Paleoenvironmental interpretation using fossil record: San Juan Raya Formation, Zapotitlán basin, Puebla, Mexico

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ABSTRACT

The San Juan Raya Formation is world-wide recognized because of the high diversity and abundance of fossils. In this study nine biofacies, three ichnofacies and ten lithofacies were recognized and interpreted on the basis of the influence of several environmental factors such as water depth change, sedimentation rate, water salinity and substrate consistency. Among these factors, salinity variations were apparently crucial for developing and replacement of the different biofacies. Most of biofacies and ichnofacies inhabited in subtidal, shoreface and inner shelf zones. The aim of this investigation is to provide a comprehensive reconstruction of the different faunal benthonic assemblages and paleoenvironments in a sector of the San Juan Raya Formation during Early Cretaceous time. The results indicate that the paleoenvironmental model for the study area corresponds to a shallow marine, open-coast, storm-dominated clastic system, characterized by several variations in subenvironments, from foreshore to offshore. Along a measured composite column of about 765.5 m in length, nine cycles of transgression-regression were identified, with the shallowest stage at the 200 and 500 m levels and the deepest conditions at 300, 400 and 765.5 m in the column.

Key words: biofacies, ichnofacies, sea level, San Juan Raya Formation, Lower Cretaceous, Mexico.

RESUMEN

La Formación San Juan Raya es mundialmente reconocida debido a su alta diversidad y abundancia fosilífera. En este estudio se reconocieron e interpretaron nueve biofacies y tres icnofacies tomando como base la influencia de diversos factores como los cambios relativos en el nivel del mar, la tasa de sedimentación, la salinidad del agua y la consistencia del substrato. Entre estos factores, al parecer las variaciones en la salinidad del agua fueron muy importantes en el desarrollo y remplazo de las asociaciones de organismos. La mayor parte de los organismos que conformaron las distintas biofacies e icnofacies, habitaron en ambientes de zona de rompiente y de plataforma interna. El objetivo de este trabajo es el de proveer una reconstrucción de las diferentes comunidades bentónicas y de los ambientes de depósito de un sector de la Formación San Juan Raya durante el Cretácico Temprano. Los resultados indican que el modelo paleoambiental del área de estudio corresponde a un sistema clástico marino somero dominado por tormentas. Finalmente, a lo largo de los 765.5 m de la columna estratigráfica compuesta, se identificaron nueve ciclos transgresivos-regresivos, en los cuales las etapas de somerización se encuentran en los niveles de 200 y 500 m, mientras que las condiciones de mayor profundidad están ubicadas en los 300, 400 y 765.5 m respectivamente.

Palabras clave: biofacies, Icnofacies, nivel del mar, Formación San Juan Raya, Cretácico Inferior, México.

INTRODUCTION

Coastal marine environments can be divided into different sectors or zones through recognition of particular benthic faunas or biofacies. According to these notions, biofacies replacement is influenced by water depth and a series of physical, chemical and biological factors. This information has been proved to be useful for the analysis and reconstruction of ancient environments (Brenchley, 1990; Wignall, 1990; Lazo, 2007a).

For a better comprehension of paleoenvironments, a combined study of lithological and taphonomical information has to be performed in conjunction with biofacies analysis of the fossil record. In this way, lithofacies allow to interpret sedimentary paleoenvironments while taphofacies in combination with biostratigraphic data allow estimating the time-averaging and spatial mixing rates. Therefore, autochthonous and parauthocthonous associations can be recognized and evaluated in a paleoecological sense.

This paper presents a study of the systematics, palaeoecology and taphonomy of bivalves, gastropods, corals, annelids (serpulids), echinoids, ammonoids and trace fossils that constitute the majority of the benthonic fauna in San Juan Raya Formation. Information obtained from biofacies is complemented with lithofacies determination and their interpretation regarding depositional environments and paleo–water depths.

The main contribution of this work is to provide an interpretation of fossil distribution as biofacies associations, and to propose interpretations on depositional environments and relative water depth changes.

It also contains the first stratigraphic framework for the highly diverse fossil fauna of the San Juan Raya Formation, allowing further studies to understand changes in environment and deposition.

We suggest that the paleoenvironmental model for the studied stratigraphic section corresponds to a shallow marine storm-dominated system, characterized by a down slope subenvironments series. Fair-weather wave base and storm wave base depth levels were calculated according to Howard and Reineck (1981). Collected data provided information about depths where the different organisms developed. This work contributes to understand the evolution of the Zapotitlán basin.

REGIONAL STRATIGRAPHY AND STUDY AREA

Region-wide, the Jurassic-Cretaceous stratigraphy of southern Mexico records a major transgression. Although ages of initiation vary geographically from Early to Late Jurassic, the stratigraphy is very similar elsewhere. The succession begins with terrestrial redbeds, followed by transitional to marine clastic sedimentation and continues with a thick calcareous succession. This has been interpreted as a transgressive stage associated with the development of a passive margin during the Early to mid-Late Cretaceous. However, this rough interpretation of the evolution of the sedimentation needs more detailed studies to determine the stratigraphy and depositional environments of both clastic and calcareous rocks. Once a more accurate depositional model is constructed, the tectonic and sedimentary history could be understood in the near future.

The Zapotitlán basin in Puebla State that major transgressive stage is recorded in a more than 2 km thick succession of clastic and lesser calcareous strata. This 35 km wide siliciclastic depositional basin developed in a half-graben fault system (Mendoza-Rosales, 2010). The basin formed during Early Cretaceous (Barremian to Lower Aptian) times (Mendoza-Rosales, 2010; Mendoza-Rosales *et al.*, 2010), and the related sedimentary rocks change upward in the column from fault bounded syn-tectonic clastic sedimentation to a regionally subsiding calcareous seaway platform (Mendoza-Rosales, 2010). There is little known about the tectono-sedimentary history of the Zapotitlán basin. Mendoza-Rosales (2010) suggested that its evolution is closely related to the opening of the Gulf of Mexico.

Sedimentary rocks of the Zapotitlán basin have been grouped in two to ten formations, depending on the author. Among those, the Zapotitlán and San Juan Raya are the main and largest clastic formations (Calderón-García, 1956; Ortega-Gutiérrez *et al.,* 1990; Mendoza-Rosales, 2010). Particularly, the San Juan Raya Formation is world-wide recognized because of the high diversity and abundance of fossil material. The fossil fauna of this formation had been studied since the 19th Century; however, most works were focused on systematics research (Nyst and Galeotti, 1840; d'Orbigny, 1850; Desor, 1850; Coquand, 1869; Müllerried, 1933; Alencáster de Cserna, 1956; Reyeros, 1963; Buitrón, 1970; González-Arreola, 1974; Buitrón and Barceló-Duarte, 1980; Feldmann *et al.*, 1995; Escalante-Ruiz, 2006; Escalante-Ruiz and Quiroz-Barroso, 2006; Mora-Almazán and Quiroz-Barroso, 2006; Löser, 2006; and Mora-Almazán, 2008).

The San Juan Raya Formation at Santa Ana Teloxtoc area consists of gray/bluish-gray and greenish-gray calcareous mudstone, intercalated with gray calcareous fossiliferous siltstone that ranges in thickness from 10 to 40 cm, and gray calcareous fine to medium-grained sandstone, from 10 cm to 2 m in thickness. Sandstone forms both planar and heterolithic stratification. Previous investigations estimate a total thickness between 700 and 1287 m for this formation (Calderón-García, 1956). Recent field work revealed that the unit was originally thicker, because it was tilted previous to the deposition of limestone units, and it was also folded and eroded during the end of the Cretaceous (Calderón-García, 1956; Mendoza-Rosales, 2010). The formation has been considered Lower Aptian in age, on the basis of its fossil content, but Mendoza-Rosales (2010) proposed that this age can be extended to the Upper Barremian.

The San Juan Raya Formation transitionally overlies and laterally changes to the Zapotitlán Formation; it is also laterally intertongued with conglomerate and sandstone of Agua del Cordero Formation to the west, and unconformably underlies the Cipiapa Formation to the north, at Santa Ana Teloxtoc area.

The study area is locally known as Barranca San Lucas and is located 11 km west of Zapotitlán Salinas town, 4 km east of San Lucas village and 5 km southeast of the small town of Santa Ana Teloxtoc, in southern Puebla state (Figure 1).

MATERIAL AND METHODS

A composite stratigraphic column was measured on a bed-by-bed scale up to a total thickness of 765.5 m (Electronic Appendix A). The column was divided in six stretches that are in part continuous, and some are fault bounded or separated by covered areas. Sedimentologic and stratigraphic features were recorded during measuring, such as thickness, lateral extension, geometry of the strata, stratigraphic contacts, primary structures, composition and texture. On the basis of this information, the rocks were grouped in lithofacies and facies associations. A discussion regarding the interpretation of lithofacies is not included in this paper because it is not the main goal of the study. Detailed field observations on fossil content and distribution were obtained during the measurement of the stratigraphic column, and some fossil material was collected for identification. Taphonomical features, such as preservation grade, orientation in plan view and in cross section, degree of articulation, fragmentation, sorting and corrasion were recognized following Brett and Baird (1986). These features were used for preliminary taphonomic interpretations, such as relative degree of allochthony.

Fossil organisms found in the study area are mostly invertebrates, and they were grouped in biofacies. In addition, trace fossils were grouped in ichnofacies. Depositional environments and relative water depth changes were reconstructed by comparing the fossils identified in the area with available information in the literature about mode of life and habitat of the different groups, both fossil and recent invertebrates.

The paleoenvironmental model for clastic shallow marine sedimentation of Hampson and Storms (2003) was followed to interpret the depositional environments.

RESULTS

This paper is focused on the interpretation of fossil content, and their grouping in biofacies and ichnofacies. Therefore, main lithofacies features are only briefly described for their environmental interpretation.

The San Juan Raya Formation at the measured column is composed mostly of shale and siltstone, and in lesser amounts of fine-grained sandstone, which were grouped in 10 facies and one facies association (Table 1); their abundance and stratigraphic distribution are shown on the composite column in the Electronic Appendix A, and photographs of the lithofacies are included in the Electronic Appendix B. They are described as follows:

Cross-stratified sandstone and siltstone lithofacies association (StL)

This lithofacies association is made up of fine and medium-grained sandstone distributed as lenticular strata or as up to 2 m thick hillock-shaped bodies (Appendix B1). It shows an initial erosional surface, flat or channelized. It is mostly formed by planar to low-angle-laminated and *hummocky* cross-stratified sandstone (StL1 facies; Appendix B1 a-b); swaley cross-stratified sandstone (StL2 facies; Appendix B1 c-e); and lenticular to planar strata, either laminated or with tabular cross-stratification, of siltstone and some trapped muds (StL3 facies; Appendix B1 f-g). Some sandstone hillocks show, from bottom to top, all consecutive facies, recording the storm energy peak (StL1 and StL2) and, as the storm wanes, the suspension fallout (StL2 and StL3). This facies association contains abundant wood fragments and logs that are mixed with shell and coral fragments and sometimes complete shells of marine bivalves and gastropods.

Planar siltstone and mudstone lithofacies (PSM)

Thin- to medium-bedded calcareous siltstone and mudstone strata (Appendix B2 a-b). Sometimes they display parallel or ripple cross lamination , and rarely contain symmetric parallel ripples. This is interpreted as sedimentation during times of fair-weather conditions. This is the most common and abundant lithofacies in the studied the column.

Calcareous and muddy debris flows (DF)

This facies is composed of mud-sized or calcareous sand-sized gravity flows of poorly sorted mixtures of locally produced hardparts and clay exoclasts. They lack internal structures and contain some articulated bivalves (Appendix B2 c-e).

Facies indicative of reduced to moderate sedimentation rates are:

Shell marl lithofacies (SML)

Composed of loosely and densely packed coquinas in a muddy or fine-sandy calcareous matrix. It contains disarticulated bivalve shells, serpulids and echinoid fragments (Appendix B2 f-g). Fossil associations suggest a mid-ramp depositional setting for SML.

Fossiliferous-dominated shale lithofacies (FSD)

This facies is formed by highly bioturbated calcareous shale, characterized by abundant fossil material. It contains most of the biofacies and one ichnofacies described in this paper (Appendix B2h).

Bioclastic limestone (BL)

Packstone with lumpstones, few cortoids and benthonic foraminifers (Appendix B2i). It also contains abundant ooids and carophytes, which indicate deposition in an inner ramp setting.

Laminated mudstone lithofacies (LM)

Grayish mudstone with parallel lamination; strata are thin- to medium-bedded (Appendix B2j). *Psilonichnus* ichnofossils are present. This lithofacies is interpreted to reflect sedimentation under fair-weather and low energy conditions. Fossil association suggests a supratidal depositional setting for this lithofacies.

Mudstone with sandstone lithofacies (MSL)

Abundant mudstone with subordinate fine-grained sandstone; sedimentary structures correspond to flaser lamination. Strata are thin- to medium-bedded. (Appendix B2k). *Skolithos* ichnofossils are present. This lithofacies is interpreted as sedimentation during times of fair-weather conditions. Fossil content and sedimentary structures suggest an intertidal depositional setting for MSL.

Biofacies and ichnofacies: Diagnosis and interpretation

Fossil associations were grouped in nine biofacies and three ichnofacies (Table 2). Descriptions include interpretations of possible depositional environments and, in some cases, specific environmental conditions, based mostly on the occurrence of the taxa in modern environments. We are aware of the fact that organisms might have
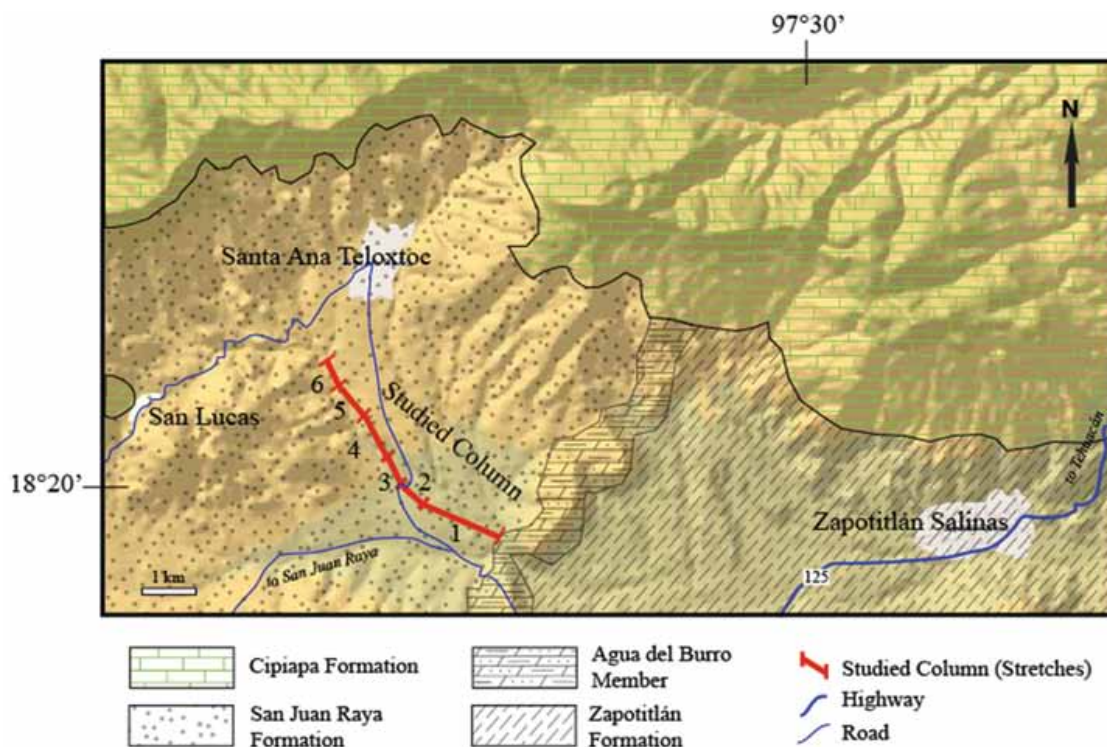

Figure 1. Study area near Santa Ana Teloxtoc town.

Table 1. Summary of the main features of the San Juan Raya Formation lithofacies. Abbreviations: F-Sand = fine sandstone; M-Sand = medium sandstone; C-Silt = calcareous siltstone; C-Mud = calcareous mudstone; C-Sand = calcareous sandstone; C-Sha = calcareous shale; Silt = siltstone; Pack = packstone; Mud = mudstone.

Lithofacies	StL1	StL2	StL3	PSM	DF	SML	FSD	BL	LM	MSL
Thickness (cm)	30 - 200	10 - 20	10 - 50	10 - 50	10 - 30	30	10 - 50	50	20	30
Lithology	F-Sand / M-Sand	F-Sand	Silt	C-Silt / C-Mud	C-Sand	C-Sand	C-Sha	Pack	Mud	Mud
Sedimentary structures										
Parallel lamination	---	---	X	X	---	---	---	---	X	---
Flaser lamination	---	---	---	---	---	---	---	---	---	X
Ripple cross-lamination	---	---	---	X	---	---	---	---	---	---
Tabular cross-bedding	---	---	X	---	---	---	---	---	---	---
Hummocky cross-bedding	X	---	---	---	---	---	---	---	---	---
Swaley cross-bedding	---	X	---	---	---	---	---	---	---	---
Without structures	---	---	---	---	X	X	X	---	---	---
Carbonate grains										
Ooids	---	---	---	---	---	---	---	X	---	---
Carophytes	---	---	---	---	---	---	---	X	---	---
Cortoids	---	---	---	---	---	---	---	X	---	---
Lumpstones	---	---	---	---	---	---	---	X	---	---
Benthonic foraminifers	---	---	---	---	---	---	---	X	---	---
Skeletal grains										
Bivalves	X	X	---	---	X	X	---	---	---	---
Serpulids	---	---	---	---	X	---	---	---	---	---
Echinoids	---	---	---	---	X	---	---	---	---	---
Gastropods	X	---	---	---	---	---	---	---	---	---
Corals	X	---	---	---	---	---	---	---	---	---

had different environmental distributions in the past, so we point out that proposed depositional environments and water depths may have an error range. Biofacies were named on the basis of the most abundant taxa, but they contain other fossil organisms that are also described.

Ostrea alicula biofacies (OaB)

This biofacies consists of lens-shaped oyster aggregates of Ostrea alicula Hamlin, 1890 up to 1 m high and 4 m wide (Figure 2 a-c). Organisms are densely packed and highly disarticulated, good to bad sorted, in a poor pelithic matrix or without matrix at all. No other organisms were found within this biofacies.

Isognomon lamberti biofacies (IsB)

This biofacies corresponds to monospecific bivalve aggregations (Figure 2 d-e) of *Isognomon lamberti* Müllerried, 1934. Articulated organisms have a preferred oblique orientation with respect to the bed surfaces suggesting they were buried at life position. Some of them are concordant and most of the disarticulated valves have a convex-down position. Individuals have evidence of bioerosion and some valves are filled with shell detritus. No other organisms were found within this biofacies.

Gregarious serpulid biofacies (GSB)

This biofacies consists of calcareous tubes of monospecific serpulid aggregates of *Serpula* sp. (Figure 2 f-h) that are concordant with bed surface, but in some cases they are in life position. This biofacies is characterizsed by a dense (>70%), medium dense (50%) to disperse packing concentration, good to bad sorting (tube fragments mixed with complete tubes), and poor to abundant pelitic matrix (up to 50%). Paleoenvironmental conditions of GSB seem to be very similar to those of the *Ostrea alicula* biofacies because they develop in similar environments (Fürsich and Werner, 1984; Ten Hove and Van Den Hurk, 1993). However, they were not observed in the same bed along the measured

stratigraphic column, but are present at different stratigraphic levels. Ten Hove and Van Den Hurk (1993) suggested that monospecificity, as observed in GSB, may be indicative of a medium to high energy stressful environment.

Coral biofacies (CB)

This biofacies consists of bioclastic deposits immersed in a pelitic matrix, with a medium to dense packing concentration, normal gradation and an erosive base. Organisms correspond to mound-shaped, branching and globose coral colonies but few solitary corals are also present (Figure 3). Mound-shaped and globose corals are usually closely spaced and occur mostly in growth position. Mound-shaped forms are represented by *Procyathophora aguilerai* Reyeros, 1963, *Procyathophora poblana* Reyeros, 1963, *Complexastrea cyclops* Felix, 1891, *Thamnasteria crespoi* Felix, 1891, *Cyathophora atempa* Felix, 1891, *Baryphyllia confusa* d'Orbigny, 1850 and *Myriophyllia* sp. Globose, branching and solitary corals have not been taxonomically studied at present date. Globose and mound-shaped corals have variable bioerosion and incrustation grades, produced by bivalves and serpulids. Ramose corals have one or two main branches; some of them are fragmented, with low corrasion grades. Majority of branching and solitary corals are concordant to bedding, so they were interpreted as parauthoctonous. Branching corals are the most abundant organisms in the biofacies with exception of *Procyathophora aguilerai* Reyeros, 1963 and *Procyathophora poblana* Reyeros, 1963 which are mound-shape species. Other benthic organisms included in this biofacies are gastropods *Cerithium bustamantii* Nyst and Galeotti, 1840, *Pyrazus maldonadoi* Alencáster de Cserna, 1956, *Turritella minuta* Nyst and Galeotti, 1840, *Uchauxia poblana* Alencáster de Cserna, 1956, *Nerinea* sp., *Cossmanea* sp., *Craginia floresi* Alencáster de Cserna, 1956 and *Tylostoma aguilerai* Alencáster de Cserna, 1956; bivalves *Isognomon lamberti* Müllerried, 1934 and *Corbis corrugate* Sowerby, 1845; regular echinoids *Pseudocidaris clunifera* Agassiz, 1840, "*Cidaris*" *müellerriedi* Lambert, 1935 and *Phymosoma mexicanum* Böse, 1910. These benthic

macrofauna is filling the spaces between the coral heads. Vertical distribution of CB is especially extensive in column's stretch 1. Because of the absence of true hardgrounds in this biofacies, corals may have managed to encrust firm sediment; this is indicated by the presence of irregular, small attachment surfaces, similar to those described by Lazo *et al.* (2005).

Cerithium bustamantii biofacies (CbB)

This biofacies corresponds to gastropod pavements of *Cerithium bustamantii* Nyst and Galeotti, 1840 (Figure 2i). We observed that these organisms range from 3 to 4 cm in size and are characterized by mostly complete specimens who have low corrasion levels, no incrustation and variable ornament preservation. All organisms are concordant to bedding and do not have a preferred orientation, so they were interpreted as parauthoctonous.

Cerithium bustamantii – Turritella minuta – Pyrazus maldonadoi biofacies (CTPB)

This biofacies is formed by different types of casts of external molds of gastropods, being *Cerithium bustamantii* Nyst and Galeotti, 1840, *Turritela minuta* Nyst and Galeotti, 1840 and *Pyrazus maldonadoi* Alencáster de Cserna, 1956, the most abundant species (Figure 4 a-d). Other gastropods found at the same strata are *Tylostoma aguilerai* Alencáster de Cserna, 1956, *Cossmannea* sp., *Cassiope mülleriedi* Alencáster de Cserna, 1956, *Craginia floresi* Alencáster de Cserna, 1956, *Uchauxia poblana* Alencáster de Cserna, 1956, *Lunatia* sp. and *Nerinea* sp. We concluded, based on field observations that CTPB has a higher diversity than other biofacies because it contains the majority of gastropods groups identified for the San Juan Raya Formation. This biofacies is also characterized by mostly complete organisms with a low corrasion grade, no incrustation and variable ornament preservation. All organisms are concordant to bedding and do not have a preferred orientation, which suggests little or no allochthony.

Pterotrigonia plicatocostata biofacies (PplB)

This biofacies consists of a majority of facultative infaunal bivalves that correspond to *Pterotrigonia plicatocostata* Nyst and Galeotti, 1840. They have different orientations within strata but near 80% are in life position (Figure 4 e-g); they have low corrasion levels and some of them have serpulid incrustations, especially at 1/3 of the shell posterior region. Few disarticulated shells of *Isognomon lamberti* Müllerried, 1934 were also found. They are concordant to strata and were probably transported from the shoreface zone. The presence of trigoniids in life position demonstrates a rapid burial that protected them from bioturbation and posterior erosion events.

Ammonoid biofacies (AMB)

Biofacies AMB corresponds to ammonoids and some bivalves, gastropods, serpulids, few echinoids and minor concentrations of shell detritus (Figure 4 h-k). Overall, fossil individuals are not common in this biofacies, and among them, the most abundant organisms are ammonoids with little or no reworking, compared to the other fossilized organisms. Ammonoids correspond to casts and external molds of *Phylloceras* Suess, 1865 and *Lytoceras* Suess, 1865 (González-Arreola, 1974), which have a low corrasion grade, are matrix filled and mostly concordant to bedding. Bivalve specimens are mainly *Panope neocomiensis* d'Orbigny, 1843, *Pterotrigonia plicatocostata* Nyst and Galeotti, 1840 and *Pholadomya* cf. *gigantea* Sowerby, 1836. Bivalves are disarticulated and valve orientation is variable but is mostly convex-down. Specimens have a high corrasion grade with exception of *Pterotrigonia plicatocostata* Nyst and Galeotti, 1840 and *Pholadomya* cf. *gigantea* Sowerby, 1836 which have a medium corrasion grade. *Serpula* sp. tubes are preserved as small sub-cylindrical fragments concordant to bedding. Gastropods are preserved as complete external mold casts, which are concordant to bedding and have high corrasion levels; they correspond to *Cerithium bustamantii* Nyst and Galeotti, 1840 and *Turritella minuta* Nyst and Galeotti, 1840. A few radiolas

Table 2. Summary of the main features of biofacies and ichnofacies in the San Juan Raya Formation.

| Biofacies and Ichnofacies	Macrofossil content	Related lithofacies	Depositional environment
OaB	*Ostrea alicula* Hamlin, 1890 bivalves	FSD	Foreshore (subtidal) / Shoreface
IsB	*Isognomon lamberti* Müllerried, 1934 bivalves	FSD	Foreshore (subtidal) / Shoreface
GSB	*Serpula* sp. serpulids	FSD	Foreshore (subtidal) / Shoreface
CB	Mostly mound-shaped, branching and globose coral colonies but few solitary corals are also present.	FSD	Inner Shelf
CbB	*Cerithium bustamantii* Nyst and Galeotti, 1840 gastropods	FSD	Foreshore(subtidal)
CTPB	*Cerithium bustamantii* Nyst and Galeotti, 1840, *Turritela minuta* Nyst and Galeotti, 1840 and *Pyrazus maldonadoi* Alencáster de Cserna, 1956 gastropods. Other types of gastropods are present.	FSD	Foreshore (subtidal)
AMB	Ammonoids, some bivalves, gastropods, serpulids, few echinoids and minor concentrations of shell detritus	FSD	Medium-External Shelf
PplB	*Pterotrigonia plicatocostata* Nyst and Galeotti, 1840 bivalves	FSD	Inner Shelf
CPPB	*Cardium* cf. *cottaldinum* d'Orbigny, 1843, *Pholadomya* cf. *gigantea* Sowerby, 1836 and *Panope neocomiensis* d'Orbigny, 1843 bivalves	FSD	Inner Shelf
PsI	*Psilonichnus* and *Macanopsis* ichnofossils	LM	Foreshore (supratidal)
SkI	*Skolithos* ichnofossils	MSL	Foreshore (intertidal)
CrI	Mostly *Thalassinoides* ichnofossils / other horizontal traces and associated vertical burrows belonging to *Cruziana* ichnofacies	FSD	Shoreface - Shelf
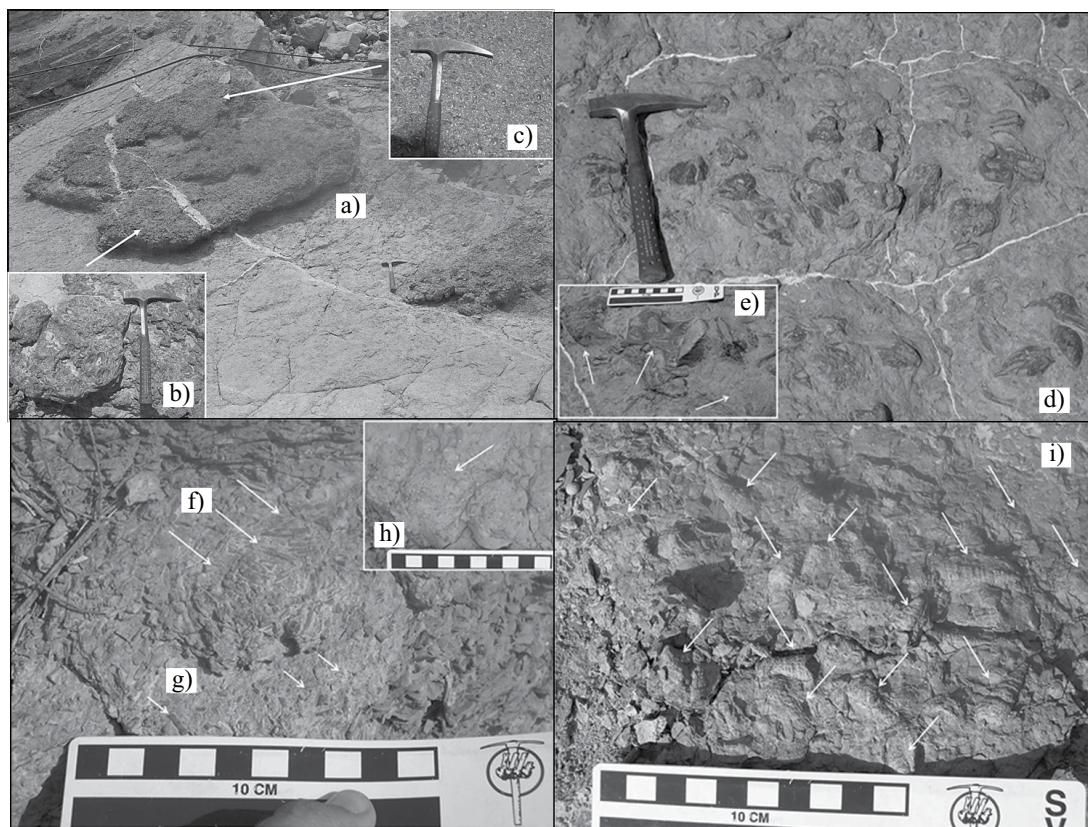
Figure 2. *Ostrea alicula* biofacies (OaB). (a) Outcrop; (b) bigger oyster specimens at the base of the aggregate (5 cm); (c) smaller oyster specimens at the top of the aggregate (1 – 2 cm). *Isognomon lamberti* biofacies (IsB): (d) Outcrop; (e) valves fill with shell detritus and incrusted by *Ostrea alicula* oysters Hamlin, 1890. Gregarious serpulids biofacies (GSB): (f) Concordant calcareous tubes of *Serpula* sp.; (g) tube fragments of *Serpula* sp.; (h) *Serpula* sp. tubes in life position. *Cerithium bustamantii* biofacies (CbB): (i) gastropod specimens.
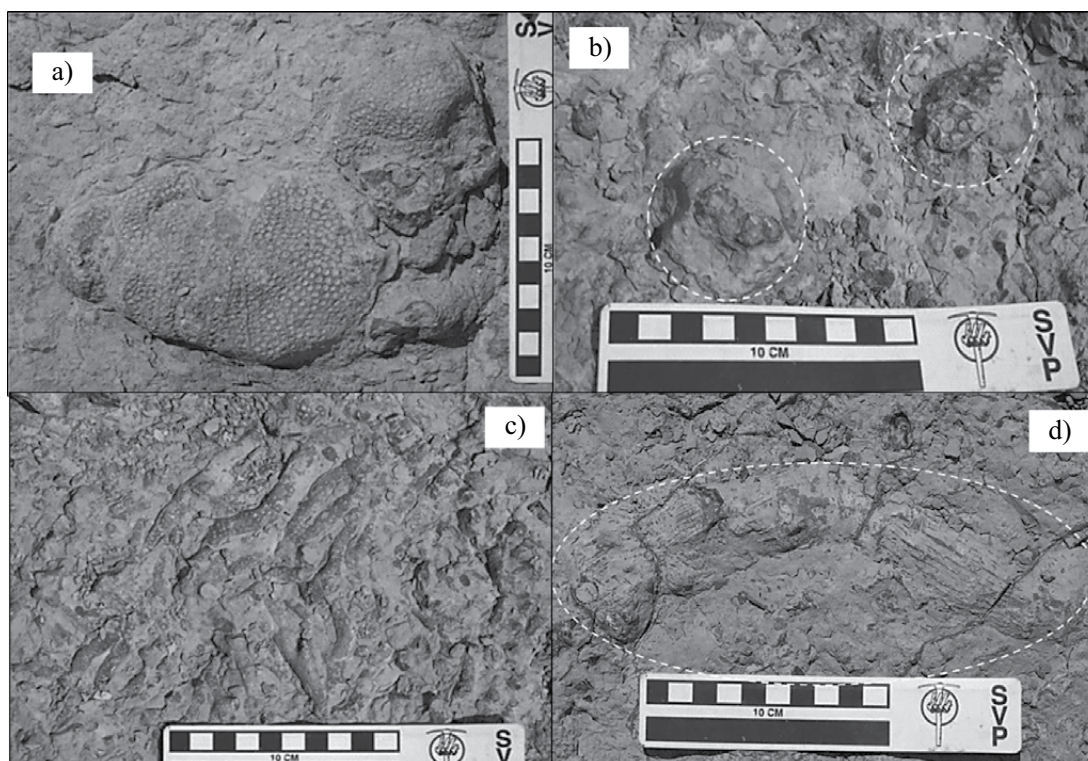
Figure 3. Coral biofacies (CB): (a) *Cyathophora atempa* Felix, 1891; (b) *Baryphyllia confuse* d'Orbigny, 1850; (c) unknown ramose corals; (d) unknown solitary coral.
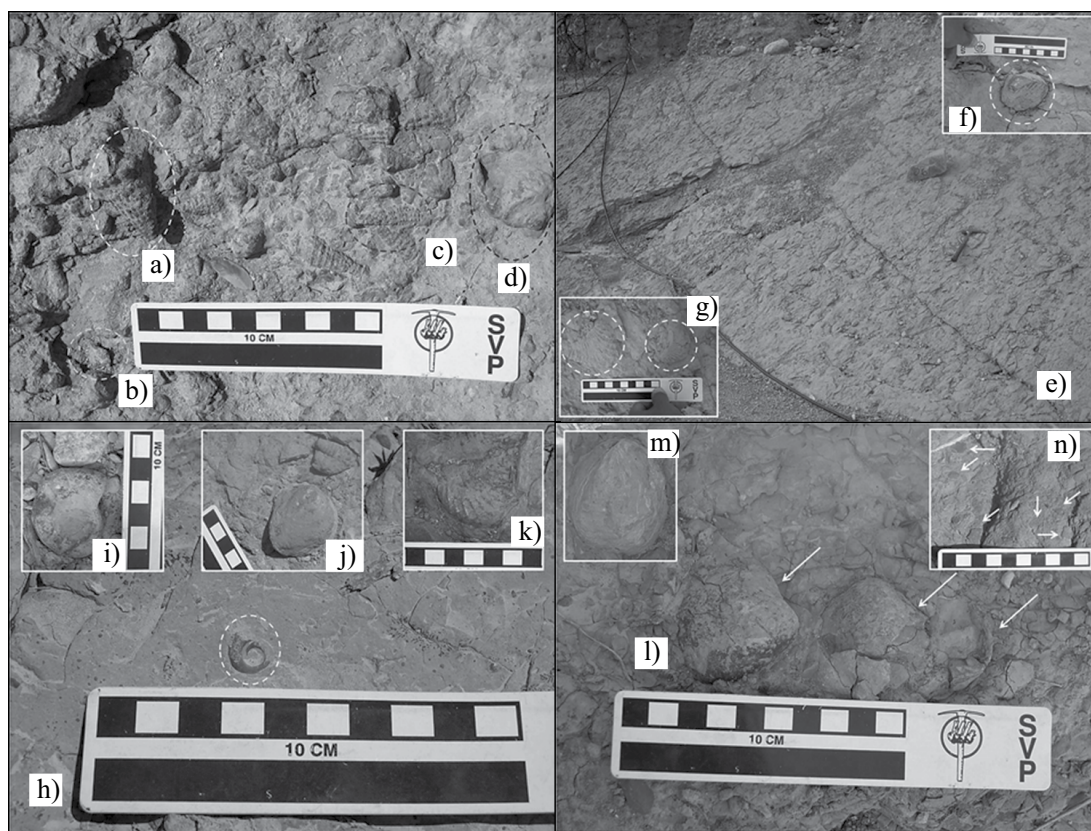
Figure 4. *Cerithium bustamantii – Turritella minuta – Pyrazus maldonadoi* biofacies (CTPB): Outcrop with different gastropods specimens: (a) *Cerithium bustamantii* Nyst and Galeotti, 1840; (b) *Turritella minuta* Alencáster de Cserna, 1956; (c) *Pyrazus maldonadoi* Nyst and Galeotti, 1840; (d) *Tylostoma aguilerai* Alencáster de Cserna, 1956. *Pterotrigonia plicatocostata* biofacies (PplB): (e) Outcrop; (f) specimen in life position; (g) removed specimens. Ammonoid biofacies (AMB): (h) Unknown ammonoid; (i) *Phylloceras* sp. ammonoid; (j) *Pholadomya* cf. *gigantea* Sowerby,1836 and *Cerithium bustamantii* Nyst and Galeotti, 1840; (k) *Pterotrigonia plicatocostata* Nyst and Galeotti, 1840. *Cardium* cf. *cottaldinum - Pholadomya* cf. *gigantea* – *Panope neocomiensis* biofacies (CPPB): (l) Disarticulated specimens of *Panope neocomiensis* d'Orbigny, 1843; (m) specimen of *Pholadomya* cf. *gigantea* Sowerby, 1836 in life position; (n) shell fragments. White arrows points to the bivalve specimens.

from *Pseudocidaris clunifera* Agassiz, 1840 were also found (Buitrón, personal communication).

We suggest that the higher disarticulation rates and the concordant position of fossils in the strata may be indicative of significant transportation and extensive bottom-current action. This biofacies was found at a few levels in the studied area.

Cardium cf. cottaldinum - Pholadomya cf. gigantea – Panope neocomiensis biofacies (CPPB)

A bivalve biofacies formed mostly (>50%) by deep infaunal and few epifaunal forms. *Cardium* cf. *cottaldinum* d'Orbigny, 1843, *Pholadomya* cf. *gigantea* Sowerby, 1836 and *Panope neocomiensis* d'Orbigny, 1843 (Figure 4 l-n) are the most abundant. There are two types of specimen preservation in this biofacies: (a) Disarticulated or articulated casts of internal and external molds, with all organisms having low corrasion and fragmentation grades; the cast material is the same as the rock-matrix. Disarticulated valves are concordant with strata and have a convex-down position, while articulated organisms are concordant, oblique or in life position. (b) Pavements of disarticulated casts of external molds and fragmented organisms that have a low corrasion grade but a higher fragmentation (>95%). The majority of the specimens have a convex-down position in the bed, so they were interpreted as parauthoctonous. Valve ornamentation is well-preserved and epibionts are absent.

Psilonichnus ichnofacies (PsI)

PsI ichnofacies consists of a series of two types of small galleries (Figure 5 a-b): (1) Vertical shaft-structures referable to *Macanopsis*, with basal habitation chambers that can reach up to 7 cm in length; (2) vertical "J"-shaped dwelling burrows, 4 cm in length, that belong to *Psilonichnus*. This ichnofacies has a low diversity and abundance of organisms and a very limited distribution in the studied stratigraphic column.

Skolithos ichnofacies (SkI)

This ichnofacies has also a low diversity and abundance of organisms; it consists mostly of vertical burrows (habitation chambers and escape structures from 6 to 13 cm in length) and only few horizontal trails (up to 5 cm in length; Figure 5 c-d). Such structures were probably created by suspensivorous or passive-carnivorous organisms (Pemberton *et al.*, 2001). This ichnofacies was found only at three levels within the measured stratigraphic column.

Cruziana ichnofacies (CrI)

Cruziana ichnofacies consists of a series of horizontal traces and associated vertical burrows, which can be up to 50 cm long and 20 cm wide (Figure 5 e-h). Gallery shapes are more diverse than in the other two ichnofacies (PsI and SkI), since they are straight, undulated, "J" shaped and branched. *Thalassinoides* is the most abundant
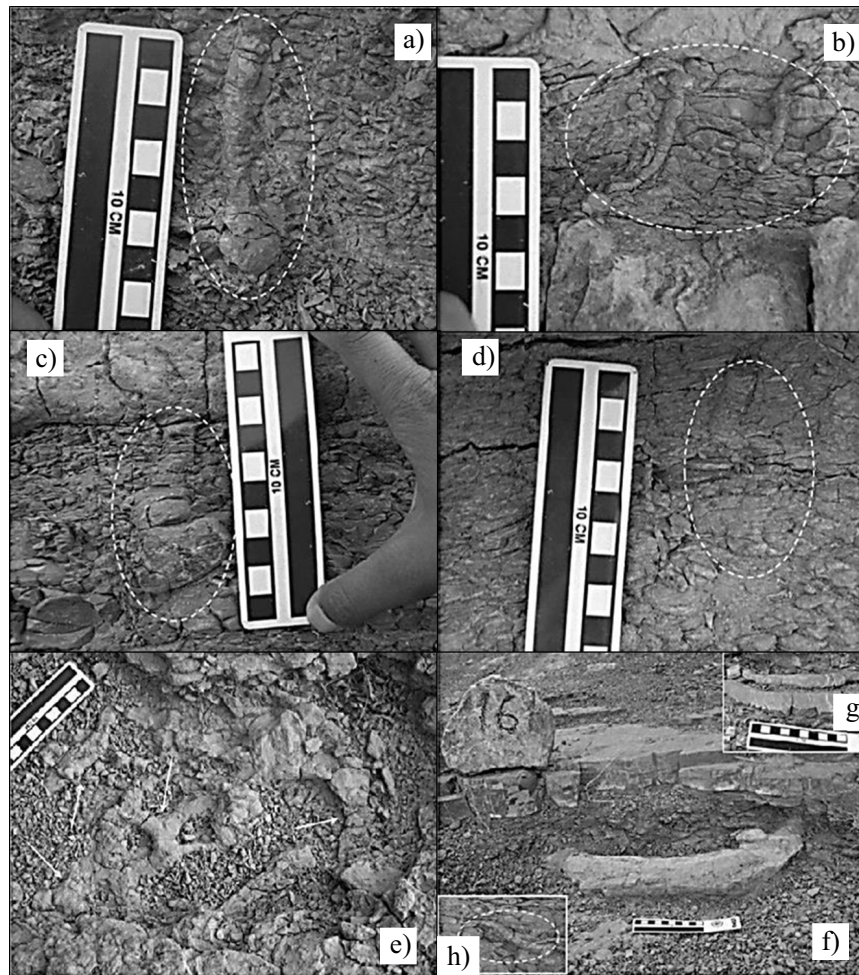
Figure 5. Recognized ichnofacies in the study area. *Psilonichnus* ichnofacies (PsI): (a) *Macanopsis* burrows, (b) *Psilonichnus* vertical "J" shaft-burrows. *Skolithos* ichnofacies (SkI): (c) Siphonated bivalve habitation chambers (domichnia), (d) escape structures (fugichnia). *Cruziana* ichnofacies (CrI): (e) *Thalassinoides*; (f-g) horizontal traces; (h) semivertical traces.

ichnofossil in this ichnofacies. CrI is widely distributed along the measured column.

DISCUSSION

A calm water lagoonal environment was originally proposed for the San Juan Raya Formation by previous authors (Feldmann *et al*., 1995; Escalante-Ruiz and Quiroz-Barroso, 2006; Escalante-Ruiz, 2006). However, our field observations and the interpretation of biofacies and their change throughout time, indicate a wider variety of depositional environments, with a complex vertical and lateral distribution. The same conclusion was addressed in the work done by Mendoza-Rosales (2010) at the southern part of the basin, who reported depositional environments ranging from subaerial to deep marine.

Our results indicate that the San Juan Raya Formation at the study area corresponds to a shallow marine open-coast, storm-dominated clastic system, characterized by alternated variations in subenvironments, from foreshore to offshore (Figure 6).

On the basis of the present occurrence and discussions of ancient environments in other regions (Pryor, 1975; Howard and Reineck, 1981; Ronan *et al*., 1981; Hampson and Storms, 2003), variations in biofacies and ichnofacies can be attributed to several environmental

factors such as changes in water depth, sedimentation rate, water conditions (temperature, salinity, etc), food availability and/or substrate consistency, among other factors.

It is always difficult to determine which the main controlling factor was. Since the goal of this work is to determine the distribution and association of the wide variety of fossil organisms along the stratigraphic column, the following discussion gives a preliminary interpretation of depositional settings and other environmental conditions. Further work needs to be done to reconstruct sea level fluctuations, and their relationship with tectonic subsidence and sedimentation rate. Biofacies that probably were influenced by a specific factor are first discussed. In order to simplify the discussion, bio- and lithofacies are discussed together for each proposed paleoenvironment.

Salinity

Traditionally, San Juan Raya Formation had been interpreted as a fully marine environment deposited under normal salinity conditions because of its fossil content (Alencáster de Cserna, 1956; Salmones-Zarate, 1994; Feldmann *et al*., 1995). In this study, *Ostrea alicula* (OaB), *Isognomon lamberti* (IsB), gregarious serpulid (GSB) biofacies, and *Psilonichnus* ichnofacies, suggest that salinity variations occurred through time (Appendix A), because of continental fresh
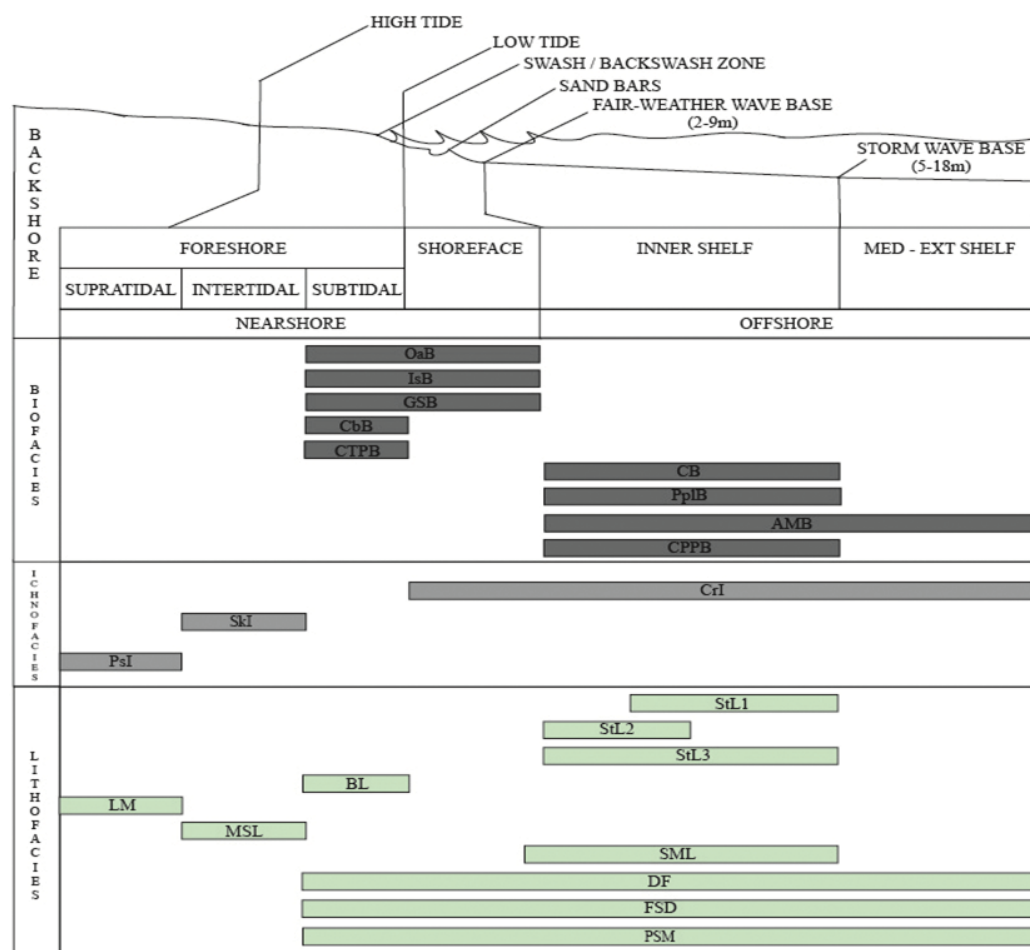
Figure 6. Nearshore–offshore shelf schematic profile showing the biofacies and ichnofacies distribution; main morphological elements are also presented. Palaeoenvironmental model modified from Hampson and Storms (2003).

water influence, particularly when the coast moved toward the studied area (foreshore and shoreface environments). These salinity variations caused the replacement of the benthic community.

The presence of monospecific aggregates reflects stressful environmental conditions with a lower sedimentation rate and different water salinity levels. Oysters and serpulids may switch from a solitary mode of life to a gregarious habit under the influence of fluctuations in water chemistry (Ten Hove and Van der Hurk, 1993; Livingston *et al*., 2000; Cranfield *et al*., 2004; Lazo *et al*., 2007a; Lazo *et al*., 2008; Brian, 2008; Campbell, 2010; Brown, 2011). Modern discoveries point out that oyster aggregation reach their maximum development under low salinity conditions (Brown, 2011; Campbell, 2010). In contrast bivalves belonging to *Isognomon* live and proliferate in high salinity zones (Mcpherson *et al*., 1984). Serpulids can acquire a gregarious life habit under diverse water salinities, from brachyhaline to hyperhaline (Fürsich and Werner, 1984). *Psilonichnus* ichnofacies is indicative of lower salinity levels (Pemberton *et al*., 2001).

Abundant euhaline organisms belonging to Coral biofacies (CB), *Cerithium bustamantii–Turritela minuta–Pyrazus maldonadoi* (CTPB), *Cerithium bustamantii* (CbB), *Cardium* cf. *cottaldinum–Pholadomya* cf. *gigantea–Panope neocomiensis* (CPPB), *Pterotrigonia plicatocostata* (PplB), Ammonoid (AMB) biofacies, and *Cruziana* ichnofacies (CrI), suggest that most of the sedimentation of the San Juan Raya Formation occurred under normal marine salinity conditions (see Appendix A).

Sedimentation rate

According to the behavior of modern organisms, it seems that clastic input varied during the deposition of the San Juan Raya Formation (Appendix A). At present, higher sedimentation rates inhibits the growth of oysters and other types of bivalves and also inhibits the establishment of new larvae. On the basis of this evidence, clastic input probably was relatively low during maximum expansion of the organisms belonging to OaB, IsB and CPPB biofacies. Also the abundance of suspensivorous forms in the CPPB biofacies probably indicates lower sedimentation rates.

On the other hand, a predominance of reef-patches and the absence of coral overgrowth and truly hardgrounds in CB biofacies, suggest times of constant sedimentation that prevented the formation of coral reefs. The development of a shelf area below shallower deposits created a more extended environment for the proliferation of infaunal trigonids (PplB biofacies; Francis and Hallam, 2003). Finally, scarce fossil concentration in the AMB biofacies may be, among other plausible factors, the result of higher sedimentation rates (Appendix A).

Paleoenvironments and water depth

Water depth changes along with storm activity produced drastic environmental modifications that generated a habitat alternation and benthonic fauna replacements (Lazo *et al*., 2008; Rioja-Nieto *et al.,* 2012). On the basis of the variations in litho- and biofacies along the

measured stratigraphic column, several changes in the paleoenvironment, from foreshore (subtidal zone), to shoreface and shelf environments, were identified in the study area (Appendix A). Figures 6 and 7 summarize the results of this work.

We would like to point out that *Cruziana* ichnofacies (CrI) and calcareous and muddy debris flow (DF) and planar siltstone and mudstone (PSM) lithofacies are not indicative of certain depositional environment; those are shown on Figure 6 as bars covering a wide range of environments. Because most of the fossils were found in the fossiliferous shale-dominated lithofacies (FSD), its corresponding bar covers almost the whole range as well. A discussion on the identified subenvironments is presented in the following sections.

Supratidal zone (foreshore)

This sub-environment was established according to the presence of *Psilonichnus* ichnofacies (PsI) and LM lithofacies (Figure 6). In modern environments the lower part of supratidal flats consists of laminated muds with relatively little sand, representing a mixture of quasimarine and non-marine conditions (Dalrymple *et al.*, 1991). *Psilonichnus* burrows are typical of this zone (Pemberton *et al.*, 2001). Hence, on the basis of rock composition, sedimentary structures

and fossil content, we suggest that the strata containing *Psilonichnus* ichnofacies corresponded to soft-muddy flats in the lower part of the supratidal zone. Therefore, PsI indicates times of minimum sea levels (maximum regression peaks; Appendix A and Figure 7).

Intertidal zone (foreshore)

This zone was characterized by *Skolithos* Ichnofacies (SkI) and MSL lithofacies (Figure 6). *Skolithos* ichnofacies is common and sometimes it may partially or completely obliterate the sedimentary structures (Dalrymple *et al.*, 1991). Based on the presence of *Skolithos* galleries in mudstone with little fine-grained sandstones and flaser lamination, which are common in modern intertidal zones (Dalrymple *et al.*, 1991), we interpreted that the strata containing SkI ichnofacies corresponded to mixed flats in intertidal sub-environments. Therefore SkI indicates also times of minimum sea levels (regression peaks; Appendix A and Figure 7).

Subtidal (foreshore) / shoreface

Different types of biofacies characterized these two zones (Figure 6). According to Ronan *et al.*(1981), Houbrick (1992) and Cranfield *et al.*(2004), in modern environments *Cerithium, Turritella* and *Pyrazus*
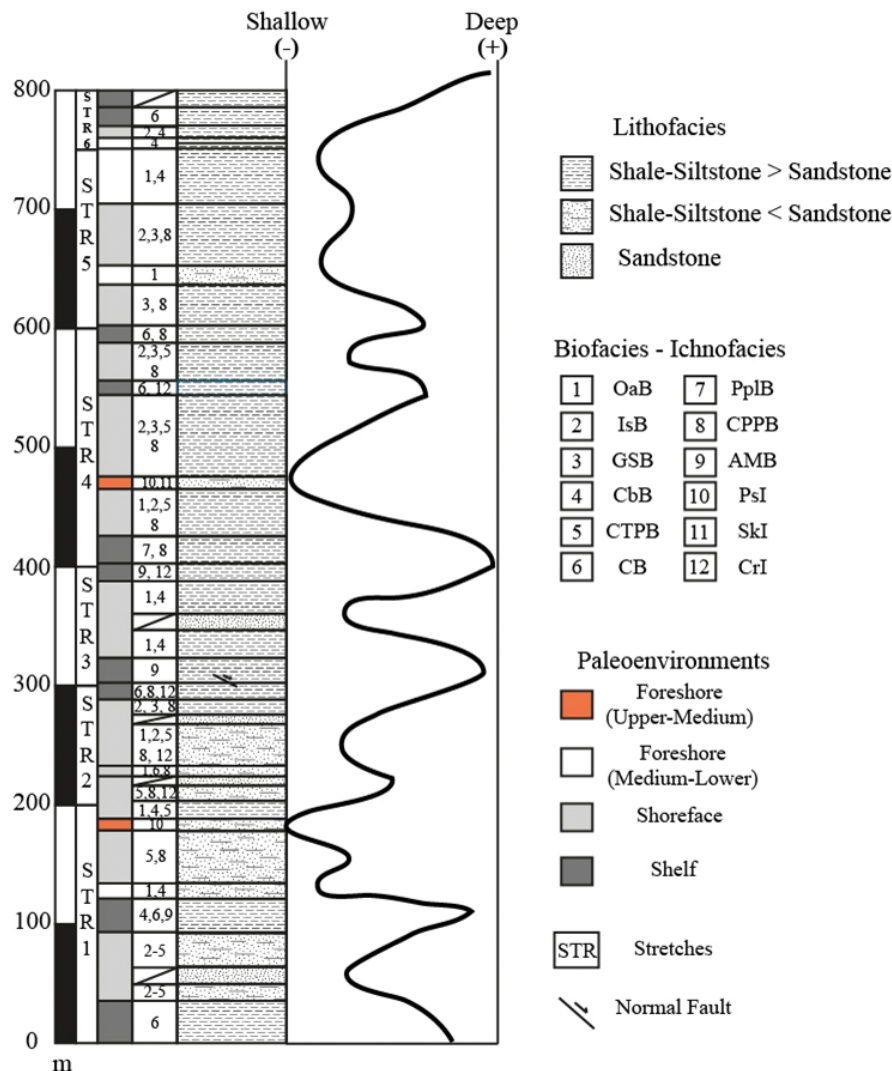

Figure 7. Facies association column and palaeowater depth curve of the San Juan Raya Formation at the study area.

gastropods live in shallow and well oxygenized waters between the subtidal and shoreface zones (1 to 5 m depth) around coral areas under a low to medium energy conditions. Based on the present occurrence of similar organisms, we interpret that *Cerithium bustamantii* biofacies (CbB) and *Cerithium bustamantii– Turritella minuta–Pyrazus maldonadoi* biofacies (CTPB), probably inhabited muddy and silty bottoms (interpretation corroborated by the FSD lithofacies that contains these fossil associations) on foreshore (subtidal zone) and shoreface environments between the lower tidal flats line and fair-weather wave base.

On the other hand, recent discoveries pointed out that oyster aggregation reaches its maximum development in foreshore (subtidal zone) and shoreface environments above fair-weather wave base, particularly between 3 and 4 m of water depth, (Livingston *et al.*, 2000; Campbell, 2010; Brown, 2011). Meanwhile, Mcpherson *et al.* (1984) made observations in modern bivalves belonging to *Isognomon* that also proliferate in this type of environments, but in water depths between 3 and 9 m. Finally, Fürsich and Werner (1984), Fornós *et al.*, (1997) and Ten Hove and Van Den Hurk (1993) discovered that calcareous tubeworms develop in marine waters ranging from 2 to 10 m depth.

Based on these evidences, we propose that *Ostrea alicula* (OaB), *Isognomon lamberti* (IsB) and gregarious serpulid biofacies probably formed under similar conditions and are indicative of these environmental zones. Therefore CbB, CTPB, OaB, IsB and GSB biofacies indicate times of deeper water depths, perhaps associated to a regression (regression peaks; Appendix A and Figure 7).

Lithofacies information suggests that the presence of abundant ooids and carophytes in the Bioclastic lithofacies (BL) indicate deposition in an inner-ramp setting during times of reduced siliciclastic input (Figure 6; Scholle and Ulmer-Scholle, 2003).

Shelf zone

In modern settings, coral colonies live in shallow seas in inner shelf environments ideally above 25 m depth, where they can constitute different types of biogenic structures including barrier systems. The shift from branching corals to mixed/massive and platy corals in recent reef fronts is a response to decreasing light and environmental energy, accompanied by increasing sedimentation with depth (Spalding *et al.*, 2001; Shears, 2007). In the case of the San Juan Raya Formation, coral size (3 to 25 cm), the lack of colonies overgrowth, and laterally discontinuous build-ups indicate that these organisms did not constitute a barrier system and only represented a patch-reef structure. Some investigations have shown that a moderate sedimentation rate and the lack of hard-bottoms can act as inhibitor factors for reef development (Fürsich *et al.*, 1994). Although some authors pointed out that some types of fossil coral colonies could inhabit deeper environments (Bover-Arnal *et al.*, 2012), because of the presence of a mixture of branching and massive corals, we suggest that Coral biofacies (CB) probably developed in an inner shelf environment above 20 m depth (Figure 6).

Francis (2000) points out the occurrence of trigoniid bivalves in transgressive-type deposits. Most species are associated to shelf environments of less than 30 m water depths (Francis, 2000; Francis and Hallam, 2003). Meanwhile, Lazo (2007b) and Fijuni and Maeda (2013) mentioned that modern species of *Pholadomya*, *Cardium* and *Panope* are common bivalves in low-energy inner shelf environments. Based on this evidence, *Pterotrigonia plicatocostata* (PplB) and *Cardium* cf. *cottaldinum–Pholadomya* cf. *gigantea–Panope neocomiensis* (CPPB) biofacies probably developed in silty-muddy seafloor, as indicated by the rock composition (FSD), but probably at different depths of the inner shelf (Figure 6). The presence of a strong valve dentition, narrow ribs, and an elaborate ornamentation of valves in PplB organisms indicates that they probably lived in shallower depths of the inner shelf where moderate to higher environmental energy levels were present.

On the other hand, CPPB biofacies probably developed in deeper waters where low environmental energy prevailed.

The presence of ammonoids that show little or no reworking indicates an open shelf environment (Figure 6). Despite these organisms lived along the water column, it is known that only few ammonoids drift significantly after death (Batt, 1989; Tsujita and Westermann, 1998). So, based on all that evidence we suggest that CB, PplB, CPPB and AMB biofacies indicates times of deeper water depths (transgression peaks; Appendix A and Figure 7).

Lithofacies evidence showed that the presence of alternated Isotropic Hummocky Cross-Stratification facies (StL1) and siltstone and mudstone facies (StL3) indicates periods of deposition at the inner shelf zone closer to the storm-wave base (Dumas and Arnott, 2010; Appendix B1 and Figure 6). Shallower storm deposits that were closer to the fair-weather wave base are suggested by StL2 lithofacies (Dumas and Arnott, 2010; Appendix B1 and Figure 6). Finally for the Shell Marl lithofacies (SML), fossil associations (disarticulated bivalve shells, serpulids and echinoid fragments), erosional base strata, and a concordant orientation of bioclasts, suggest a mid-ramp depositional setting via gradual hydraulic concentration (Appendix B2 and Figure 6).

CONCLUSIONS

Ten lithofacies, nine biofacies and three ichnofacies were recognized and interpreted in San Juan Raya Formation. Development and replacement of biofacies and ichnofacies through time was based on the influence of several environmental factors: relative sea level change, sedimentation rate, water salinity and substrate consistency. Among these factors it appears that salinity variations were crucial for developing and replacement of some different biofacies.

Based on fossil and lithological evidences, the San Juan Raya Formation at Santa Ana Teloxtoc area corresponded to a shallow marine, open-coast, storm-dominated clastic system. Most of the biofacies and ichnofacies developed in foreshore (subtidal), shoreface, and inner shelf zones.

The presence of *Ostrea alicula* (OaB), *Isognomon lamberti* (IsB) and gregarious serpulid (GSB) biofacies and *Psilonichnus* ichnofacies (PsI), reflect stressful environmental conditions with a lower sedimentation rate and different water salinity levels in the San Juan Raya Formation. Normal conditions in water salinity are represented by the rest of the biofacies and ichnofacies.

Clastic input probably was relatively low during maximum expansion of the *Ostrea alicula* (OaB), *Isognomon lamberti* (IsB) and *Cardium* cf. *cottaldinum–Pholadomya* cf. *gigantea–Panope neocomiensis* (CPPB) biofacies, because higher sedimentation rates inhibits adult the growth of oysters and other types of bivalves and also inhibits the establishment of new larvae. On the other hand, the presence of Coral biofacies suggests times of constant sedimentation that prevented the formation of coral reefs. Also, the development of an increased shelf area below shallower deposits created a more extended environment for the proliferation of infaunal trigonids (*Pterotrigonia plicatocostata* biofacies).

Fossil evidence shows that minimum sea level events contained all the ichnofacies (*Psilonichnus*, *Skolithos* and *Cruziana* ichnofacies) and five from the nine biofacies (*Ostrea alicula*; *Isognomon lamberti*; Gregarious Serpulid; *Cerithium bustamantii* and *Cerithium bustamantii–Turritella minuta–Pyrazus maldonadoi* biofacies). The presence of *Psilonichnus* ichnofacies corresponded to maximum regression peaks. Transgressive deepening stages are represented by four biofacies (Coral, *Pterotrigonia plicatocostata*, *Cardium* cf. *cottaldinum–Pholadomya* cf. *gigantea–Panope neocomiensis* and Ammonoid biofacies) and one ichnofacies (*Cruziana* ichnofacies).

ACKNOWLEDGEMENTS

APPENDIX. SUPPLEMENTARY MATERIAL

Appendices A and B can be found at the journal web site <http://rmcg.unam.mx/>, in the table of contents of this issue.

REFERENCES

Agassiz, L., 1840, Études critiques sur les mollusques fossiles, Mémoire sur les trigonies: Neuchâtel, aux frais de l'auteur, 58 pp.

Alencáster de Cserna, G., 1956, Pelecípodos y gasterópodos del Cretácico Inferior de la región de San Juan Raya-Zapotitlán, estado de Puebla: Paleontología Mexicana, 2, 1-47.

Batt, R.J., 1989, Ammonite shell morphotype distribution in the Western Interior Greenhorn sea and some paleoecological implications: Palaios, 4, 32-42.

Böse, E., 1910, Monografía geológica y paleontológica del Cerro de Muleros cerca de Ciudad Juárez, estado de Chihuahua, y descripción de la fauna cretácica de la Encantada, Placer de Guadalupe, estado de Chihuahua: México, Instituto Geológico de México, Boletín 25, 193 pp.

Bover-Arnal, T., Löser, H., Moreno-Bedmar, J.A., Salas, R., Strasser, A., 2012, Corals on the slope (Aptian, Maestrat Basin, Spain): Cretaceous Research, 37, 43-64.

Brenchley, P.J., 1990, Biofacies, *in* Briggs D.E.G and P.R. Crowther (eds) Palaeobiology as a synthesis: Cambridge, Blackwell Scientific Publications, 395-400.

Brett, C.E., Baird, G.C., 1986, Comparative taphonomy: a key for paleoenvironmental reconstruction: Palaios, 1, 207-227.

Brian, M., 2008, The Diurnal Rhythm and Tidal Rhythm of Feeding and Digestion in *Ostrea edulis*: Biological Journal of the Linnean Society, 3(49), 329-342.

Brown, S.N., 2011, Ecology and Enhancement of the Flat Oyster *Ostrea chilensis* (Phillipi, 1845) in Central New Zealand: University of Canterbury, Ph. D. thesis, 120 pp.

Buitrón, B.E., 1970, Equinoides del Cretácico Inferior de la región de San Juan Raya – Zapotitlán, estado de Puebla: Paleontología Mexicana, 30, 1-45.

Buitrón, B.E., Barceló-Duarte, J., 1980, Nerineidos (Mollusca-Gastropoda) del Cretácico Inferior de la Región de San Juan Raya, Puebla: Paleontología Mexicana, 4(1), 46-55.

Calderón-García, A., 1956, Estratigrafía del Mesozoico y tectónica del Sur de Puebla; Presa de Valsequillo, Sifón de Huexotitlanapa y problemas hidrológicos de Puebla, *in* XX Congreso Geológico Internacional, Libro Guía, Excursión A-11: México, D. F., International Geological Congress, Universidad Nacional Autónoma de México, Instituto de Geología, 9–27.

Campbell, G., 2010, Oysters Ancient and Modern: Potential Shape Variation with Habitat in Flat Oysters (*Ostrea edulis*) and its Possible Use in Archaeology: Meeting of the ICAZ Archaeomalacology Working Group, 2(31), 176-187.

Coquand, H., 1869, Monographie du Genre *Ostrea*. Terrain Crétacé du Mexique: Bulletin Société Géologique de France, 3(8), 292-299.

Cranfield, H.J., Rowden, A.A., Smith, D.J., Gordon, D.P., Michael, K.P., 2004, Macrofaunal assemblages of benthic habitat of different complexity and the proposition of a model of biogenic reef habitat regeneration in Foveaux Strait, New Zealand: Journal of Sea Research, 52(2), 109-125.

Dalrymple, R.W., Makino, Y., Zaitlin, B.A., 1991, Temporal and spatial patterns of rhythmite deposition on mudflats in the macrotidal, Cobequid Bay Salmon River estuary, Bay of Fundy, Canada, *in* Smith, D.G., Reinson, G.E., Zaitlin, B.A., Rahmani, R.A. (eds.), Clastic Tidal Sedimentology: Canada, Canadian Society of Petroleum Geologists Memoir, 16, 137-160.

Desor, E., 1850-1859, Synopsis des échinides fossiles: Paris, 490 pp.

D'Orbigny, A., 1850, Prodome de paleontologie stratigraphique universelle: Paris, 2, 427 pp.

Dumas, S., Arnott, R.W.C, 2010, Origin of hummocky and swaley cross-stratification - The controlling influence of unidirectional current strength and aggradation rate: Geology, 34 (12), 1073-1076.

Escalante-Ruiz, A.R., 2006, Estudio paleobiológico de las trigonias de la Formación San Juan Raya, Cretácico Inferior de Puebla: Universidad Nacional Autónoma de México, Facultad de Ciencias, tesis licenciatura, 49 pp.

Escalante-Ruiz, A.R., Quiroz-Barroso, S.A., 2006, Paleobiología de las trigonias de la Formación San Juan Raya, Estado de Puebla, *in* Memoria del X Congreso Nacional de Paleontología, México, D.F.: México, Sociedad Mexicana de Paleontología, p. 35.

Feldmann, R.M., Vega-Vera, F.J., García-Barrera, P., Rico-Montiel, R., Martínez-López, L., 1995, A New Species of *Meyeria* (Decapoda: Mecochiridae) from the San Juan Raya Formation (Aptian: Cretaceous), Puebla State, Mexico: Journal of Paleontology, 69(2), 402-406.

Felix, J., 1891, Versteinerungen aus der Mexikanischen Jura und Kreide Formation: Paleontographica, 37, 140-199.

Fornós, J.J., Forteza, V., Martínez-Taberner, A., 1997, Modern polychaete reefs in western mediterranean lagoons: Palaeogeography, Palaeoclimatology, Palaeoecology, 128(1-4), 175-186.

Francis, A.O., 2000, The palaeobiology of the european Jurassic Trigoniidae: UK, University of Birmingham, Ph.D. thesis, 323 pp.

Francis, A.O., Hallam, A., 2003, Ecology and evolution of Jurassic Trigoniid bivalves in Europe: Lethaia, 36, 287-304.

Fujino, S., Maeda, H., 2013, Environmental changes and shallow marine fossil bivalve assemblages of the Lower Cretaceous Miyaco Group, NE Japan: Journal of Asian Earth Sciences, 64, 168-179.

Fürsich, F.T., Werner, W., 1984, Salinity zonation of benthic associations in the Upper Jurassic of the Lusitanian Basin (Portugal): Geobios, 8, 85-92.

Fürsich, F.T., Pandey, D.K., Oschmann, W., Jaitly, A.K., Singh, I.B., 1994, Ecology and adaptative strategies of corals in unfavorable environments: examples from the Middle Jurassic of Kach Basin, Western India: Neues Jarnbuch für Geologie und Paläontologie Abhanlungen, 194, 269-303.

González-Arreola, C., 1974, *Phylloceras* del Cretácico Inferior de San Juan Raya-Zapotitlán, estado de Puebla, México: Boletín Sociedad Geológica Mexicana, 3, 29-37.

Hamlin, C.E, 1890, Results of an examination of syrian molluscan fossils, chiefly from Mount Lebanon: Memories of Museum of Comparative Zoology, 3, 1-68.

Hampson, G.J., Storms, J.E.A., 2003, Geomorphological and sequence stratigraphic variability in wave-dominated, shoreface-shelf parasequences: Sedimentology, 50, 667-701.

Houbrick, R.S., 1992, Monograph of the genus *Cerithium* Bruguiere in the Indo-Pacific (Cerithiidae: Prosobranchia): Smithsonian Contributions to Zoology, 510, 1-21.

Howard, J.D., Reineck, H.E., 1981, Depositional facies of high-energy beach to offshore sequence: Comparison with low-energy sequence: American Association of Petroleum Geologists Bulletin, 65, 807-830.

Kidwell, S.M., 1986, Models for fossil concentrations: Paleobiologic implications: Paleobiology, 12, 6-24.

Lambert, J., 1935, Note sur quelques échinides fossils, part 3, Échinides du Mexique: Bulletin Société Géologique de France, Serie 5, 5(4-5), 365-368.

Lazo, D.G., 2007a, Análisis de biofacies y cambios relativos del nivel del mar en el Miembro Pilmatué de la Formación Agrio, Cretácico Inferior de la Cuenca Neuquina, Argentina: Ameghiniana, 44(1), 73-89.

Lazo, D.G., 2007b, The bivalve *Pholadomya gigantea* in the Early Cretaceous of Argentina: Taxonomy, taphonomy and paleogeographic implications: Acta Palaeontologica Polonica, 5(2), 375-390.

Lazo, D.G., Cichowolski, M, Rodríguez, D.L., Aguirre-Urreta, M.B., 2005, Lithofacies, Palaeoecology and Palaeoenvironments of the Agrio Formation, Lower Cretaceous of the Neuquén Basin, Argentina, *in* Veiga,

G.D., Spalletti, L.A., Howell, J.A. and Schwarz, E. (eds.), The Neuquén Basin, Argentina: A Case Study in Sequence Stratigraphy and Basin Dynamics: Geological Society, London, Special Publications 252, 295-315.

Lazo, D.G., Aguirre-Urreta, M.B., Price, G.D., Rawson, P.F., Ruffell, A., Ogle, N., 2008, Palaeosalinity variations in the Early Cretaceous of the Neuquén Basin, Argentina: Evidence from oxygen isotopes and palaeoecological analysis: Palaeogeography, Palaeoclimatology, Palaeoecology, 260, 477-493.

Livingston, R.J., Lewis, F.G., Woodsum, G.C., Niu, X., Galperin, B., Huang, W., Christensen, J.D., Monaco, M.E., Battista, T.A., Klein, C.J., Howell, R.L., Ray, G.L., 2000, Modeling oyster population response to variation in freshwater input: Estuarine, Coastal and Shelf Science, 50, 655-672.

Löser, H., 2006, Barremian corals from San Antonio Texcala, Puebla, Mexico - A review of the type material of Felix 1891 (CD-ROM): Boletín del Instituto de Geología, 114, 1-68.

McPherson, B.F., Sonntag, W.H., Sabaskas, M., 1984, Fouling community of the Loxahatchee River Estuary, Florida, 1980-1981: Estuaries, 7, 149-157.

Mendoza-Rosales, C.C., 2010, Estratigrafía y facies de las cuencas Cretácicas del Sur de Puebla y su significado tectónico: Universidad Nacional Autónoma de México, tesis de doctorado, 190 pp.

Mendoza-Rosales, C.C., Centeno-García, E., Silva-Romo, G., Campos-Madrigal, E., Bernal, J.P., 2010, Barremian rift-related turbidites and alkaline volcanism in the southern Mexico and their role in the opening of the Gulf of Mexico: Earth and Planetary Sciences, 295 (3-4), 419-434.

Mora-Almazán, E.R., 2008, Bivalvos perforadores de madera en la formación San Juan Raya, Cretácico Inferior de Puebla: Universidad Nacional Autónoma de México, Facultad de Ciencias, tesis de licenciatura, 55 pp.

Mora-Almazán, E.R., Quiroz-Barroso, S.A., 2006, Presencia de bivalvos perforadores de madera en la formación San Juan Raya, Cretácico Inferior de Puebla, *in* Memoria del X Congreso Nacional de Paleontología, México, D.F.: México, Sociedad Mexicana de Paleontología, p. 58.

Müllerried, F.K., 1933-1934, Estudios paleontológicos y estratigráficos en la región de Tehuacán, Puebla: Anales del Instituto de Biología, 4, 33-46, 79-93, 309-338 (1933); 5, 55-88 (1934).

Nyst, H., Galeotti, H., 1840, Description des mollusques et rayonnés fossiles, Tehuacán au Mexique: Royal Academy Bruxelles Bulletin, 7, 212 - 221.

Ortega-Gutiérrez, F., Elías-Herrera, M., Reyes-Salas, M., Macías-Romo, C., López, R., 1990, Late Ordovician–Early Silurian continental collision orogeny in southern Mexico and its bearing on Gondwana-Laurentia connections: Geology, 27(8), 719-722.

Pemberton, S.G., Spila, M., Pulham, A.J., Saunders, T., MacEachern, J.A., Robbins, D., Sinclair, I.K., 2001, Ichnology and sedimentology of shallow to marginal marine systems: Ben Nevis and Avalon Reservoirs, Jeanne D'Arc Basin: Canadian Society of Petroleum Geologists, Short Course Notes 15, chapter 5.

Pryor, W.A., 1975, Biogenic sedimentation and alteration of argillaceous sediments in shallow marine environments: Geological Society of America Bulletin, 86, 1244-1254.

Reyeros, M., 1963, Corales del Cretácico Inferior de San Juan Raya, estado de Puebla: Paleontología Mexicana, 17, 1-21.

Rioja-Nieto, R., Chiappa-Carrara, X., Sheppard, C., 2012, Efecto de los huracanes sobre la estabilidad de paisajes asociados con arrecifes coralinos: Ciencias Marinas, 30(1A), 47-55.

Ronan, T.E. Jr., Miller, M.F., Farmer, J.D., 1981, Organism-sediment relationships on a modern tidal flat, Bodega Harbor, California, *in* Frizzell, V. (ed.), Modern and ancient biogenic structures, Bodega Bay, California, Pacific section: California, Society of Economic Paleontologists and Mineralogists, 15-31.

Salmones-Zarate, J.M., 1994, Los moluscos juveniles de la Formación San Juan Raya, Puebla: Universidad Nacional Autónoma de México, Facultad de Ciencias, tesis de licenciatura, 153 pp.

Scholle, P.A., Ulmer-Scholle, D.S., 2003, A color guide to the petrography of carbonate rocks: grains, textures, porosity, diagenesis: Canada, AAPG Memoir 77, 470 pp.

Shears, N.T., 2007, Biogeography, community structure and biological habitat types of subtidal reefs on the South Island West Coast, New Zealand: Wellington, Science for Conservation, 281, 53 pp.

Sowerby, J.C., 1823-1846, The mineral conchology of Great Britain: London, 384-648.

Spalding, M.D., Ravilious, C., Green, E.P., 2001, World atlas of coral reefs: Berkeley, University of California Press, 424 pp.

Ten Hove, H.A., Van Den Hurk, P., 1993, A review of recent and fossil Serpulid 'reefs', actuopalaeontology and the 'Upper Main' serpulid limestones in NW Germany: Geologie en Mijnbouw, 72, 23-67.

Tsujita, C.J., Westermann, G.E.G., 1998, Ammonoid habitats and habits in the Western Interior Seaway: A case of study from the Upper Cretaceous Bearpaw Formation of southern Alberta, Canada: Palaeogeography, Palaeoclimatology, Palaeoecology, 144 (1-5), 135-160.

Wignall, P.B., 1990, Benthic palaeocology of the Late Jurassic Kimmeridge clay of England: Special papers in palaeontology, 43, 1-74.

APPENDIX

to the paper

Paleoenvironmental interpretation using fossil record: San Juan Raya Formation, Zapotitlán Basin, Puebla, Mexico
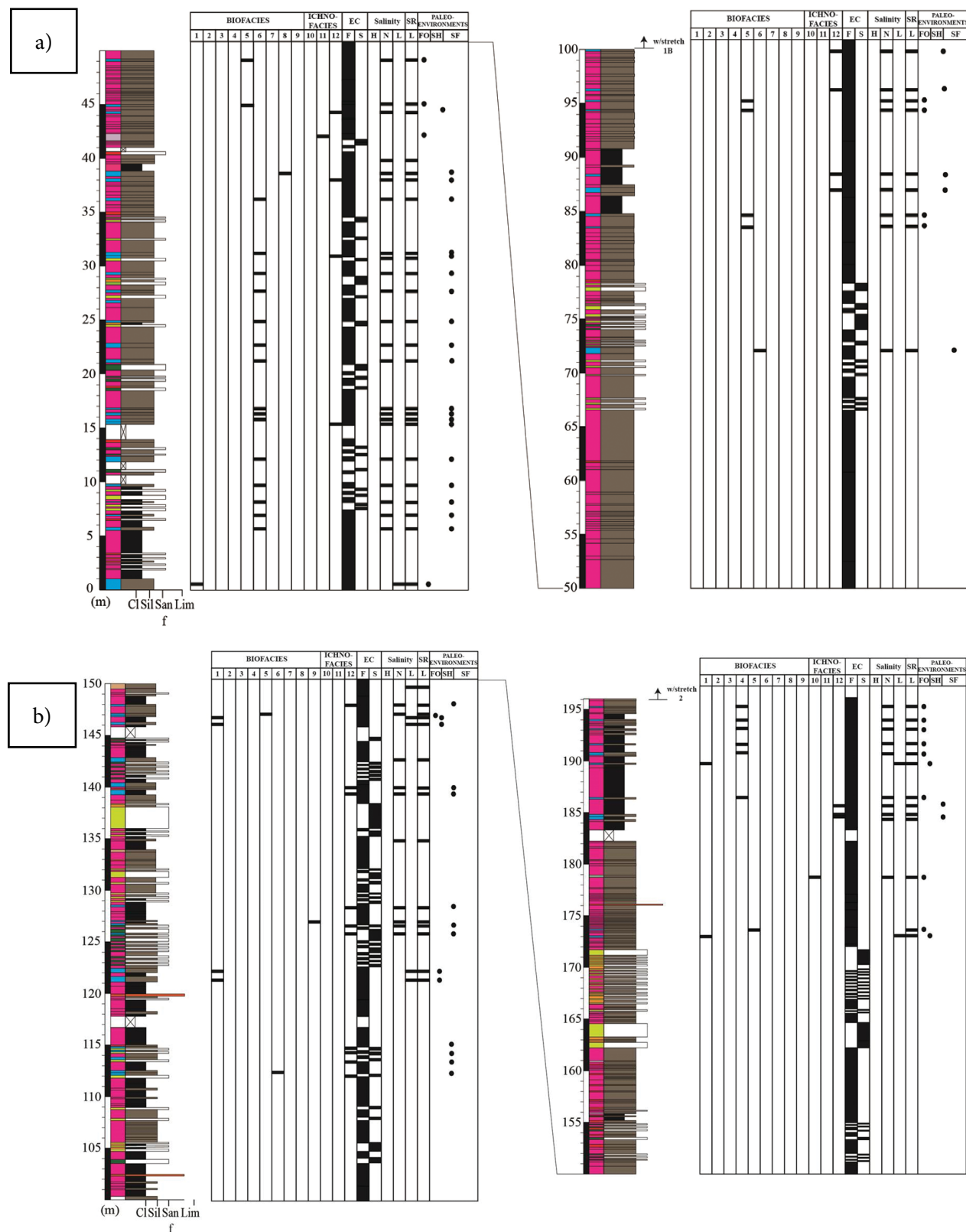
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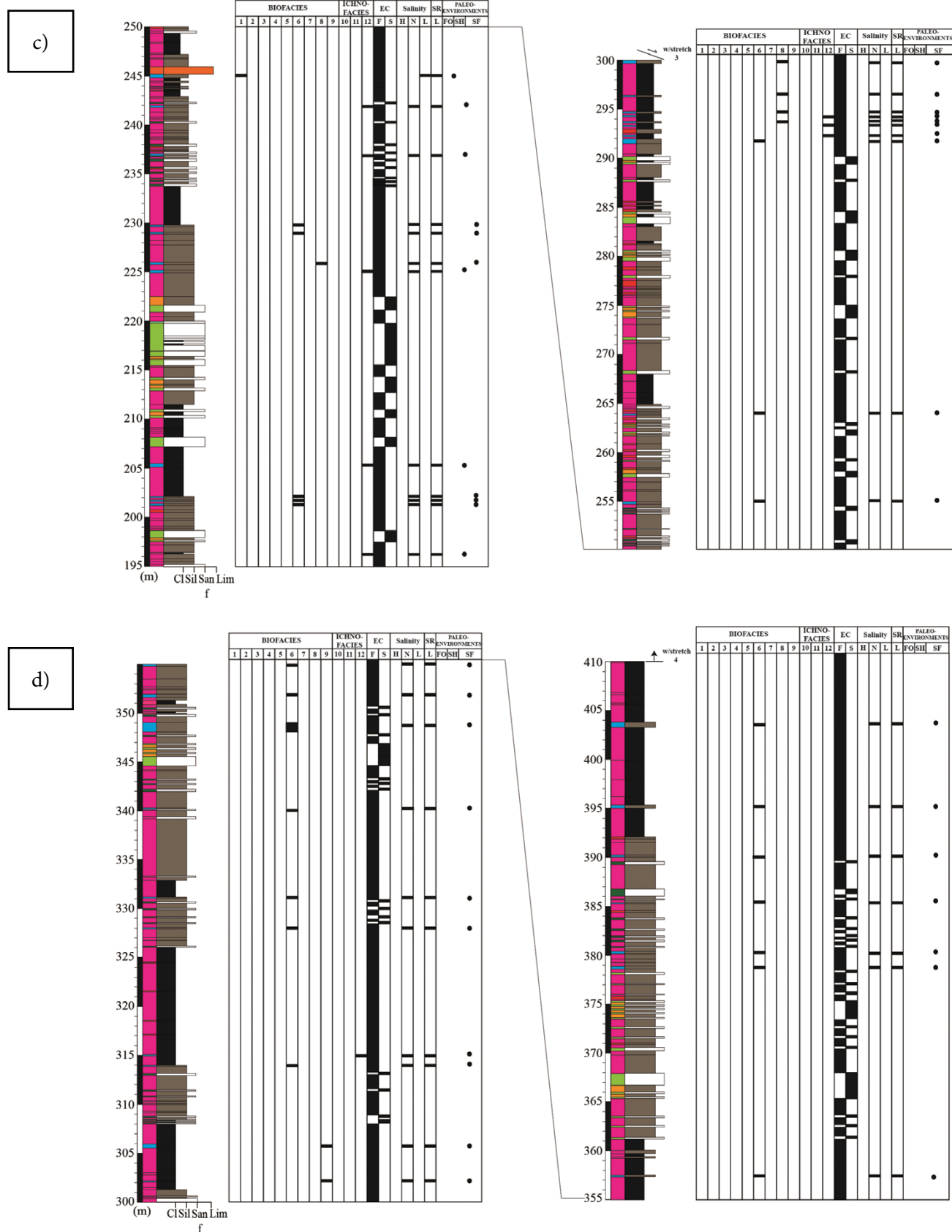**Claudia Inés Serrano-Brañas and Elena Centeno-García**

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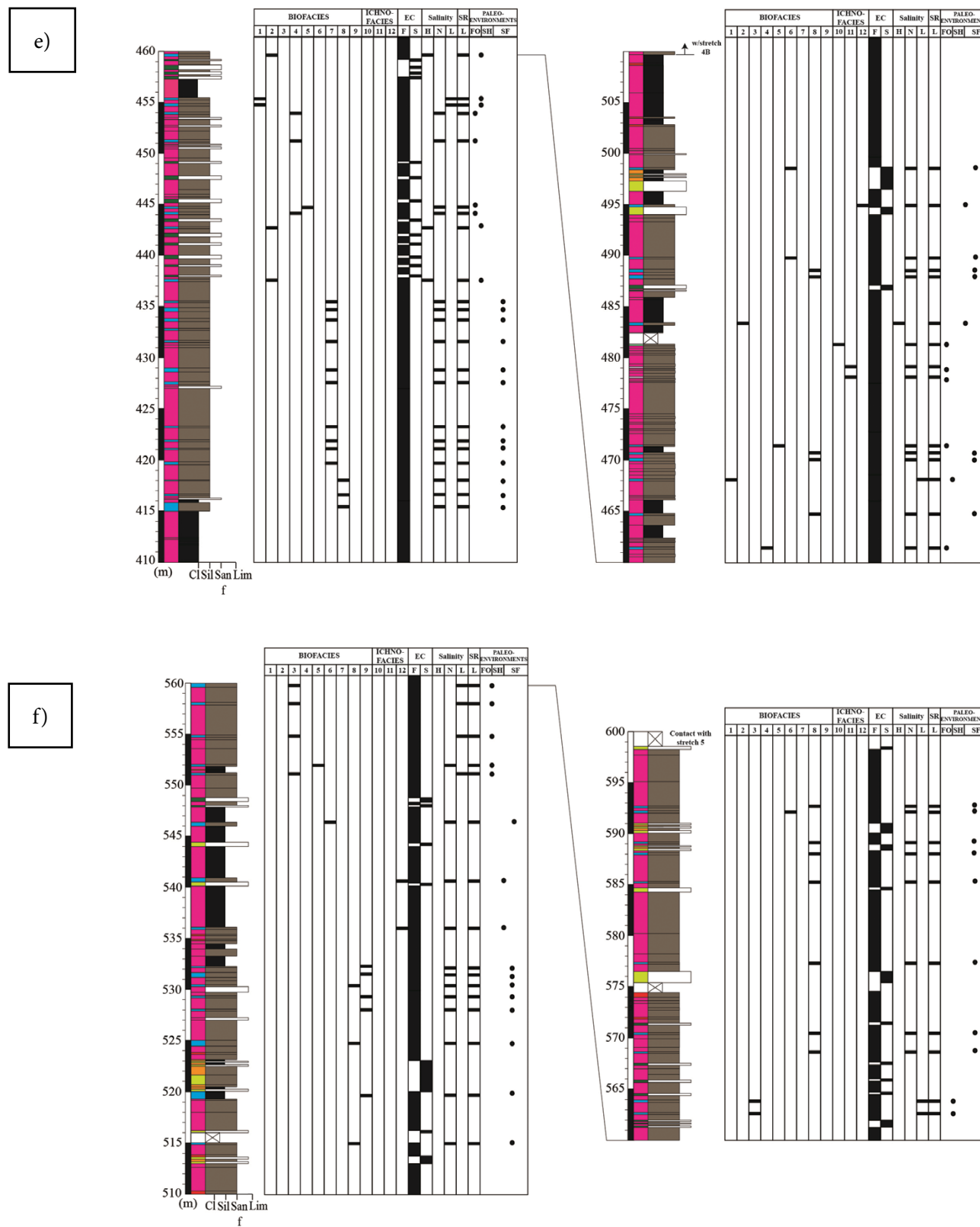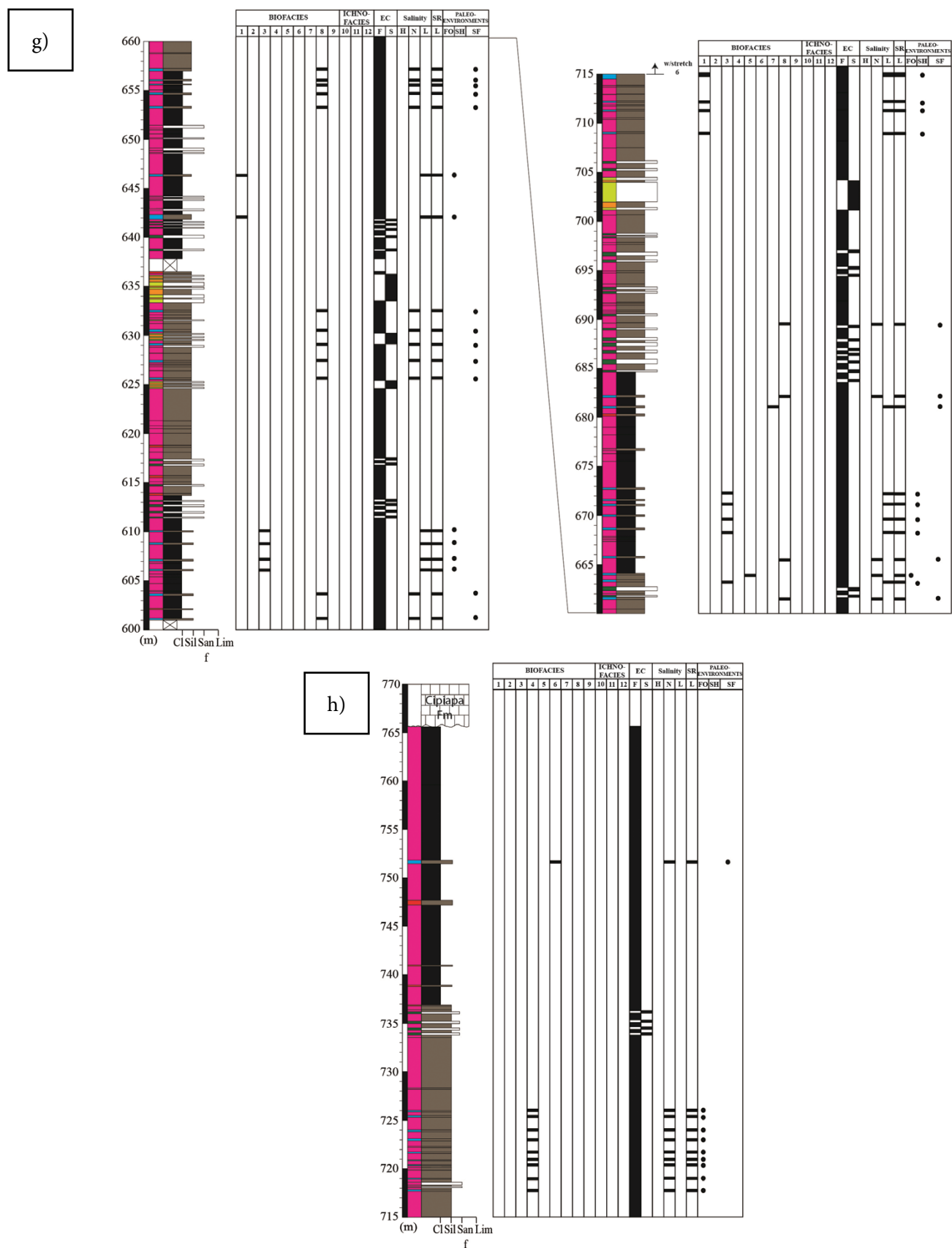# APPENDIX A

A1. Composite stratigraphic column measured on a bed-by-bed scale at Barranca San Lucas, south of Santa Ana Teloxtoc area. (a-b) stretch 1; (c) stretch 2; (d) stretch 3; (e-f) stretch 4; (g) stretch 5; (h) stretch 6; (i) Key. Stratigraphic columns contain data about biofacies, ichnofacies, environmental conditions, salinity, sedimentation rate and paleoenvironment distribution.

A1. Composite stratigraphic column measured on a bed-by-bed scale at Barranca San Lucas, south of Santa Ana Teloxtoc area (continues). (a-b) stretch 1; (c) stretch 2; (d) stretch 3; (e-f) stretch 4; (g) stretch 5; (h) stretch 6; (i) Key. Stratigraphic columns contain data about biofacies, ichnofacies, environmental conditions, salinity, sedimentation rate and paleoenvironment distribution.

A1. Composite stratigraphic column measured on a bed-by-bed scale at Barranca San Lucas, south of Santa Ana Teloxtoc area (continues). (a-b) stretch 1; (c) stretch 2; (d) stretch 3; (e-f) stretch 4; (g) stretch 5; (h) stretch 6; (i) Key. Stratigraphic columns contain data about biofacies, ichnofacies, environmental conditions, salinity, sedimentation rate and paleoenvironment distribution.
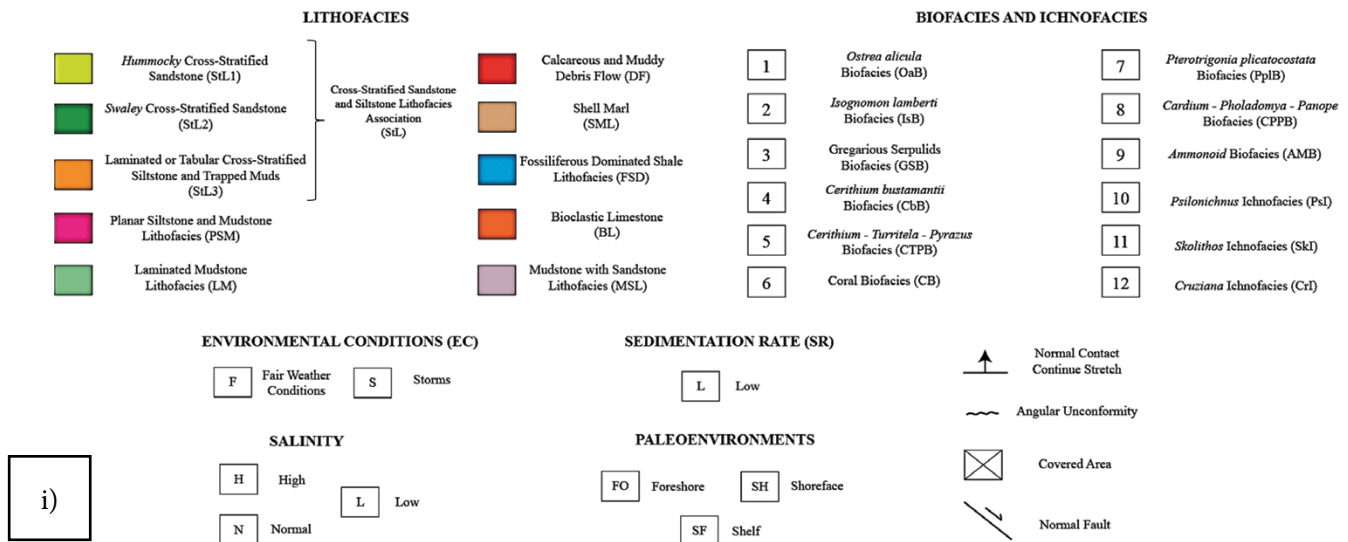
A1. Composite stratigraphic column measured on a bed-by-bed scale at Barranca San Lucas, south of Santa Ana Teloxtoc area (continues). (a-b) stretch 1; (c) stretch 2; (d) stretch 3; (e-f) stretch 4; (g) stretch 5; (h) stretch 6; (i) Key. Stratigraphic columns contain data about biofacies, ichnofacies, environmental conditions, salinity, sedimentation rate and paleoenvironment distribution.
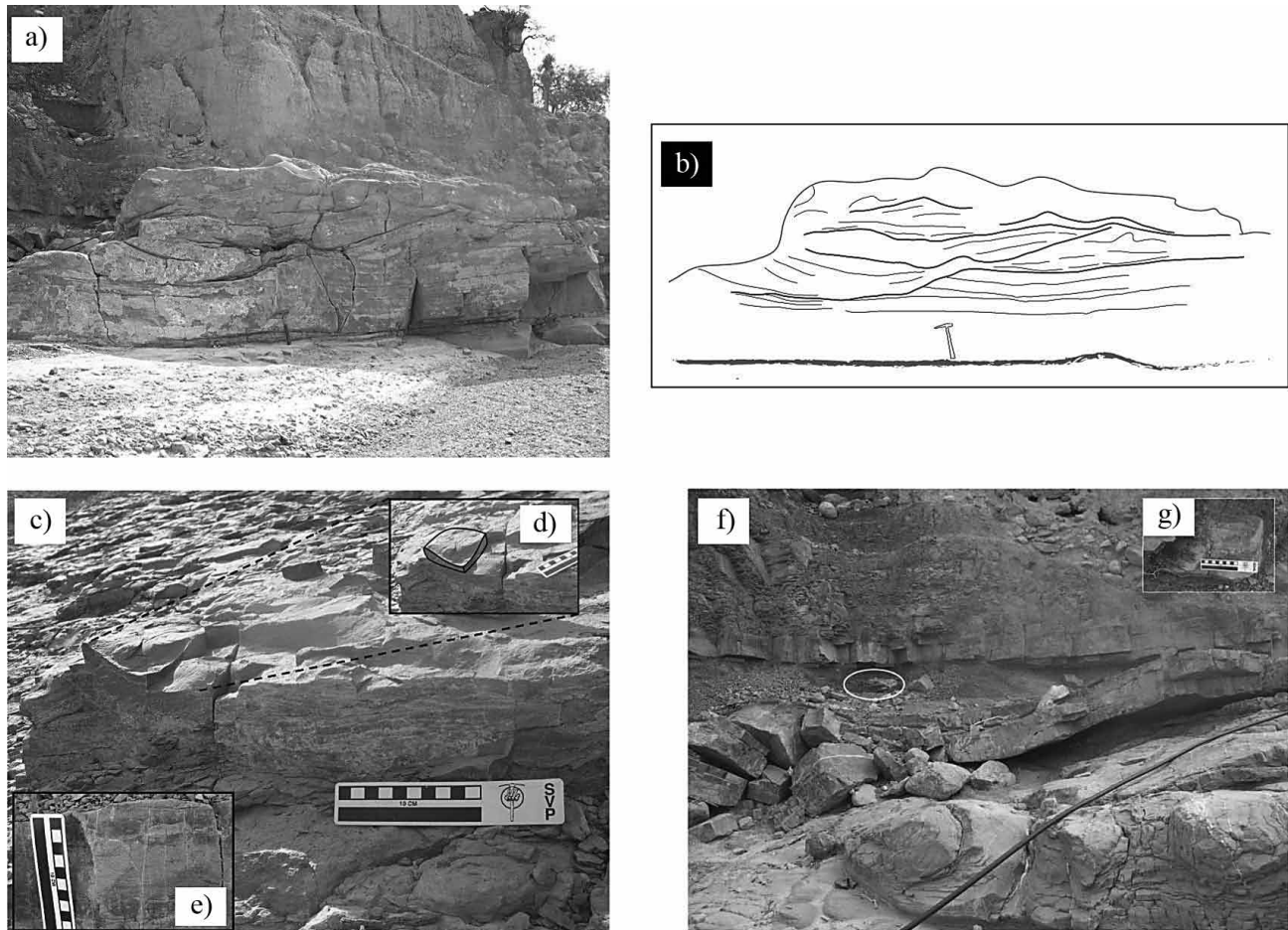
LITHOFACIES

- *Hummocky* Cross-Stratified Sandstone (StL1)
- *Swaley* Cross-Stratified Sandstone (StL2)
- Laminated or Tabular Cross-Stratified Siltstone and Trapped Muds (StL3)

Cross-Stratified Sandstone and Siltstone Lithofacies Association (StL)

- Planar Siltstone and Mudstone Lithofacies (PSM)
- Laminated Mudstone Lithofacies (LM)
- Calcareous and Muddy Debris Flow (DF)
- Shell Marl (SML)
- Fossiliferous Dominated Shale Lithofacies (FSD)
- Bioclastic Limestone (BL)
- Mudstone with Sandstone Lithofacies (MSL)

BIOFACIES AND ICHNOFACIES

1. *Ostrea alicula* Biofacies (OaB)
2. *Isognomon lamberti* Biofacies (IsB)
3. Gregarious Serpulids Biofacies (GSB)
4. *Cerithium bustamantii* Biofacies (CbB)
5. *Cerithium - Turritela - Pyrazus* Biofacies (CTPB)
6. Coral Biofacies (CB)
7. *Pterotrigonia plicatocostata* Biofacies (PplB)
8. *Cardium - Pholadomya - Panope* Biofacies (CPPB)
9. *Ammonoid* Biofacies (AMB)
10. *Psilonichnus* Ichnofacies (PsI)
11. *Skolithos* Ichnofacies (SkI)
12. *Cruziana* Ichnofacies (CrI)

ENVIRONMENTAL CONDITIONS (EC)

- F Fair Weather Conditions
- S Storms

SEDIMENTATION RATE (SR)

- L Low

SALINITY

- H High
- L Low
- N Normal

PALEOENVIRONMENTS

- FO Foreshore
- SH Shoreface
- SF Shelf

Normal Contact Continue Stretch

Angular Unconformity

Covered Area

Normal Fault

i)

A1. Composite stratigraphic column measured on a bed-by-bed scale at Barranca San Lucas, south of Santa Ana Teloxtoc area (continues). (a-b) stretch 1; (c) stretch 2; (d) stretch 3; (e-f) stretch 4; (g) stretch 5; (h) stretch 6; (i) key. Stratigraphic columns contain data about biofacies, ichnofacies, environmental conditions, salinity, sedimentation rate and paleoenvironment distribution.

APPENDIX B

B1. Cross-stratified sandstone and siltstone lithofacies (StL). (a) *Hummocky* cross-stratification sandstone (StL1): outcrop, (b) interpretation of *Hummocky* cross-stratification sandstone lithofacies (StL1). (c) *Swaley* cross-stratification sandstone (StL2): outcrop, (d) swale, (e) sets of cross-stratification, (f) lenticular to planar strata of siltstone and some trapped muds (StL3): outcrop, (g) wood log.
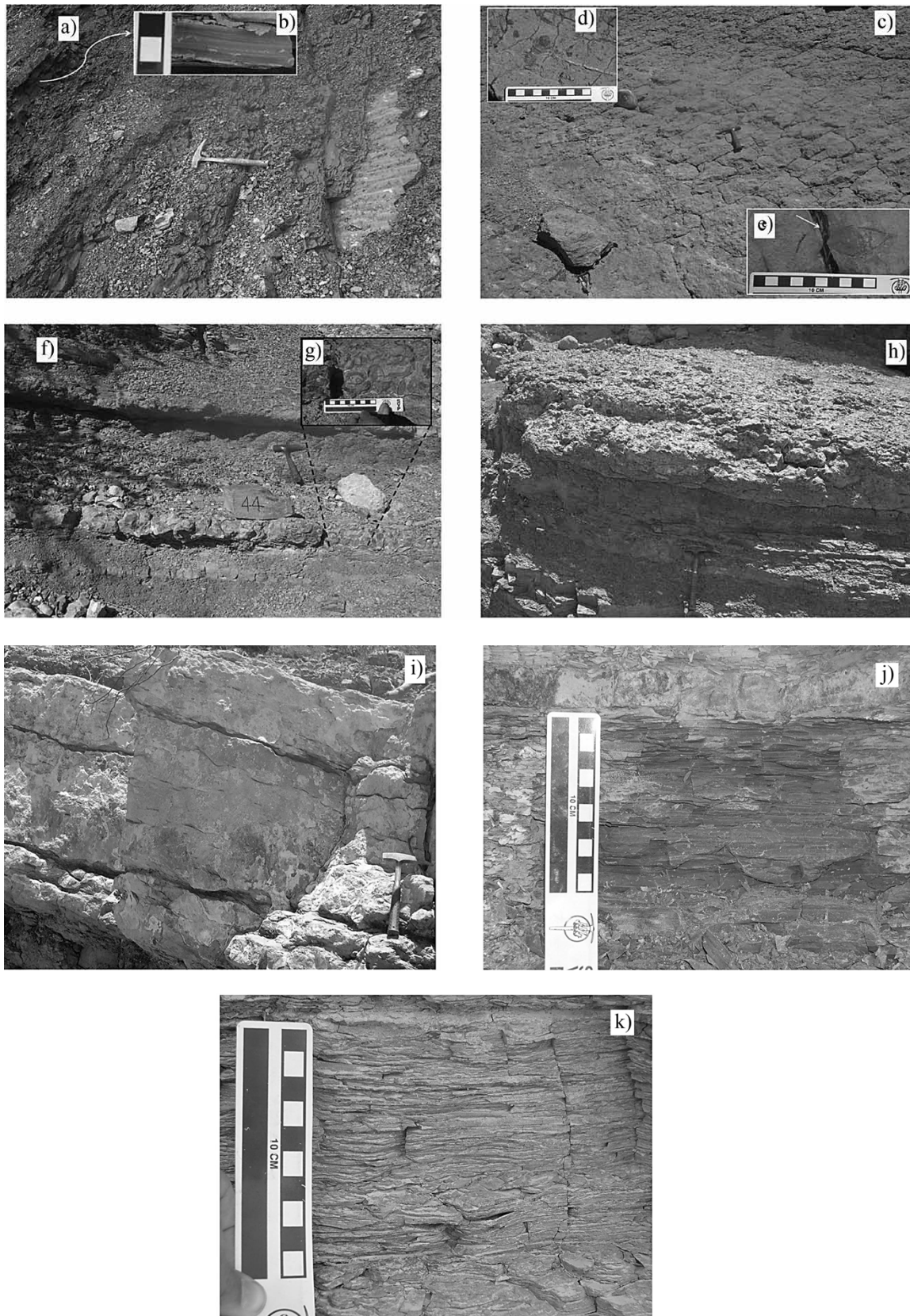
B2. Other lithofacies present in San Juan Raya Formation at the Santana Teloxtoc Area. (a) Planar siltstone and mudstone lithofacies (PSM) outcrop; (b) laminations; (c) Calcareous and muddy Debris flow lithofacies (DF), muddy debris flow bed; (d) shell debris at the top of stratum; (e) articulated bivalves; (f) Shell marl lithofacies (SML) outcrop; (g) packed bivalve coquina immerse in muddy massive matrix; (h) fossiliferous shale dominated lithofacies (FSD) outcrop; (i) bioclastic limestone lithofacies (BL) outcrop; (j) laminated mudstone lithofacies (LM), parallel laminations; (k) mudstone with sandstone lithofacies (MSL), flaser bedding.