

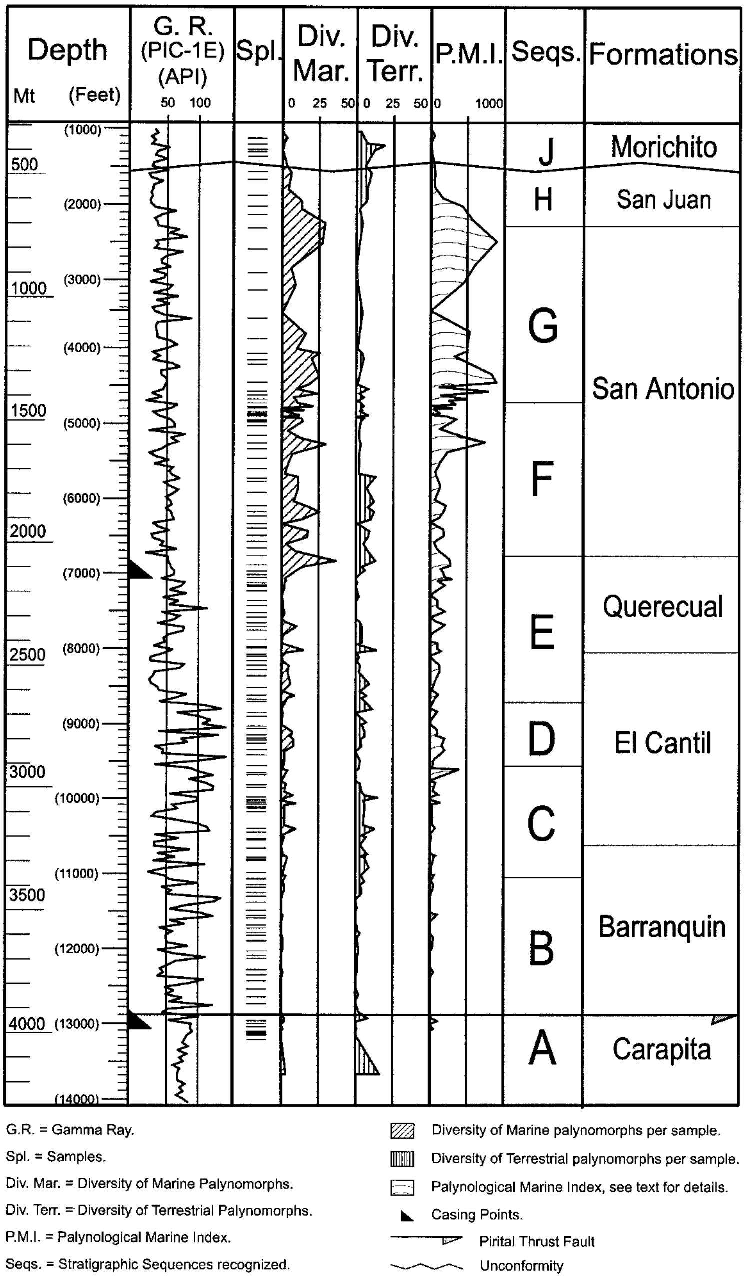


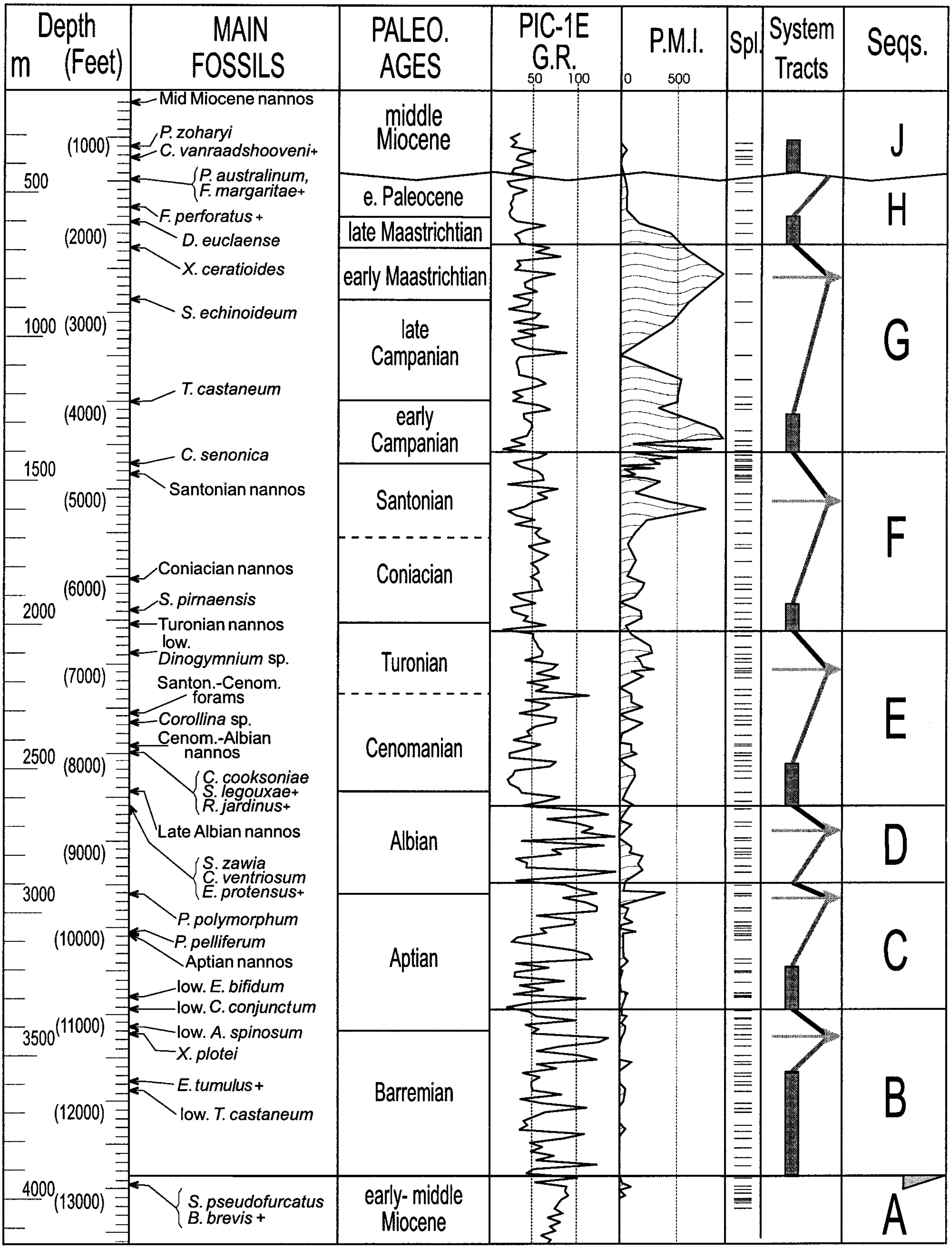
Figure 3. Gamma ray log, palynological statistics, sequences, and formations recognized in PIC-1E.

paleobathymetric curve based on benthonic foraminifera, the higher values of the PMI generally correspond to neritic environments, while lower PMI values correspond to either paralic or bathyal environments.

Palynological analyses of Recent sediments from the Orinoco Delta (Müller, 1959) indicate that dinoflagellate cyst recovery is restricted to brackish and marine environments, being more abundant in fully marine environments. On the other hand, the abundance of spores and pollen in marine environments generally decreases offshore (Hoffmeister, 1954; Müller, 1959; Heusser, 1978).

The lower PMI values in bathyal environments reflect the tendency of cyst-forming dinoflagellates to inhabit shelf or coastal areas (Dale, 1996) where seasonal changes, such as temperature, that trigger excystment are more pronounced (Evitt, 1985).

The PMI is particularly useful when comparing adjacent samples. Significant differences suggest changes in depositional environment represented in


Depth
m (Feet)
MAIN FOSSILS
PALEO. AGES
PIC-1E G.R.
50 100
P.M.I.
0 500
Spl.
System Tracts
Seqs.
500
1000
1500
2000
2500
3000
3500
4000
(1000)
(2000)
(3000)
(4000)
(5000)
(6000)
(7000)
(8000)
(9000)
(10000)
(11000)
(12000)
(13000)
Mid Miocene nannos
P. zoharyi
C. vanraadshooveni+
P. australinum,
F. margaritae+
F. perforatus +
D. euclaense
X. ceratioides
S. echinoideum
T. castaneum
C. senonica
Santonian nannos
Coniacian nannos
S. pirnaensis
Turonian nannos
low. Dinogymnium sp.
Santon.-Cenom. forams
Corollina sp.
Cenom.-Albian nannos
C. cooksoniae
S. legouxae+
R. jardinus+
Late Albian nannos
S. zawia
C. ventriosum
E. protensus+
P. polymorphum
P. pelliferum
Aptian nannos
low. E. bifidum
low. C. conjunctum
low. A. spinosum
X. plotei
E. tumulus+
low. T. castaneum
S. pseudofurcatus
B. brevis +
middle Miocene
e. Paleocene
late Maastrichtian
early Maastrichtian
late Campanian
early Campanian
Santonian
Coniacian
Turonian
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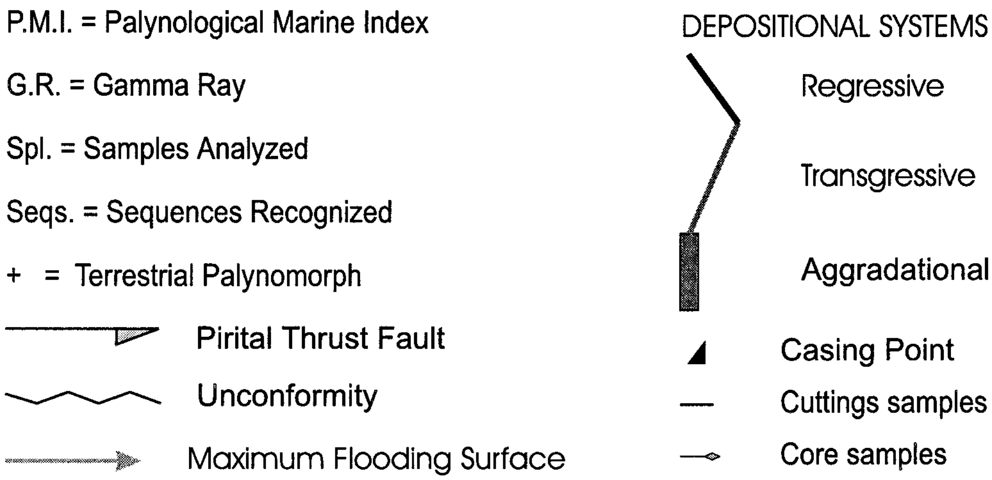

Figure 4. Main fossils, paleontological ages, and sequences recognized in PIC-1E (on facing page). Key to symbols and abbreviations (above) also applies to Figures 5–7: Low. = lowermost.

the section and help in the recognition of sequence boundaries and maximum flooding surfaces. Sequence boundaries will normally be found in intervals with upward decreasing values of PMI; while maximum flooding surfaces will be near the maximum values of PMI in each sequence.

2.4. Other analyses

Foraminifera and calcareous nannofossils have been studied (Paredes *et al.*, 1994) and the age assignments based on these calcareous fossils are used here in conjunction with those determined on the basis of palynology.

The gamma ray and conductivity logs were analyzed to determine grain size gradation. Results from these analyses, together with the lithology observed in core and cuttings samples, and the PMI values obtained from the palynological analyses, allow interpretation of the depositional systems and the stratigraphic sequences represented. Finally, the integration of the stratigraphic sequences recognized and the palynological ages assigned, are the bases for a correlation with the chronostratigraphic chart of Haq *et al.* (1988).

2.5. Previous palynological studies

Most of the information on the stratigraphic distribution of Cretaceous dinoflagellates is based on samples from either mid- to high latitudes in the northern hemisphere (Helenes, 1984; Williams & Bujak, 1985; Aurisano, 1989; Powell, 1992; Williams *et al.*, 1993), or from the southern hemisphere (Cookson & Eisenack, 1960a, b, 1962; Helby *et al.*, 1987; Stover & Helby, 1987).

The palynological content of Cretaceous strata from Venezuela and the Tethyan region in general, particularly the terrestrial palynomorphs, have been extensively studied (Germeraad *et al.*, 1968; Müller *et al.*, 1987; Colmenares & Teran, 1993). Fossil dinoflagellates from these areas are not so well known. However, some of the publications on Cretaceous dinoflagellates related to this region are: Lentin & Williams (1980); Malloy (1972); Jain & Millepied (1973); Pares-Regali *et al.* (1974); Davey (1978); Below (1984); Fasola & Paredes-de-Ramos (1991); Paredes *et al.* (1994); Helenes *et al.* (1991, 1994, 1998).

3. Paleoenvironments and sequences

3.1. General observations

The paleoenvironmental changes in the section drilled are interpreted from the gamma ray logs and the palynomorph assemblages. PMI values are used to summarize the palynological data, providing a means of discriminating marine from non-marine environments.

PIC-1E (Figures 3, 4) had the best palynomorph recovery and highest abundances of marine palynomorphs, and therefore provides the best record of paleoenvironmental changes in the basin. Comparatively, PIC-5E (Figure 5) contains fewer marine palynomorphs and PIC-3E (Figure 6) and SBC-3 (Figure 7) have less complete Cretaceous sections.

The values of PMI from PIC-1E and PIC-5E (Figures 4, 5) show relatively poor recovery of

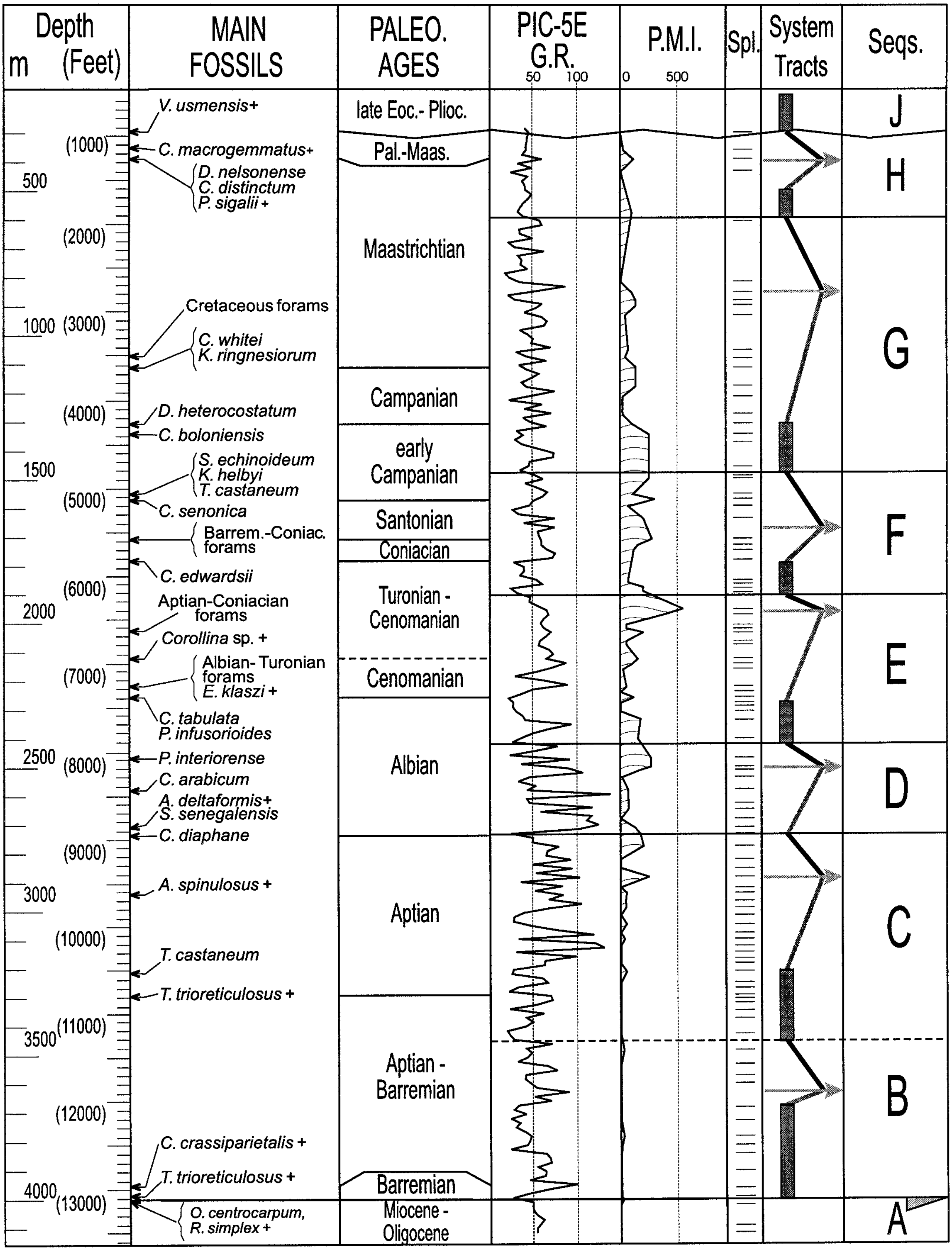

Figure 5. Main fossils, paleontological ages, and sequences recognized in PIC-5E. For key to symbols and abbreviations, see Figure 4.

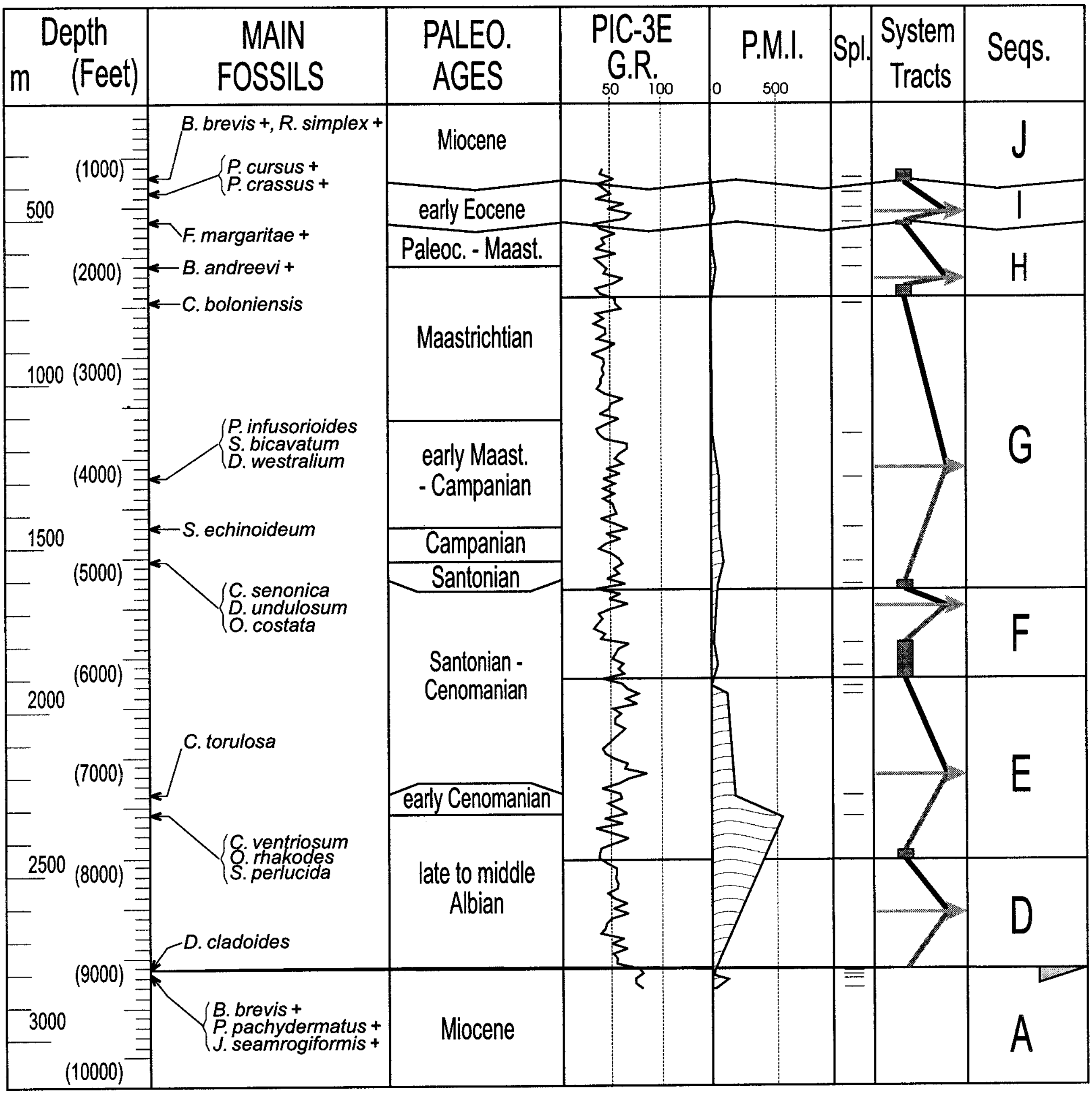

Figure 6. Main fossils, paleontological ages, and sequences recognized in PIC-3E. For key to symbols and abbreviations, see Figure 4.

marine palynomorphs in the bottom half and a considerable increase in the upper part of the section. These characteristics of the palynomorph assemblages and the interpretation of the gamma ray logs are used to define seven Cretaceous sequences, labeled from B to H, in PIC-1E. Based on their lithologic and palynological characteristics, some of the sequences are also recognized in the other wells.

3.2. Tertiary sequences

Sequences A, I, and J are Tertiary in age, so they are not described in detail in this paper. Their general characteristics are the following.

Sequence A. Corresponds to the Miocene sedimentary rocks underlying the thrust fault and represents Supercycle TB-2 of Haq *et al.* (1988).

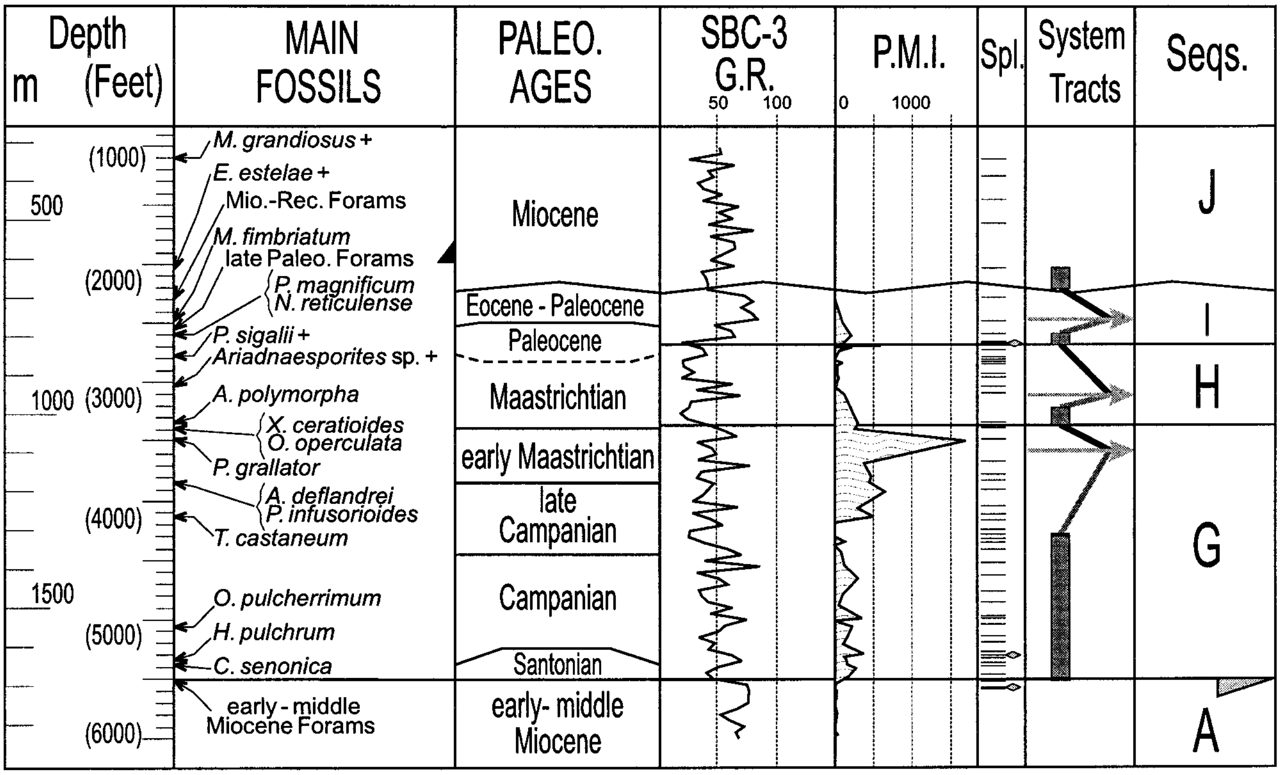

Figure 7. Main fossils, paleontological ages, and sequences recognized in SBC-3. For key to symbols and abbreviations, see Figure 4.

Sequence I. Present only in short intervals of PIC-3E and SBC-3, it is probably incompletely represented. Characterized by low values of the PMI, it contains the dinoflagellate species *Muratodinium fimbriatum*, *Nematosphaeropsis reticulense*, *Phelodinium magnificum* and the terrestrial palynomorphs *Proxapertites cursus* and *Psilatricolporites crassus*. In SBC-3, this sequence contains late Paleocene planktonic foraminifera. Sequence I is Paleocene to early Eocene in age and represents Supercycle TA-2 of Haq *et al.* (1988).

Sequence J. This sequence is also Miocene in age, but is found overlying the unconformity and, as Sequence A, also represents Supercycle TB-2 (Haq *et al.*, 1988).

3.3. Cretaceous sequences

The seven Cretaceous sequences (B–H) interpreted with their associated dinoflagellate assemblages are in ascending order from oldest to youngest:

Sequence B. Recognized in PIC-1E and PIC-5E only, this sequence is characterized by low PMI and diversities, particularly in the lower part. The paleoenvironments represented are fluvial in the lower part and deltaic to shallow marine in the upper part. The lower part corresponds to the Barranquín Formation, while the upper represents the basal part of El Cantil.

The sequence contains the dinoflagellate species *Apteodinium spinosum*, *Cepadinium ventriosum*, *Cribroperidinium conjunctum*, *Trichodinium castaneum* and *Xenascus plotei*. Together with the spores *Auritulinasporites deltaformis*, *Callialasporites trilobatus*, *Cardiangulina crassiparietalis*, *Exesipollenties tumulus*, *Impardecispora* (*Trilobosporites*) *trioreticulosa*, and *Matonisporites* SCI 56 of Jardine et Magloire (1965), this assemblage indicates a Barremian-early Aptian age.

Sequence C. Recognized in PIC-1E and PIC-5E only, this sequence also shows low values of PMI. The paleoenvironments represented are marine, probably inner to middle neritic in the lower part and middle neritic in the upper part. The latter includes the basal Miembro Garcia of the El Cantil Formation (González de Juana, *et al.*, 1980; Falcon, 1988; Giovannina *et al.*, 1994).

The sequence yields the dinoflagellate species *Apteodinium spinosum*, *Oligosphaeridium albertense*, *O. pulcherrimum*, *Pseudoceratium eisenackii*, *P. interiorense*, *P. polymorphum*, *P. securigerum*, *Subtilisphaera terrula*, and the terrestrial palynomorphs *Aequitriradites spinulosus*, *Araucariacites australis*, *Auritulinasporites deltaformis*, *Crybelosporites pannuceus*, and *Impardecispora* (*Trilobosporites*) *trioreticulosa*. The age assignation is Aptian-early Albian.

Sequence D. Recognized in PIC-1E, PIC-5E and PIC-3E, this sequence is characterized by a slight increase in the values of the PMI. The paleoenvironments represented are marine, mostly middle neritic, with some transgressions reaching outer neritic depths. The upper part of the sequence contains calcareous nannofossils in PIC-1E.

The sequence contains the dinoflagellate species *Cepadinium ventriosum*, *Chichaouadinium arabicum*, *Cribroperidinium diaphane*, *Pseudoceratium interiorense*, *Subtilisphaera senegalensis*, *S. zawia* and the lowermost occurrences of *Dinopterygium cladoides*, and the spores *Auritulinasporites deltaformis* and *Elaterosporites protensus*.

Sequence E. Recognized in PIC-1E, PIC-5E, and PIC-3E, the PMI values in this sequence are low in the lower part and increase towards the top. The paleoenvironments represented are marine, mainly inner neritic in the lower part and outer neritic to bathyal in the upper part. The Querecual Formation is within the upper part of this sequence. The lithological characteristics of this unit (described above), and the content of planktonic foraminifera and calcareous nannofossils indicate that it was deposited in upper bathyal, anoxic environments, reflecting the deepest environments and the greatest extent of flooding in the entire section.

The upper part of sequence E contains the lowermost occurrence of the dinoflagellate genus *Dinogymnium* sp. In addition, the dinoflagellate species *Cerbia tabulata*, *Cribroperidinium cooksoniae* and the lowermost occurrences of *Palaeohystrichophora infusorioides* are encountered. Sequence E also yields the terrestrial palynomorphs *Afropollis jardinus*, *Corollina* sp., *Elaterosporites klaszi*, *E. verrucosus*, *Ephedripites* sp., and *Sofrepites legouxae*. The assigned age is late Albian-Turonian.

Sequence F. Recognized in PIC-1E, PIC-5E and PIC-3E, this sequence is characterized by a gradual increase in PMI values in the upper part. The paleoenvironments represented are marine, outer to middle neritic. The sequence corresponds to the lower part of the San Antonio Formation. It yields the dinoflagellate species *Canningia senonica*, *Cyclonephelium vannophorum*, *Kallosphaeridium helbyi*, *Subtilisphaera pirnaensis* and *Trichodinium castaneum*. Terrestrial palynomorphs are scarce to absent. The age assignation is Turonian-early Campanian.

Sequence G. Recognized in all four wells studied, this sequence is characterized by the highest PMI values, particularly in the upper part. The paleoenvironments represented are marine, mainly middle neritic, with occasional transgressions to outer neritic. The sequence corresponds to the upper part of the San Antonio Formation, which contains more sand than the lower part.

The sequence contains the dinoflagellate species *Aldorfia deflandrei*, *Andalusiella* spp., *Cerodinium* spp., *Cometodinium whitei*, *Dinogymnium heterocostatum*, *Isabelidinium* spp., *Kallosphaeridium ringnesiorum*, *Odontochitina operculata*, *Palaeohystrichophora infusorioides*, *Palynodinium grallator*, *Senegalinium bicavatum*, *Spinidinium echinoideum*, and *Xenascus ceratiodes*. Terrestrial palynomorphs are very scarce. The age assignation is early Campanian-Maastrichtian.

Sequence H. Recognized in all four wells studied, this sequence is characterized by a sharp decrease in the PMI values as compared to the underlying sequence. It corresponds to the sandy San Juan Formation. The paleoenvironments represented are shallow marine to deltaic. The sequence is partially Paleocene in age, representing Supercycle TA-1.0 of Haq *et al.* (1988).

It contains the highest occurrence of the dinoflagellate genus *Dinogymnium* sp. and the dinoflagellate species *Andalusiella polymorpha*, *Circulodinium distinctum*, *Palaeocystodinium australinum*, and *Senegalinium obscurum*. Also present are the terrestrial palynomorphs *Ariadnaesporites* spp., *Buttinia andreevi*, *Echitriporites trianguliformis*, *Foveotriletes margaritae*, *F. perforatus*, and *Proteacidites sigalii*. The age assignation is late Maastrichtian-early Paleocene.

4. Ages and correlation with global record

4.1. Chronostratigraphy

Based on dinoflagellates, planktonic foraminifera, and calcareous nannofossil analyses, it is apparent that sediments of Barremian-Maastrichtian age (Paredes *et al.*, 1994) are represented in the Eastern Basin of Venezuela. In general, the majority of the ages assigned are based on the stratigraphic ranges of the marine palynomorphs reported here (Figure 8).

The combination of the paleontological ages with the sedimentary sequences defined previously, allows correlation with the second Order Cycles of the Mesozoic-Cenozoic Cycle Chart of global eustatic

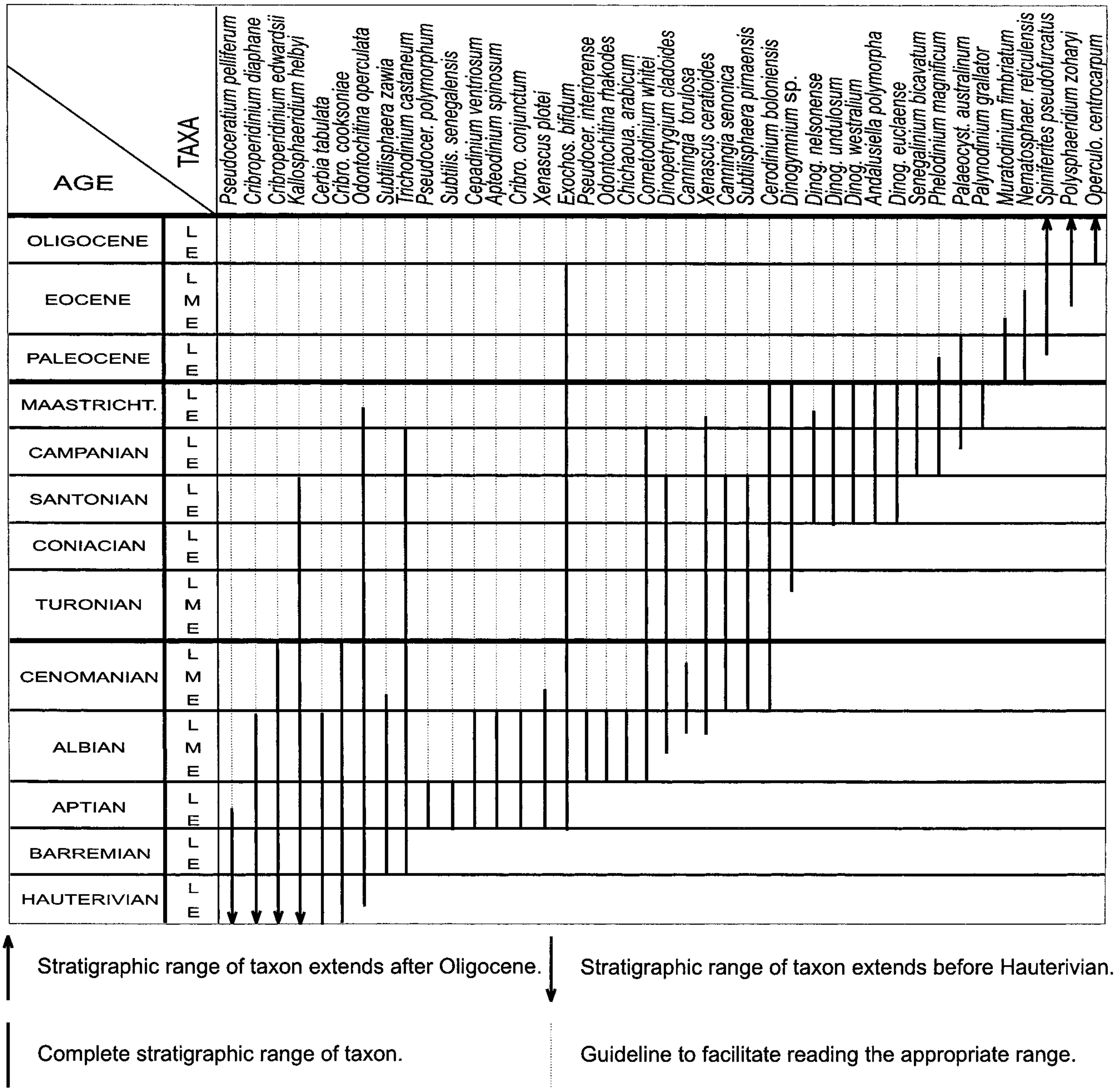

Figure 8. Stratigraphic ranges of the main marine palynomorph taxa found in the Eastern Basin of Venezuela.

events (Haq *et al.*, 1988). Correlation with this chart is the basis for the assignment of numerical ages to the sequence boundaries defined in the sections studied (Figure 9). The Cycle Chart is related to the global cycle chart of sea-level changes proposed by Vail *et al.* (1977), which was constructed with results from seismic stratigraphy studies of various regions including eastern Venezuela (Vail *et al.*, 1977, fig. 4).

The Cretaceous section from Venezuela's Eastern Basin represents marine sedimentation in a passive margin setting, from approximately 112 Ma to about 65 Ma. Considering only the age assignments for the sequence boundaries recognized, there are 64 Ma represented in approximately 4000 m of sediments.

4.2. *Correlation of sequences to supercycles*

The sequences described above can be correlated to the supercycles proposed by Haq *et al.* (1988). As noted above, Sequence A corresponds to the Miocene sedimentary rocks underlying the thrust fault and represents Supercycle TB-2. Sequence J is also

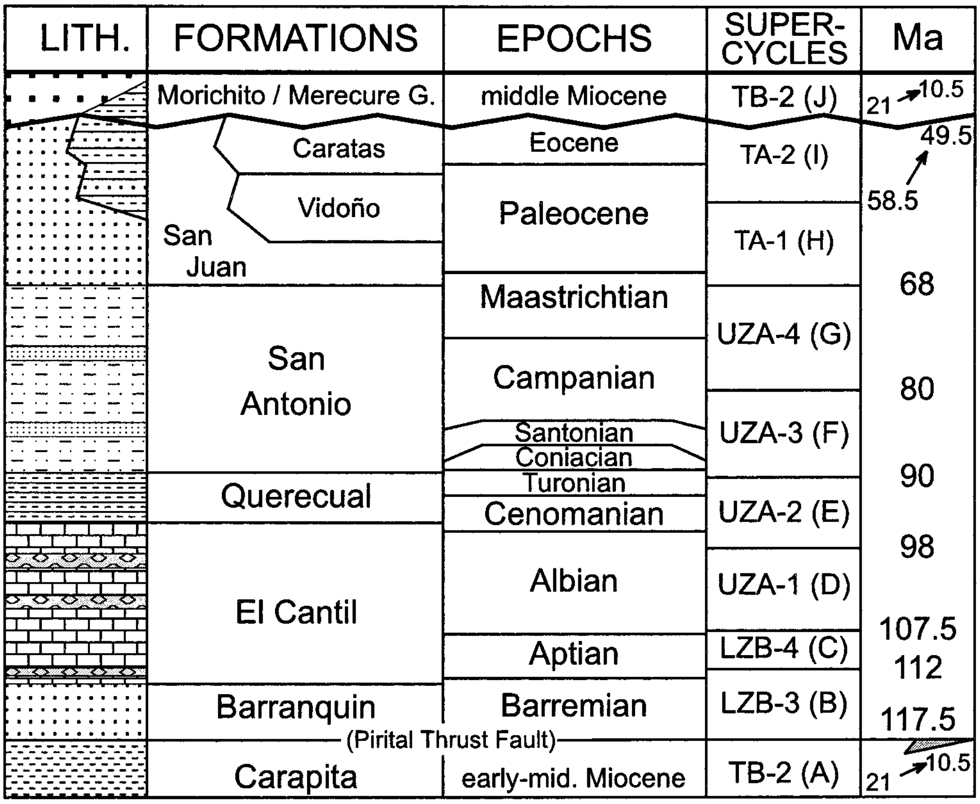

Figure 9. Cretaceous sequences and chronostratigraphy in the Eastern Basin of Venezeula. Supercycles from Haq *et al.* (1988)). A to J are the stratigraphic sequences recognized in this study. Lithologic symbols are the same as those in Figure 2.

Miocene, but overlying the unconformity and also represents Supercycle TB-2. Sequence I is early Eocene and represents Supercycle TA-2, while sequence H is partially Paleocene in age and represents Supercycle TA-1. The rest of the sequences are Cretaceous, and in ascending stratigraphic order are:

Sequence B. Barremian-early Aptian, corresponds to the upper part of Supercycle LZB-3 (Haq *et al.*, 1988) dating from 117.5 to 112.2 Ma.

Sequence C. Aptian-early Albian, corresponds to Supercycle LZB-4 (Haq *et al.*, 1988) dating from 112 to 107.5 Ma. In addition to the palynomorphs reported above, the upper half of sequence C contains Aptian calcareous nannofossils in PIC-1E.

Sequence D. Albian, corresponds to Supercycle UZA-1 (Haq *et al.*, 1988) dating from 107.5 to 98 Ma. The upper half of this sequence contains late Albian calcareous nannofossils in PIC-1E.

Sequence E. Late Albian-Turonian, corresponds to Supercycle UZA-2 (Haq *et al.*, 1988) dating from 98 to 90 Ma. This sequence in PIC-1E contains Albian-Cenomanian calcareous nannofossils in the lower part, and Cenomanian-Santonian planktonic foraminifera in the middle.

Sequence F. Turonian-early Campanian, corresponds to Supercycle UZA-3 (Haq *et al.*, 1988) ranging from 90 to 80 Ma. In PIC-1E, this sequence contains calcareous nannofossils indicating age-ranges from Turonian to Santonian. Barremian-Coniacian planktonic foraminifera are present in the middle part of the sequence in PIC-5E.

Sequence G. Early Campanian to late Maastrichtian, corresponds to Supercycle UZA-4 (Haq *et al.*, 1988) dating from 80 to 68 Ma.

Sequence H. Late Maastrichtian-early Paleocene, corresponds to the lower part of Supercycle TA-1 (Haq *et al.*, 1988) ranging from 68 to 58.5 Ma. The location of the Cretaceous-Tertiary boundary cannot be determined paleontologically because of the poor fossil recovery from the sandy part of the San Juan Formation. It is likely to be unconformable. In SBC-3 the interval from 1018 to 815 m contains a mixture of Paleocene and Maastrichtian taxa. Core samples at 815 m and 817 m contain scarce specimens of the Cretaceous dinoflagellate *Circulodinium distinctum* and the spore *Bahiaporites reticularis* which we consider to be reworked, based on their poor state of preservation and the combined presence of several Paleocene species, such as (Paleocene to middle Eocene) *Nematosphaeropsis reticulensis* and *Cordosphaeridium exilimurum* (Paleocene to early Eocene).

5. Regional distribution

Based on our chronostratigraphic framework, the analysis of the sedimentary evolution of the area studied allows us to recognize the following regional distribution of some of the most important stratigraphic units and sedimentological events.

5.1. Barremian to early Aptian

The Barremian to early Aptian non-marine to marginally marine sediments of the Barranquin Formation are widespread in eastern Venezuela (Erikson, 1994). Apparently these strata represent the initial stages of an extensional regime in the area.

In western Venezuela, the Rio Negro and lower part of the Apon Formations (Lugo, 1994; Parnaud *et al.*, 1995) represent paralic to shallow marine environments. In Colombia, the Paja Formation represents completely marine conditions related to the development of the Pacific margin of South America (Cooper *et al.*, 1995).

5.2. Aptian transgression

The first important flooding surface observed in these sections corresponds to the lower part of the El Cantil Formation, and represents the Aptian transgression dated at 111 Ma. In our area of study this transgression attained middle neritic depths as indicated previously. In the Serranía del Interior, this transgression is represented by the Miembro García of the El Cantil Formation (Falcon, 1988), and represents outer neritic to upper bathyal environments as indicated by the presence of common planktonic foraminifera and calcareous nannoplankton.

In western Venezuela (Lugo, 1994; Parnaud *et al.*, 1995) this event correlates with the Apon Formation, and in Colombia it is represented by the Caballos and Tablazo Formations (Cooper *et al.*, 1995).

5.3. Albian transgression

The Albian transgression indicated in the upper part of the El Cantil Formation is correlatable with that dated at 98.5 Ma, which corresponds to the upper part of Supercycle UZA-1 (Haq *et al.*, 1988). This event is closely related to the first marine transgression observed in the Barinas-Apure Basin of western Venezuela by Lugo (1994), Helenes *et al.* (1994, 1998), and Parnaud *et al.* (1995). In the Maracaibo Basin area of western Venezuela (Lugo, 1994; Parnaud *et al.*, 1995) and in northwestern and central Colombia (Cooper *et al.*, 1995), this transgressive event is related to the early phases of deposition of the La Luna Formation.

5.4. Turonian transgression

The black shales of the Querecual Formation in eastern Venezuela represent deposition in bathyal environments (González de Juana *et al.*, 1980; Villamil, 1996). These strata commonly contain planktonic foraminifera and calcareous nannofossils, and are the product of one of the most important transgressions observed in the sections studied. They correspond to the Turonian transgression (91.5 Ma) found in the upper part of Supercycle UZA-2 (Haq *et al.*, 1988).

In western Venezuela, these strata can be correlated to the La Morita Member of the Navay Formation of the Barinas-Apure Basin (Lugo, 1994; Helenes *et al.*, 1998), and parts of the La Luna Formation in the Maracaibo Basin (Lugo, 1994; Parnaud *et al.*, 1995) and in central and northern Colombia (Martinez & Hernandez, 1992; Cooper *et al.*, 1995).

In Central America, there are few reports of Cretaceous sediments correlatable with these events. In Costa Rica (Sprechmann, 1984, fig. 16), mid-Cretaceous rocks in the west are related to the ophiolites of the Nicoya Complex while in the east they have not been reported. In Honduras (Finch, 1981), the mid- to upper Cretaceous Los Angeles Group is represented mostly by red beds. However, they include the Cenomanian Jaitique Formation, which is composed of thick-bedded limestones with shallow water benthonic foraminifera in the lower part (the Jaitique Member), and by thin-bedded, dark, shaly limestones with planktonic foraminifera in the upper part (Guare Member). The Guare Member may represent the Turonian transgression.

5.5. Santonian to Maastrichtian transgressions

In general, from Coniacian to Maastrichtian the area was completely within the marine realm. However, the San Antonio Formation contains two main flooding surfaces; the Santonian one correlates with the condensed section dated at 86 Ma, and that of the early Maastrichtian correlates with the condensed section dated at 73.5 Ma. Similar conditions also prevailed in western Venezuela during deposition of the Burguita Formation in the Barinas-Apure Basin (Lugo, 1994; Helenes *et al.*, 1998), the upper part of the La Luna and the Colón Formations in the Maracaibo Basin (Lugo, 1994; Parnaud *et al.*, 1995), and in much of central and northern Colombia (Martínez & Hernández, 1992; Cooper *et al.*, 1995). In the Llanos Basin of eastern Colombia, only one of these transgressions is represented by fine grained clastics in the Guadalupe Formation (Cooper *et al.*, 1995).

5.6. Maastrichtian-Paleocene fall in sea-level

The coarse to medium sandstones of the San Juan Formation represent deposition after a sharp fall in sea level, corresponding to the 68 Ma sequence boundary. In western Venezuela and Colombia, this event is obscured by the tectonic accretion of the Western Cordillera in Colombia (Cooper *et al.*, 1995).

6. Conclusions

In the relatively shallow marine environments of deposition commonly indicated in the sections studied, dinoflagellates provide better biostratigraphic resolution than either planktonic foraminifera or calcareous nannofossils. A Palynomorph Marine Index is useful in identifying flooding surfaces and sequence boundaries within these deposits.

Cretaceous strata in the subsurface of eastern Venezuela have a maximum thickness of 3658 m and encompass ages ranging from Barremian to Maastrichtian. Seven stratigraphic sequences are recognized and correlated with Supercycles LZB-3 to TA-1 of Haq *et al.* (1988).

The first important flooding surface corresponds to the lower part of the El Cantil Formation, and represents the Aptian transgression correlated to the condensed section dated at 111 Ma. The Albian transgression found in the upper part of the El Cantil Formation is correlatable to the condensed section dated at 98.5 Ma. After this transgression, and for most of the Cenomanian, deposition in shallow marine environments, with an input of large amounts of terrestrial palynomorphs, is indicated.

The most important maximum flooding surface observed corresponds to the Turonian transgression (91.5 Ma) of the Querecual Formation, and can be correlated with sections in western Venezuela and Colombia.

The Santonian flooding surface in the lower part of the San Antonio Formation is correlated with the condensed section dated at 86 Ma, and the early Maastrichtian flooding surface in the upper part of the San Antonio Formation with the condensed section dated at 73.5 Ma. The San Juan Formation represents deposition after a sharp fall in sea level, corresponding to the 68 Ma sequence boundary.

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