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Paleoceanographic changes at the Jurassic–Cretaceous boundary in the Western Tethys, northeastern Mexico

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Mexico is usually considered to have formed the western end of the Tethys during Late Jurassic and Early Cretaceous times. The circumstances of the opening of the Gulf of Mexico Basin towards the Tethys and the exact stratigraphic timing, however, are not clear. Four sections covering this time interval, located in northeastern Mexico, have been measured and sampled in detail, in order to clarify their stratigraphic position during the Late Jurassic to Early Cretaceous time interval and the paleogeographic and oceanographic changes that accompanied this opening. Our studies include microfacies, micro- and macropaleontology, whole rock and clay-mineral x-ray diffraction and stable isotopes analyses. Our data indicate that the Jurassic–Cretaceous boundary, as defined by the Lyon-Neuchâtel Colloquium of 1973, cannot be determined precisely in northeastern Mexico due to the near-absence of calpionellids and endemism of ammonite taxa. In the lower and upper Berriasian sediments, we detected Mediterranean ammonite taxa so far unknown from Mexico, corresponding to the appearance of typical calpionellid-rich facies. These faunas allow direct biostratigraphic correlation with European ammonite and calpionellid zones.

We propose that a major oceanographic change occurred in the upper part of calpionellid Zone B of the Early Berriasian. At this time, sediments in northeastern Mexico present increasingly pelagic facies, a dramatic appearance of Tethyan microfossils (calpionellids) and ammonites, changes in stable isotopic values, whole rock and clay-mineral mineralogy. We suggest that these changes are due to a global sea-level rise that connected directly northeastern Mexico to the European Tethys and ended the endemic, semi-restricted and anoxic environment of the Late Jurassic La Casita and equivalent La Caja and La Pimienta Formations.

KEY WORDS: Mexico; Tithonian; Berriasian; ammonites; calpionellids; clay minerals; stable isotopes; correlation; Tethys; anoxia; source-rocks; sea-level rise.

1. Introduction

It is generally believed that Mexico formed the western end of the Tethys during Late Jurassic to Early Cretaceous time and thus constitutes a key area for correlating Tethyan and pacific domains.

The paleogeographic setting of northeastern Mexico, however, is not yet clear (Fourcade *et al.*, 1991) and biostratigraphic correlations with the European Tethys are difficult due to endemism of ammonite and microfossils taxa (Imlay, 1938, 1939; Verma & Westermann, 1973; Contreras *et al.*, 1988). Preliminary data about calpionellid and ammonite distribution (Adatte *et al.*, 1994) suggested that Mediterranean calpionellid zones can be applied to northeastern Mexican

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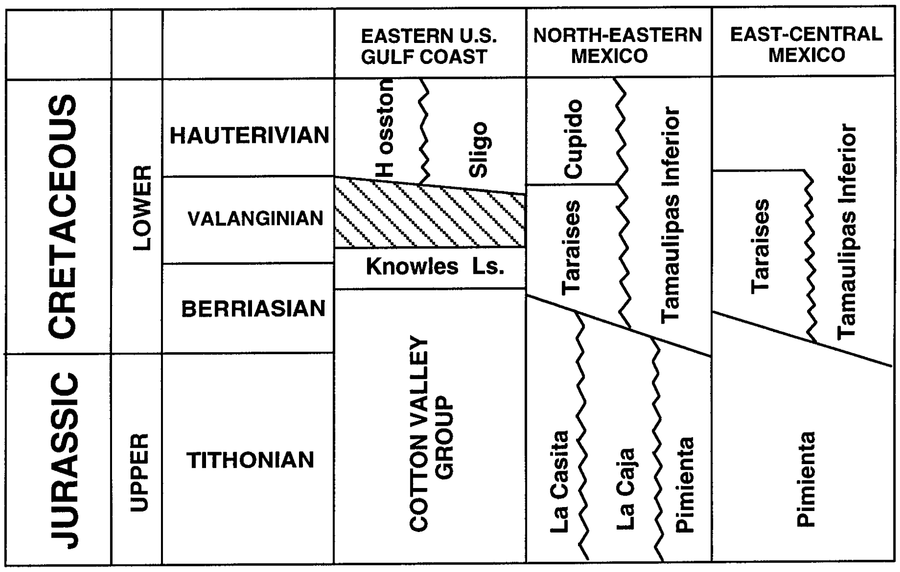

Figure 1. Simplified stratigraphic correlation chart, Upper Jurassic–Lower Cretaceous in eastern US Gulf Coast, northeastern and east-central Mexico (modified from Salvador, 1991).

series from Lower Berriasian to Lower Valanginian, thus putting an end to controversies among different ammonite stratigraphers.

The Jurassic–Cretaceous boundary in northeastern Mexico is usually placed at the boundary between the La Casita and Taraises (Figure 1) Formations, which present a wide geographic distribution in northeastern Mexico and correlate to the Cotton Valley Group in Texas, USA (e.g., Imlay, 1938; Verma & Westermann, 1973; Cantu Chapa, 1982, 1989; Salvador, 1991). The upper part of the La Casita Formation usually consists of shales rich in organic matter, sandy shales and calcareous sandstones with phosphorite levels and calcareous concretions. The basal Taraises Formation is characterized by marls and limestones with shaly interlayers showing a reduced detrital input. In northeastern and east-central Mexico, the boundary between these formations corresponds to a change from detrital to carbonate sedimentation. Due to high contents of organic matter, the La Casita and equivalent La Caja and La Pimienta Formations are the main source-rocks for hydrocarbon generation in Mexico (Holguin Quiñones, 1988; Ortuño *et al.*, 1990; Nehring, 1991; Santamaria *et al.*, 1992).

The present study attempts to clarify the paleoceanographic setting of northeastern Mexico during the Jurassic–Cretaceous interval. We studied the upper part of the La Casita and the Taraises Formations (Figures 4–7) in sections at San Pedro del Gallo, in the Durango Basin (PG, Figure 2), Puerto Piñones (PP) and Sierra de Jabali (SJ) in the western part of the ancient Gulf of Mexico Basin and Iturbide (IT) in the northern Sierra Madre Oriental (Figure 2). Each section was measured and sampled in detail. Laboratory investigations included microfacies analyses, micropaleontology, macropaleontology, whole rock and clay-mineral studies and stable isotope analyses.

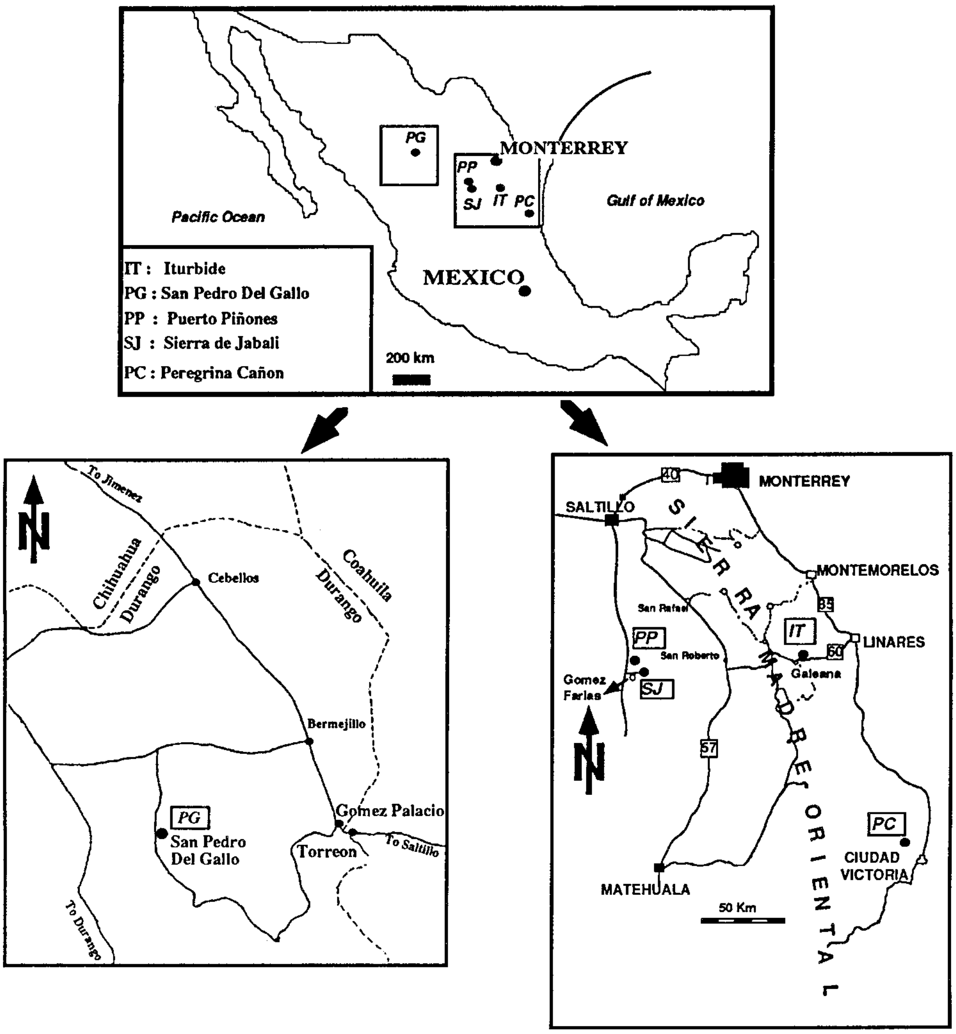

Figure 2. Map showing the locations of the sections examined.

2. Localization and lithostratigraphic description of the studied sections

The Puerto Piñones section (PP) is located on the Mexican Altiplano in the internal part of the Sierra Madre Oriental, approximately 80 km south of the city of Saltillo (State of Coahuila). The outcrop exposes Late Jurassic to Early Cretaceous sediments along the Saltillo–Concepcion del Oro railway line, 5 km south of the Carneros railway station (Figure 2). The sampled section is 40 m thick and includes the lithostratigraphic boundary between the La Casita and the Taraises Formations. The La Casita Formation is mainly shaly and becomes more calcareous towards the top. Its transition to the micritic limestones of the Taraises Formation is gradual (Figure 4).

The Sierra Jabali section (SJ) is located about 25 km (Figure 2) south of the Puerto Piñones in the Sierra Jabali east of the Gomez Farias railway station. This section is 90 m thick and also shows the transition from the La Casita to the

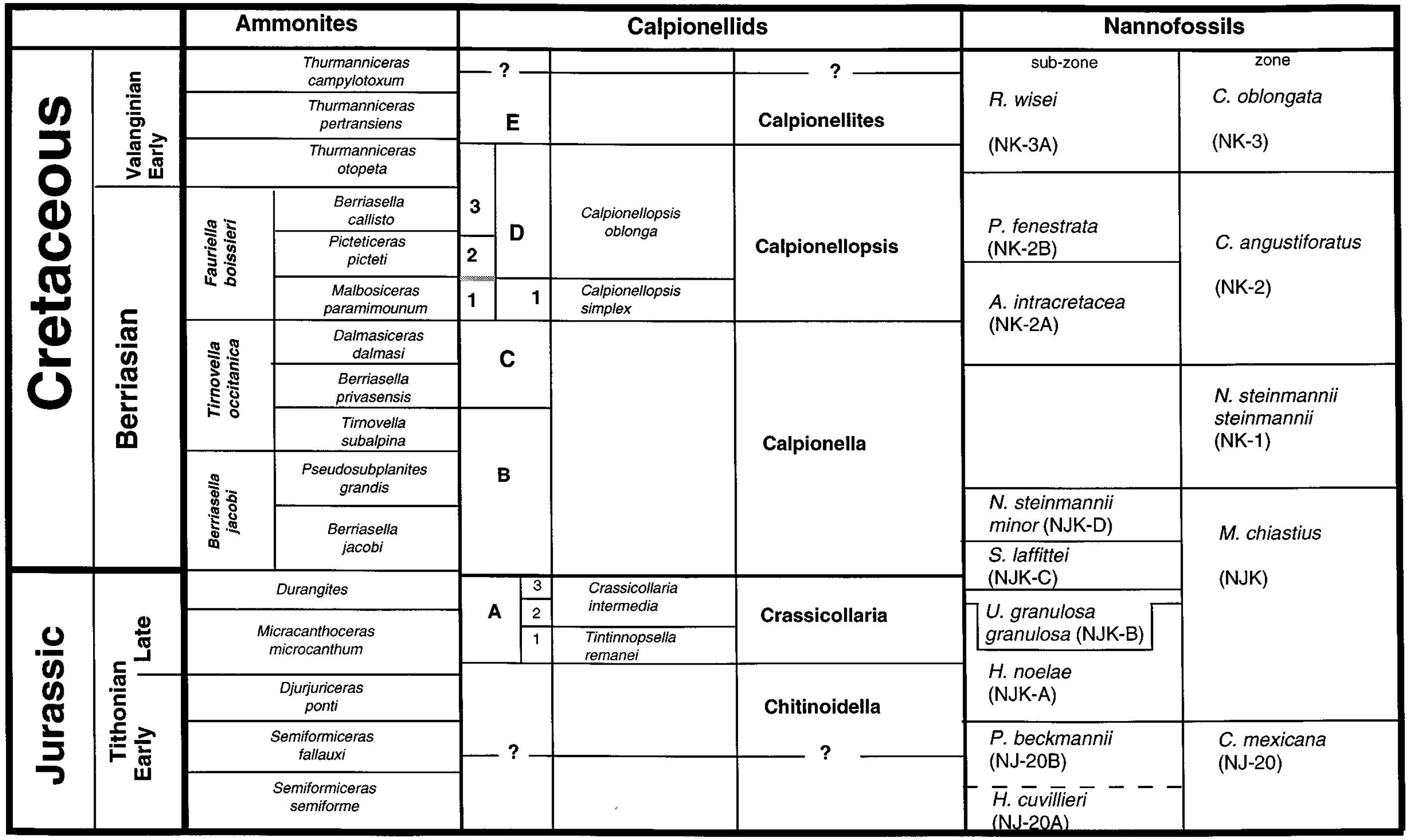

Figure 3. Correlation between Western Mediterranean ammonite zones, calpionellid and nannofossil zones. From left to right: Vocontian calpionellid zones after Remane (1985); Sümeg and Rome standard zones after Remane *et al.* (1986) and Allemann *et al.* (1971). Correlation with nannoplankton zones according to Bralower *et al.* (1989). NJ Jurassic nannoconids; NJK Jurassic to Cretaceous nannoconids; NK Cretaceous nannoconids.

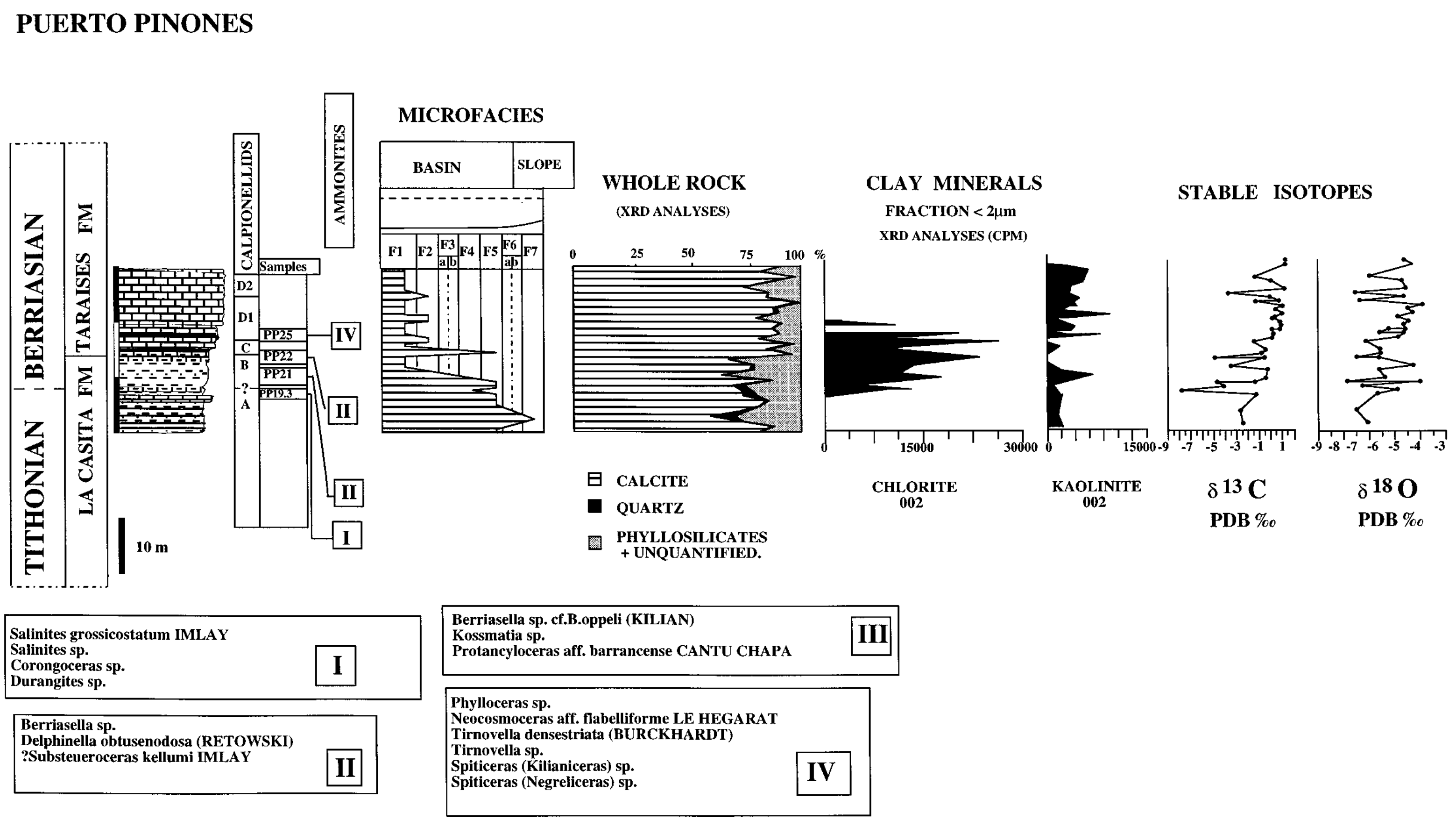

Figure 4. Puerto Piñones section, from left to right: lithological column; distribution of the main ammonite species compared to calpionellid zonation; succession of microfacies; composition of whole rock; distribution of chlorite and kaolinite, size fraction $<2\ \mu m$, air-dried, in counts by minutes (CPM); and oxygen and carbon stable isotopes of bulk rock.

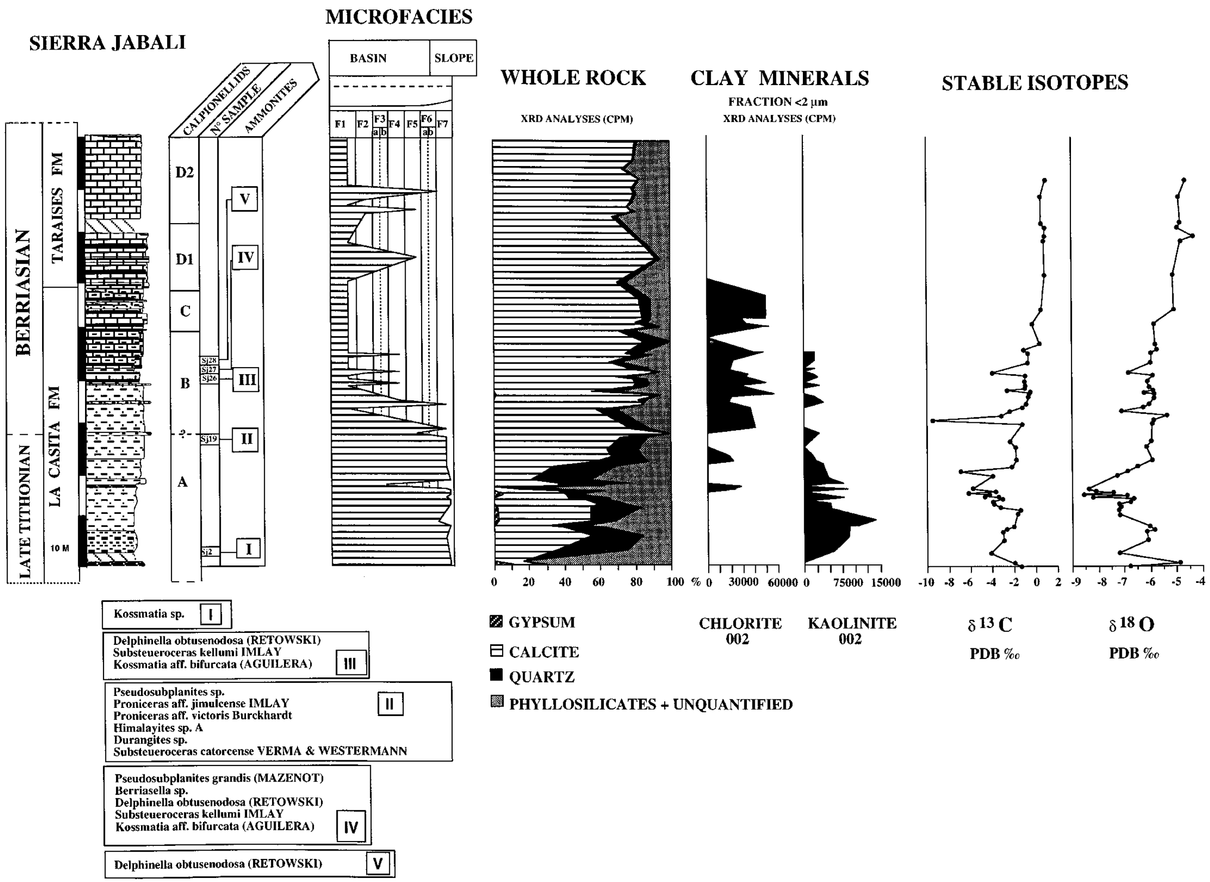

Figure 5. Sierra Jabali section (SJ), from left to right: lithological column; distribution of the main ammonite species compared to the calpionellid zonation; succession of microfacies; composition of whole rock; distribution of chlorite and kaolinite, size fraction $<2\ \mu m$, air-dried, in counts by minutes (CPM); and oxygen and carbon stable isotopes of bulk rock.

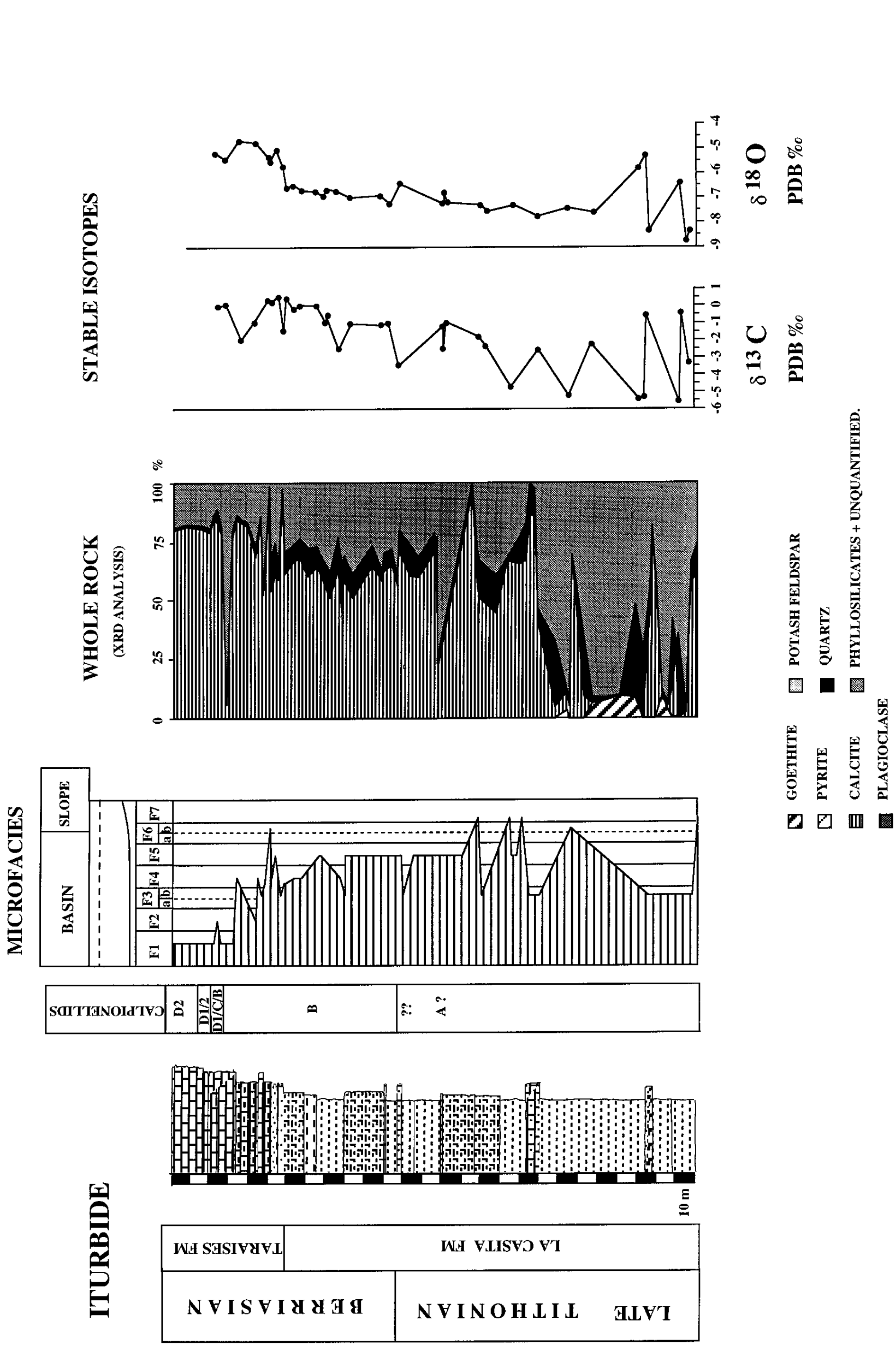

Figure 6. Iturbide section, from left to right: lithological column; calpionellid zonation; succession of microfacies; composition of whole rock; and oxygen and carbon stable isotopes of whole rocks. Note that chlorite is not represented and kaolinite has disappeared, resulting from very low grade metamorphism.

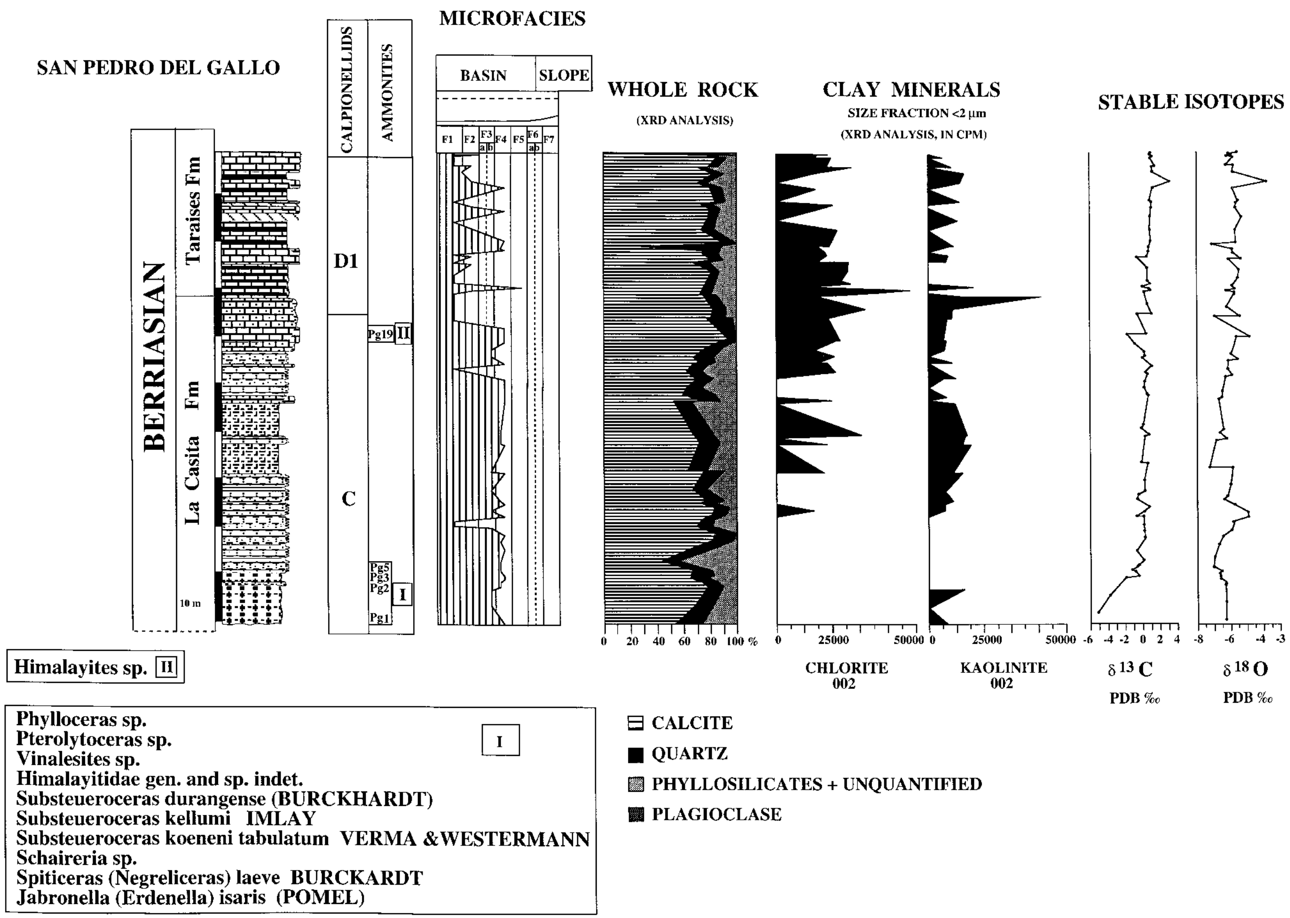

Figure 7. San Pedro Del Gallo section, from left to right: lithological column; distribution of the main ammonite species compared to the calpionellid zonation; succession of microfacies, composition of whole rock; distribution of chlorite and kaolinite, size fraction $<2\ \mu m$, air-dried, in counts by minutes (CPM); and oxygen and carbon stable isotopes of whole rocks.

Taraises Formation. The lithological characteristics resemble those at the PP section (Figure 5).

The village of Iturbide is located in the Sierra Madre Oriental fold belt, along the road N 60 that links Linares and San Roberto (Figure 2). Two hundred and sixty-eight metres of section were measured on a mountain flank, at the northern entrance of the village (IT). The section includes the top of the La Casita Formation and the lower part of the Taraises Formation. The La Casita Formation consists of alternating black and yellow shales, siltstones, calcareous phosphatic sandstones and intercalated calcareous concretions. The transition to the Taraises Formation is marked by the change from terrigenous sedimentation towards thick beds of micritic limestones (Figure 6).

San Pedro del Gallo (PG) in the State of Durango is approximately 400 km W of Saltillo (Figure 2). The section is located at a site called La Peña, about 10 km N of San Pedro del Gallo, along the road that connects the village with La Cadena. From bottom to top, the upper part of the La Casita Formation consists of 70 m of calcareous sandstones, black to yellow shales with rare phosphatic layers and marly to argillaceous limestones. The transition to the Taraises Formation is characterized by the appearance of thick limestone (Figure 7). Thirty-five metres of the basal Taraises Formation were sampled.

3. Results

3.1. Micropaleontology: calpionellids

Details of calpionellid zones and their correlation with zonations based on other fossil groups are given in Figure 3. All calpionellid species known from Mexico also occur in Europe (Bonet, 1956; Trejo, 1960, 1980), but the opposite is not true. No typical associations of the *Crassicollaria* Zone (=A of the Vocontian standard zonation) have been encountered; some poorly represented faunas with occasional large *Crassicollaria* (*C. massutiniana* or *C. intermedia*, Figure 8) might belong to Zone A, but *Calpionella alpina* is always predominant, as commonly seen in Zone B (Figure 8). Hence, the lower boundary of the *Calpionella* Zone (corresponding to the Tithonian-Berriasian boundary), i.e., the Jurassic–Cretaceous boundary as defined by the Lyon-Neuchâtel Colloquium of 1973, cannot be determined precisely in northeastern Mexico. The *Chitinoidella* Zone and the *Saccocoma* microfacies are also absent in this area (Figures 2–6). Isolated levels with *Saccocoma* or *Chitinoidella* were, however, observed further south in central-east Mexico (Adatte *et al.*, 1996).

The subdivision of the *Calpionella* Standard Zone (B + C of the Vocontian zonation) is also problematic. Three different subdivisions of the *Calpionella* Standard Zone have been proposed for different regions: Catalano & Liguori (1971) used the first occurence of *Calpionella elliptica* to define the base of the *Calpionella elliptica* Subzone in the upper part of the *Calpionella* Zone; Pop (1986) distinguished a *Remaniella cadischiana* Subzone in the middle part of the *Calpionella* Zone, whereas Remane (1963, 1985, 1986) subdivided this interval in Zone B (below) and Zone C (above).

The *Calpionella elliptica* Subzone cannot be applied in northeastern Mexico, because *C. elliptica* is present only sporadically. The *Remaniella cadischiana* Subzone, established in the eastern Carpathians and Cuba, cannot be used either in NE Mexico because this species is also rare. Zone C is defined by a rapid increase in abundance of *Tintinnopsella carpathica* (Figure 8), along with the presence of large forms of this species. In all studied sections, anomalously high

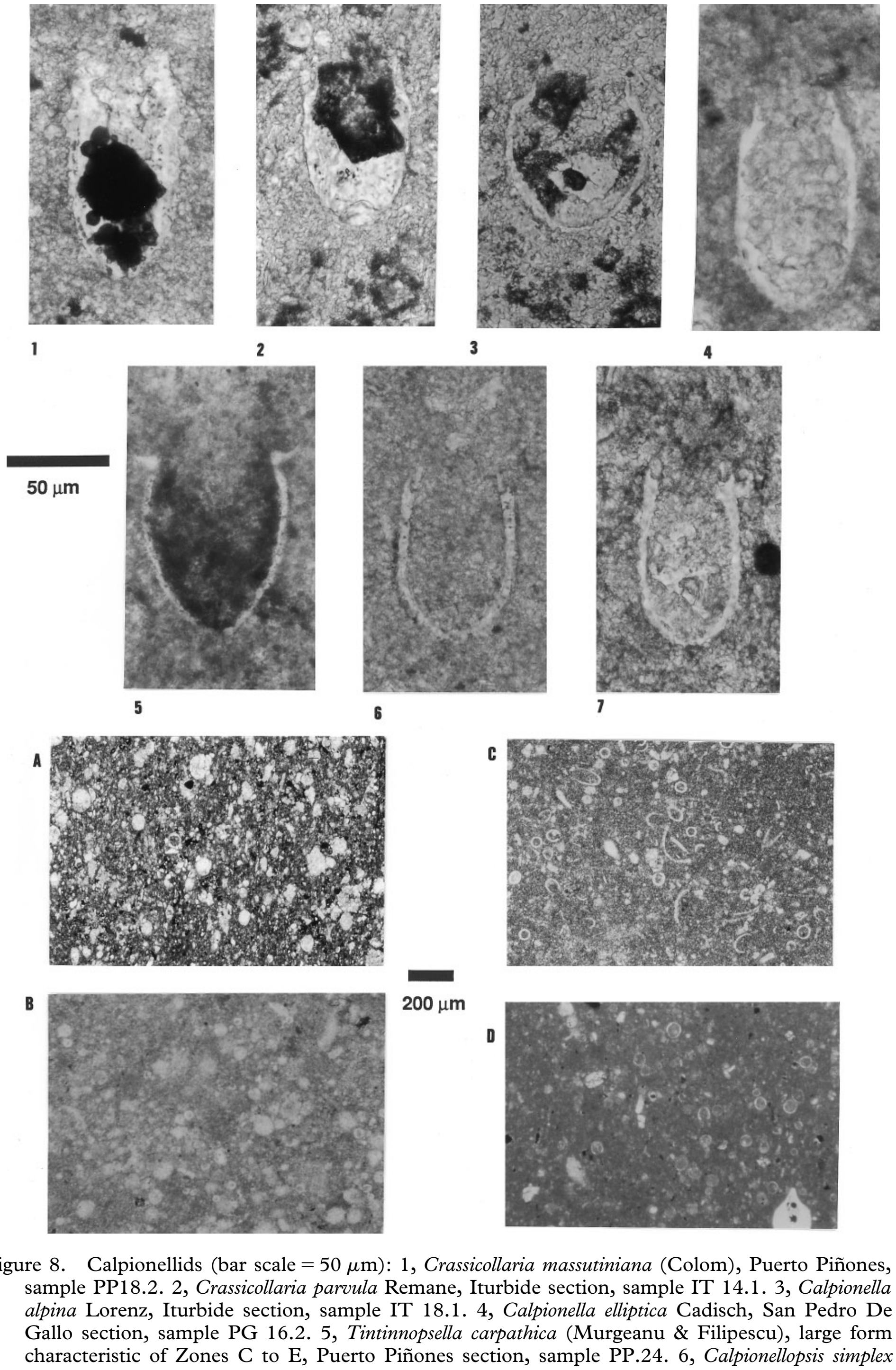

Figure 8. Calpionellids (bar scale = 50 μm): 1, *Crassicollaria massutiniana* (Colom), Puerto Piñones, sample PP18.2. 2, *Crassicollaria parvula* Remane, Iturbide section, sample IT 14.1. 3, *Calpionella alpina* Lorenz, Iturbide section, sample IT 18.1. 4, *Calpionella elliptica* Cadisch, San Pedro De Gallo section, sample PG 16.2. 5, *Tintinnopsella carpathica* (Murgeanu & Filipescu), large form characteristic of Zones C to E, Puerto Piñones section, sample PP.24. 6, *Calpionellopsis simplex* (Colom), Puerto Piñones section, sample PP.25.1. 7, *Calpionellopsis oblonga* (Cadisch), Puerto Piñones section, sample PP.27.1. Microfacies (bar scale = 200 μm): A, Biomicrite with abundant recrystallised radiolarians (F3A). B, Biomicrite with equally abundant calpionellids and radiolarians (F4). C, Biomicrite with abundant calpionellids (F1). D, Biomicrite with calpionellids and few circalittoral elements (*Lenticulina* near bottom, at right, F2).

frequencies of *C. alpina* render the recognition of the B/C zone boundary difficult, and the presence of large *Tintinnopsella carpathica* cannot be confidently determined since this species is rare and poorly preserved. In all sections, however, the base of the *Calpionellopsis* Zone is clearly recognizable and exact correlation with European sections is easy from the *Simplex* Subzone (D1) to the following Valanginian *Calpionellites* Zone (E). Calpionellid faunas in NE Mexico are thus represented by species known from southern Europe, and their sequence corresponds to the zonation used in that area (Figure 3)

According to these biostratigraphic results, the extension of the La Casita Formation is not restricted to the Jurassic, but reaches up far into calpionellid Zone B or even C of the Berriasian (in San Pedro del Gallo, Figure 7). Although Zone A is not clearly documented in the shales of the La Casita Formation, sediments of this age should be present, as there are no indications for a stratigraphic gap in the sediment sequence. In the SJ, PP and IT sections, the first well-preserved and abundant calpionellid faunas indicate Upper Zone B (Adatte *et al.,* 1994).

3.2. Macropaleontology: ammonites

Ammonite faunas were recovered from Tithonian to lower Valanginian strata. The stratigraphical ranges of some genera were controversially discussed in terms of European zones, but are now calibrated by calpionellids (Adatte *et al.,* 1994). In the view of this correlation, *Durangites* and *Salinites* cross the Jurassic–Cretaceous boundary and extend into the lowermost part of Zone B of the basal Berriasian. *Kossmatia* reaches into the upper part of this zone (Figures 4–7), and *Substeueroceras* was found to extend into Zone C at San Pedro del Gallo (Figure 6).

Mediterranean ammonite taxa, so far unknown from the Berriasian of Mexico (e.g., *Delphinella obtusenodosa*, *Pseudosubplanites grandis*) were discovered in the upper part of calpionellid Zone B and higher. Their presence greatly improves direct transatlantic correlation with Europe. Their first appearance corresponds to the first occurrence of calpionellid-rich facies.

3.3. Microfacies

Seven different microfacies were recognized in the studied sections, all indicating open marine environments (Figures 4–7); F1 to F6 indicate pelagic to hemipelagic environments and F7 reflects outer platform conditions (circalittoral).

Microfacies F1 is a biomicrite with abundant calpionellids, 'filaments', rare calcispheres and ammonites. It is characteristic of pelagic to hemipelagic environments. Microfacies F2 consists of a biomicrite with abundant sponge spicules, calpionellids, filaments, ammonites and rare, small agglutinated foraminifera, *Nodosariidae* and small echinoderm debris. It indicates a hemipelagic environment with some outer platform (circalittoral) input. Microfacies F3 is characterized by a biomicrite with very abundant and strongly recrystallized radiolaria and calcispheres in a silty matrix rich in organic matter (F3A) or, more rarely, with well preserved radiolaria in a micritic matrix (F3B). Both contain some pellets, 'filaments' and scarce calpionellids (Figure 8). This microfacies indicates a pelagic to hemipelagic environment under anoxic conditions.

Microfacies F4 is a biomicrite with equal amounts of calpionellids and radiolaria (Figure 8). It indicates a pelagic environment. Microfacies F5 represents a micrite poor in calpionellids and radiolaria with rare small agglutinated foraminifera. It indicates a hemipelagic environment with sporadic

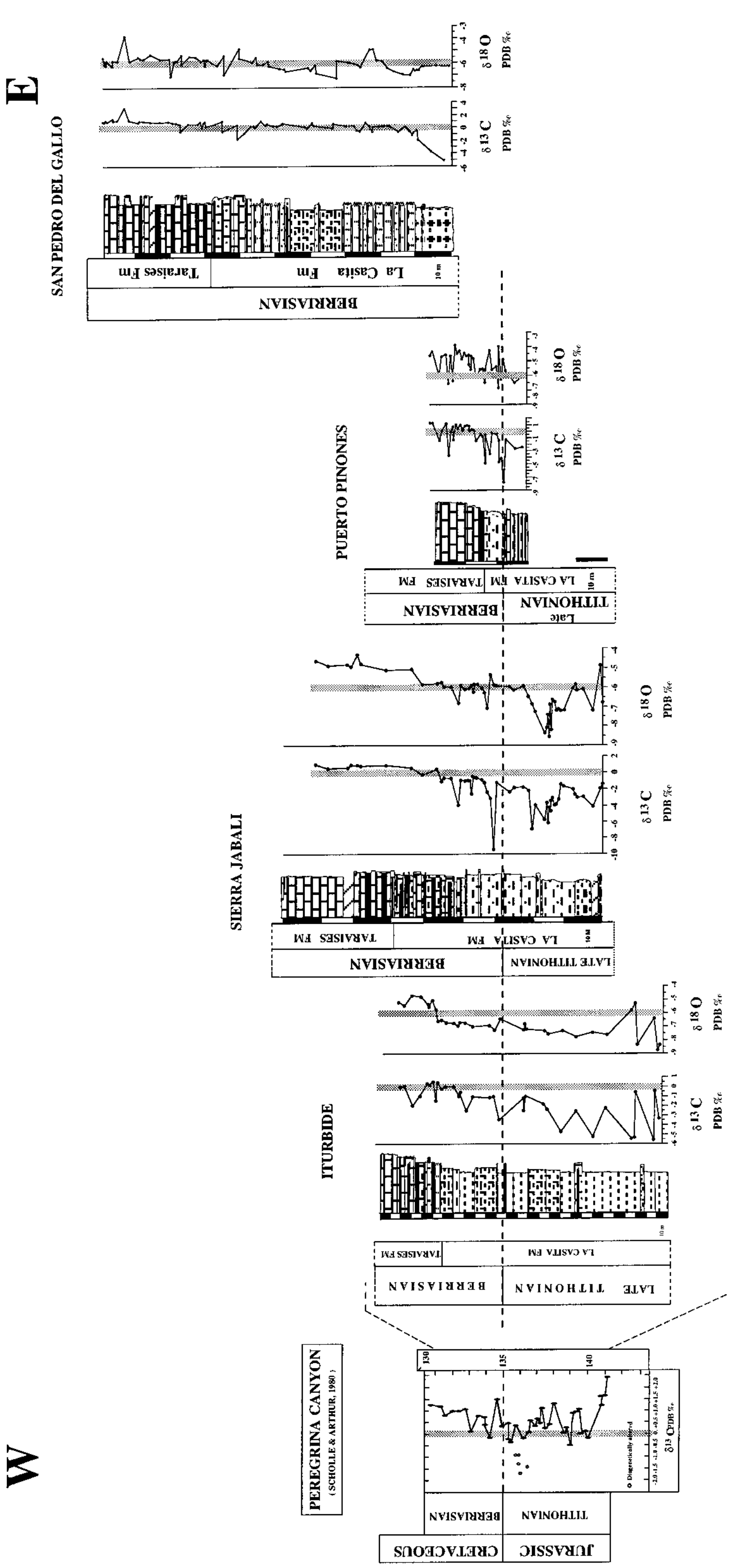

Figure 9. Biostratigraphic correlation of the four sections studied and distribution of the stable isotope, compared with stable isotopes at the Peregrina Cañon section, near Ciudad Victoria (Figure 2; Scholle & Arthur, 1980). Biostratigraphic ages are based on unpublished work by Shell Development Co., using all calcareous microfossils groups, and Elliot (1979), using microfossil and ammonite assemblages (in Scholle & Arthur, 1980). Stage calibrations are from Odin (1994).

and attenuated outer platform (circalittoral) input. Microfacies F6 includes a micrite (F6a) or a silty clay with fine quartz and abundant organic matter (F6b); both facies reflect almost azoic conditions, except for very rare radiolaria and ‘filaments’. It suggests a hemipelagic environment and anoxic conditions. Microfacies F7 is an intramicrite with phosphatic grains and rare sponge spicules, small foraminifera, bivalves, ammonites, isolated calpionellids and radiolaria. It indicates an outer platform (circalittoral) environment.

The microfacies curves (Figures 4–6) at Iturbide, Puerto Piñones and Sierra Jabali sections show a similar evolution. The upper La Casita Formation is characterized by occasional phosphorites (F7), abundant radiolaria and scarce calpionellids (F3–F6) indicating hemipelagic to outer platform environments under partly anoxic conditions. A significant change occurs in the upper part of calpionellid Zone B, near the top of the La Casita and lower Taraises Formations. In this interval, the appearance of calpionellid-rich microfacies indicates more open pelagic environments. We propose that this environmental change is related to a global sea-level rise (Figure 10), as previously observed elsewhere by Haq *et al.* (1988). The fact that calpionellid zones C and D (1–2) are very condensed at Iturbide, Puerto Piñones and Sierra Jabali can be explained by their basinward location, where condensed sedimentation prevails during transgressive intervalls and sea-level high-stands.

At San Pedro del Gallo (Figure 7) radiolaria remain abundant throughout the calpionellid Zones C to D1 (F4), but calpionellids are also well represented. In the lower Taraises Formation, this facies F4 characteristically alternates with

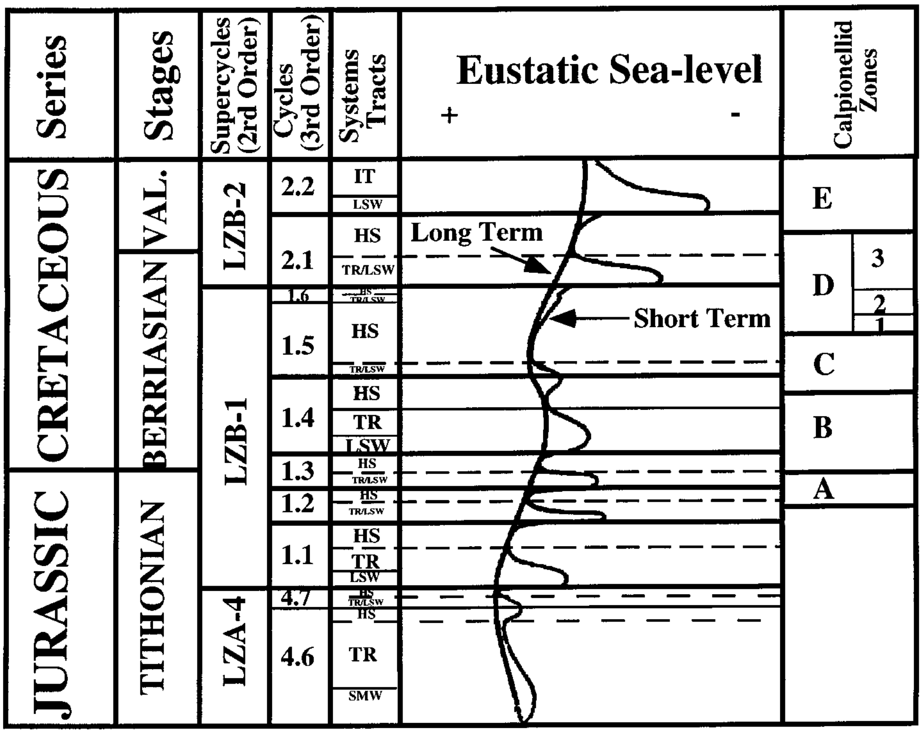

Figure 10. Eustatic sea-level curve by Haq *et al.* (1988), modified, compared with the standard calpionellid zonations for the Late Tithonian, Berriasian and Valanginian.

typical calpionellid-rich sediments (F1 to F2). Compared to other sections, the expanded C and D1 calpionellid zones observed at San Pedro del Gallo, corresponding also to transgressive intervals and high-stand sea-level (Figure 10), is probably due to a more landward location.

3.4. Mineralogy

X-ray diffraction analyses of the whole rock and insoluble residue were carried out for all the samples at the Geological Institute of the University of Neuchâtel. The samples were prepared following the procedure of Kübler (1987). Two sample preparation methods have been applied. Random powder of the bulk sample is used for characterization of the whole rock mineralogy. Nearly 20 g of each rock sample was ground with a 'jaw' crusher to obtain small chips (1–5 mm) of rock. Approximately 5 g were dried at a temperature of 60°C and then ground again to a homogenous powder with particle sizes $<40\,\mu$m. Eight hundred milligrams of this powder were pressed (20 bars) in a powder holder covered with blotting paper and analysed by XRD. Whole rock compositions were determined by XRD (SCINTAG XRD 2000 Diffractometer) based on methods described by Ferrero (1966) and Kübler (1983). This method for semi-quantitative analysis of the bulk rock mineralogy (obtained by XRD patterns of random powder samples) used external standards.

Clay mineral analyses were based on methods described by Kübler (1987). Small rock fragments were mixed with de-ionized water (pH 7–8) and agitated. The carbonate fraction was removed by addition of HCl 10% (1.25 N) at room temperature for 20 minutes or more until all carbonate was dissolved. Ultrasonic disaggregation of the rock residue was accomplished during 3 minute intervals. The insoluble residue was washed and centrifuged (five–six times) until a neutral suspension was obtained (pH 7–8). Separation of different grain size fractions ($<2\,\mu$m and 2–16 μm) was obtained by centrifugation using a timed settling method based on Stokes' law. The selected fraction was then pipetted onto a glass plate and air-dried at room temperature. Afterwards, the oriented clay samples were XRD analysed after air-drying at room temperature and under ethylene-glycol solvated conditions. Each clay mineral (e.g., chlorite, kaolinite) is characterized by specific XRD peaks expressed in intensities (counts by minutes CPM), which were measured in the size fraction $<2\,\mu$m and 2–16 μm as a semi-quantitative estimate of the proportion of clay minerals (Figures 4, 5, 7).

Whole rock compositions of the Iturbide (IT), Puerto Piñones (PP) and Sierra Jabali (SJ) sections (Figures 4–7) agree well with the observed microfacies. The upper part of Zone B (appearance of typical calpionellid rich facies) is marked by a decrease in phyllosilicates and quartz, and an increase of calcite. Goethite, pyrite and feldspars are restricted to the La Casita Formation. Gypsum is of late diagenetic origin. The San Pedro del Gallo section (Figure 7) does not show the same trend. In this section, calcite is dominant and quartz and phyllosilicates are low in the studied interval which corresponds, however, to younger calpionellid Zones C to D1. The whole rock compositions of these sections therefore support the macroscopically observed change from detrital to more carbonate-rich sedimentation in upper Zone B and lower Zone C.

Among the phyllosilicates, the distribution of detrital chlorite and kaolinite (Figures 4, 5, 7; $<2\,\mu$m fraction size) are of special interest. At SJ and PP, chlorite shows a significant increase from calpionellid Zones B to C, whereas kaolinite presents an opposite trend. This latter clay mineral is more abundant in the lower La Casita Formation and in the calpionellid Subzone D1 (PP). For these minerals, trends in the mid-Berriasian San Pedro del Gallo section are slightly different. Both kaolinite and chlorite are present in upper Zone C and Subzone D1, and correlate well with microfacies. This is specially apparent in calpionellid Subzone D1, where chlorite is linked to the occurrence of calpionellid-rich microfacies F1 and F2, whereas kaolinite is mostly related to the radiolarian-rich microfacies F3 and F4 (Figure 7). But from the middle part of Zone C, chlorite becomes dominant and, therefore, can be correlated with the clay-mineral distribution observed at Sierra de Jabali and Puerto Piñones sections.

Kaolinite forms mainly by chemical weathering in soils under constantly warm and humid conditions, while chlorite and illite mostly derive from physical weathering of crystalline rocks, and thus reflects more extreme climate conditions (Chamley, 1989). The relative abundance of kaolinite in the upper La Casita Formation and transition to the Taraises Formation (below the upper part of calpionellid Zone B) suggests warm-humid homogenous climate on land masses around northeastern Mexico during the late Tithonian up to calpionellid Zone B of the early Berriasian. Up-section, the predominance of chlorite may result from increased physical weathering and colder, drier and more contrasted climatic conditions. Such an interpretation agrees with the palynological investigations of Batten (1984) who postulated climatic changes close to the Jurassic–Cretaceous boundary, from generally warm-humid conditions in the Jurassic, to a more contrasted Cretaceous climate. The chlorite/kaolinite record reflects indirect climatic modifications, such as those affecting marine currents, sea-level changes or influx sources.

This change in clay mineral composition within upper Zone B indicates, therefore, an important modification in detrital input resulting from new hydrodynamic, hydrologic and climatic conditions, and correlates with the occurrence of more open and pelagic microfacies.

3.5. Stable isotopes

Sediment subsamples were taken for stable isotope measurements using a dental drill. Only between 60 and 80 μg of carbonate are needed for the analyses. Care was taken to prepare material showing no alteration or secondary calcite veinlets. The measurements were carried out on a Finnigan MAT 251 spectrometer coupled on-line to an automatic carbonate preparation device. The samples are reacted at 75°C by dropping orthophosphoric acid onto individual samples. Standard deviations of the measurements are $<0.04\%$ and $<0.06\%$ for carbon and oxygen, respectively (Hubberten & Meyer, 1989). Isotope ratios are given in ∂ notation versus PDB, i.e., the ∂-scale was calibrated by using NBS19 as reference sample (Hut, 1987).

The measurement of carbon and oxygen stable isotopes on bulk carbonate samples can be used to trace global change through time, but only if all factors liable to change the values within and between sections have been evaluated and their relative importance quantified. Among these factors are meteoric overprint, mixture between biogenic and detritic components and differential late diagenesis according to sediment type; they may markedly alter the original O-isotope ratios. The C-isotope ratio, however, appears to be insignificantly influenced (Hennig, 1995).

Tectonics or diagenesis may thus have altered the primary O-isotopic values.

Extremely low oxygen values are observed in the lower part of the La Casita Formation (Figures 4, 5), and probably reflect secondary recrystallization (radiolaria) or alteration by meteoric water (Veizer, 1983). Magaritz *et al.* (1992) showed that strongest $\partial^{18}O$ alterations occur across intervals of major lithologic changes and, in particular, hiatuses which favoured isotopic exchanges with meteoric water. The lower part of the La Casita Formation, characterized by extremely light $\partial^{18}O$, is therefore marked by numerous lithological changes, condensation levels and probable hiatuses.

Very low values of $\partial^{13}C$ are observed in the lower part of the sections at Iturbide and Puerto Piñones, and may be explained by the presence of lithologies enriched in organic carbon. We assume that the general trend of the carbon isotopes is still preserved. The oxygen isotopes signal seems, however, to have been significantly altered, especially in the lower La Casita Formation. But its general trend seems to be partly preserved in the upper part of the La Casita Formation up to the basal Taraises Formation. This is supported by the fact that there is no significant correlation between the $\partial^{13}C$ and $\partial^{18}O$ curves ($R^2 < 0.25$; Corfield *et al.*, 1991), nor between these isotopes and the calcite contents as determined by XRD ($R^2 < 0.35$). Moreover, if several geological sections from distant locations show the same pattern of isotopic change, it is difficult to concede that the general pattern of the signal is caused by local diagenetic alteration, although some samples may be contaminated. Furthermore, the presence of kaolinite and irregular illite–smectite mixed-layers at Puerto Piñones, Sierra Jabali and San Pedro del Gallo indicate that these rocks have not been deeply buried (mid to deep diagenesis stages). Only the Iturbide section, located near the main thrust of the Sierra Madre fold belt, suffered deeper burial and tectonics (anchimetamorphic zone), as suggested by the absence of kaolinite and irregular illite–smectite mixed-layers, the low values of illite crystallinity (0.25–0.30 °2 theta; Kübler, 1987). The general isotopic trend remains, nevertheless, quite correlatable with those measured in less disturbed areas.

Significant stratigraphic correlations of the stable isotopes were achieved among all sections (Figures 4–7, 9). Within the upper part of calpionellid Zone B, stable isotope compositions show a significant increase towards higher values, from -8 to $+1\partial^{13}C$‰ and from -8 to $-4\partial^{18}O$‰ PDB. This isotopic increase is independent of the observed lithology. Similar isotopic changes have previously been described from the Peregrina Cañon (Figure 9), 150 km south of Iturbide, by Scholle & Arthur (1980). These authors also observed diagenetic alteration of C-ratios in the enriched organic carbon lithologies of the La Casita Formation. Up-section, C-isotopes in the Berriasian part of their section present a trend towards more positive values, as observed in our coeval sections at Puerto Piñones, Jabali and Iturbide. Isotopic curves in the San Pedro del Gallo section (calpionellid Zones C to D1) correlate in absolute values with the isotopic values determined at the same younger levels of the other sections.

A major change in stable isotope composition of both $\partial^{13}C$ and $\partial^{18}O$ values is observed in the upper part of calpionelid Zone B, suggesting an increase in oceanic productivity and a possible influx of cold water. The changes in microfacies and clay mineral associations occur at the same time, indicating that a global change towards more open pelagic environments occurred in upper Zone B. Even if we do not know the extent of biogenic fractionation induced by different microfossil groups, the positive shift of $\partial^{13}C$ may be related to significant faunal changes such as the appearance of the calpionellid-rich facies.

However, critical biotic changes also imply a significant change in water mass characteristics, especially for dissolved carbon contents. They should, therefore, be linked to the new hydrological, paleoceanographic and climatic conditions prevailing from the upper calpionellid B zone. A similar $\partial^{13}C$ shift near the Jurassic–Cretaceous boundary has also been observed in other sites in the North Atlantic (DSDP 367 and 391C sites; Scholle & Arthur, 1980) and thus appears to be global and linked to the widespread sea-level rise located in the upper part of calpionellid zone B (Figure 10, from Haq *et al.*, 1988, modified).

4. Conclusions

Mediterranean calpionellid Zones (Remane, 1985) can be applied to the studied profiles in northeastern Mexico. All of the species found here are known from Europe and their succession agrees well from the lower part of Zones B to E (Adatte *et al.*, 1994). Only the *Crassicollaria* Zone (Zone A), and consequently the Jurassic–Cretaceous boundary, remain difficult to identify due to the rare occurrence of characteristic faunal elements (Figures 4–6).

According to the calpionellids, the lithological boundary between the La Casita and the Taraises Formations is diachronous and does not coincide with the Jurassic–Cretaceous boundary as generally claimed. This is also supported by correlations based on mineralogy and stable isotopes.

The appearance of Mediterranean ammonite species in northeastern Mexico coincides with the first massive occurrence of calpionellid-rich microfacies F1 and F2. This important change towards more pelagic microfacies was observed in all studied sections where calpionellid Zone B is present (Figures 4–6). It indicates the establishment of a direct communication between the Gulf of Mexico and the European Tethys.

The related change of oceanographic conditions is reflected by the distribution of chlorite and kaolinite. The appearance of abundant chlorite corresponds to the first occurrence of rich calpionellid faunas (Figures 4, 5, 7). This suggests an important change in detrital input resulting from new hydrodynamic and hydrologic conditions as current displacement and/or climatic changes. The relative abundance of kaolinite in the upper La Casita Formation and transition to the Taraises Formation indicates, therefore, a warm, humid, homogenous climate on land masses around northeastern Mexico during the late Tithonian up to early Berriasian. Up-section, the predominance of chlorite may result from increased physical weathering and colder, drier and more contrasted climatic conditions. This suggests an important change in detrital input resulting from new hydrodynamic and hydrologic conditions as current displacement and/or climatic changes.

The distribution of stable isotopes also seems to reflect these changing oceanographic parameters. For instance, the increase in values of $\partial^{13}C$ in calpionellid Zone B suggests an increased productivity as supported by the appearance of abundant calpionellids, thus reflecting new water mass characteristics. Considering that the general trend of $\partial^{18}O$ data could be qualitatively preserved and not totally altered by diagenetic overprint, the higher values of $\partial^{18}O$ thus reflect decreased water temperatures due to the influx of cooler water masses into a deepening basin during a sea-level rise.

Our study supports the hypothesis of a major sea level-rise during the early Berriasian calpionellid Zone B, as previously observed by Haq *et al.* (1988), who also correlated the upper part of calpionellid Zone B to D2 interval with a global sea-level rise (transgressive system tracts of LZB 1.4; Figure 10). At the same time, the movement of the Yucatan Block to the south and the drowning of the Bahamas Platform, opened a seaway to the Tethys (Pindell, 1985; Salvador, 1991; Hay & Wold, 1992) and consequently direct access from NE Mexico to the European Tethys. This interpretation is supported by increasingly pelagic environments, the massive influx of Tethyan microfossils (calpionellids) and ammonite fauna, and the changes in stable isotopic values and whole rock and clay-mineral mineralogy. This paleogeographic change ended the endemic, semi-restricted environments which prevailed in northeastern and central Mexico during Late Jurassic time.

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