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Heterogeneous subsidence and paleogeographic elements in an extensional setting revealed through the correlation of a storm deposit unit (Aptian, E Spain)

Subsidencia heterogénea y elementos paleogeográficos en un marco extensional deducido a partir de la correlación de un intervalo de tempestitas (Aptiense, E España)

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Abstract

A coastal marine siliciclastic unit has been studied from a palaeogeographic and structural-stratigraphic point of view. The unit was deposited during the Aptian in the extensional Las Parras sub-basin (Maestrazgo basin, E Spain), and it has been subdivided in four coarsening-upward sequences. A general description of each sequence is done but we focus in the third sequence (S3), which is built up of fine to coarse-grained sandstones, representing a vertical facies shift from storm dominated lower shoreface to upper shoreface environments. Both physical and genetic criteria have been used to correlate sequence S3. Top of sequence S3 is a minor erosive surface and is considered a reliable cronostratigraphic datum for correlation across the study area. Lateral facies changes of sequence S3 suggest the location of a siliciclastic discharge system toward the southeast of the study area. Drainage entry could be related to an intersection of basin bounding faults. Over the datum surface, coarsening upwards sequence S4 lacks its lower part in the south-easternmost area. An intra-S4 local discontinuity is defined and correlated toward the north-western area. The south-eastern area was located over a different subsiding block than the other sections and different subsidence histories for these blocks are interpreted on the basis of thickness trends and features of the intra-S4 discontinuity. Intra-S4 discontinuity marks the change from siliciclastic to carbonate dominated sedimentation, thus it could be representing a major break in the sedimentary dynamic. Spatial thickness trends of each sequence at the intra-block scale probably represent alternating episodes of homogeneous and heterogeneous subsidence that may be related to extensional dynamics.

Keywords: high-resolution correlation, differential subsidence, storm deposits, Aptian, Spain.

Resumen

Durante el Aptiense, en la Subcuenca de Las Parras (NW Cuenca del Maestrazgo) se depositó una unidad siliciclástica en un contexto tectónico extensional. Esta unidad se ha dividido en cuatro secuencias granocrecientes, de las cuales se analiza en detalle la tercera (S3) ya que presenta un alto potencial de correlación lateral. El análisis sedimentológico de la secuencia S3 ha permitido interpretar una evolución vertical de *shoreface* inferior con procesos de tormenta, a *shoreface* superior; también ha permitido correlacionar esta secuencia entre dos sectores de la subcuenca que presentan un desarrollo litológico considerablemente diferente.

El techo de la secuencia S3 es una superficie erosiva menor con valor cronoestratigráfico y se ha utilizado como datum de correlación para el análisis de la unidad siliciclástica. Las variaciones laterales de facies de la secuencia S3 permiten interpretar la proximidad de un sistema de descarga siliciclástico hacia el sureste, y se propone una zona de intersección de fallas normales, próxima al sector suroriental de la zona estudiada, como un elemento paleoestructural favorable para la entrada de un sistema de drenaje en la cuenca. En el sector suroriental, por encima del datum de correlación, la secuencia S4 presenta un desarrollo muy reducido debido a la ausencia de su parte inferior; esto ha permitido interpretar la presencia de una discontinuidad local intra-S4. Esta discontinuidad local se correlaciona con otra reconocida en el sector noroccidental. Debido a las diferencias de espesor y al grado de desarrollo de la discontinuidad intra-S4 se deduce que la historia de subsidencia de diferentes bloques de la cuenca no es exactamente la misma. Esta discontinuidad intra-S4 podría tener interés regional ya que separa sedimentos dominantemente siliciclásticos de sedimentos carbonatados y podría indicar una modificación importante del sistema sedimentario. Para uno de los bloques estudiados, las variaciones espaciales de espesor para cada secuencia podrían representar un desarrollo de la subsidencia alternando periodos con subsidencia diferencial atenuada y periodos con subsidencia diferencial acentuada, que pueden estar relacionados con la dinámica extensional.

Palabras clave: correlación de alta resolución, subsidencia diferencial, depósitos de tormenta, Aptiense, España.

1. Introduction

Two major episodes of siliciclastic followed by carbonate sedimentation are the main lithostratigraphic feature of the lower Aptian in Las Parras sub-basin, which was a marginal area of the Maestrazgo basin of eastern Spain (Canérot, 1974; Clariana, 1999; Peropadre *et al.,* 2005). This lithological trend has led to describe the system as a mixed siliciclastic-carbonate one. Similar stratigtraphic trends are present in other Aptian basins of Iberia as for example in the south-western Iberian – Prebetic regions (Vilas *et al.*, 2003) or in the Basque – Cantabrian region (García-Mondéjar, 1990; Wilmsen, 2005).

One of these siliciclastic-carbonate episodes was recorded in the Las Parras Sub-basin by the Forcall marl and the Villarroya de los Pinares limestone formations. These formations locally interfinger in the Las Parras sub-basin a siliciclastic unit (to date informal) that is build up of a variety of marine coastal facies.

The siliciclastic unit has an important lithologic variability showing localities that present a variety of sandy, muddy and calcareous facies while others are completely built up of sand. The former localities are easily correlatable on package to package basis while their correlation with sand-dominated sections needs detailed sedimentological analysis and usage of genetic criteria.

In this paper, the sedimentology of a metric-scale storm related interval of the siliciclastic unit is described in detail. We use this analysis to correlate the tempestites and related strata on a genetic basis. The correlation allows us to infer palaeogeographical features of the depositional system and their possible relationships with the palaeo-structural configuration of the studied area. Then we analyze the stratigraphic implications derived from the correlation of the storm-related deposits. Although a geographically limited depositional area has been studied in this paper, stratigraphic features derived from detailed correlations suggest initial guidelines for larger scale interpretations such as the meaning of siliciclastic to carbonate episodes and their bearing on sequence stratigraphy. Features regarding the spatial development of differential subsidence are also considered.

1.1. Geographical and geological setting

The studied area is located in the eastern Iberian Chain (Teruel Province) between the localities of Cuevas de Portalrubio and Las Parras de Martín (Fig. 1). The Iberian Chain is an alpine compressive intraplate feature in which both Mesozoic sediments deposited on the extensional Iberian basin and Variscan basement wereuplifted (Álvaro *et al.*, 1979; Guimerà and Álvaro, 1990). The outcrops studied herein are located in the hangingwall of the Portalrubio-Montalbán thrust (Figs. 1C and 1D). Palaeogeographically, the study area forms part of the Las Parras sub-basin, which started to fill up during the Barremian in relation to extensional faults (Soria, 1997). Las Parras sub-basin was part of the Maestrazgo basin and constituted its north-western marginal area during the Aptian (Fig. 1B). Subsidence analysis for the Maestrazgo basin showed that the Aptian was a period of active rifting related to an upper Jurassic – lower Cretaceous rifting phase (Salas and Casas, 1993).

The studied sector is situated toward the north-western margin of the Las Parras sub-basin. This margin was fault bounded as it is inferred by the absence of Aptian sediments in the footwall of E-W and NW-SE bounding faults (Figs. 1C and 1D; Liesa *et al.*,1996, 2000, 2004). Studied sections are located in the hangingwalls of two extensional faults of kilometric scale, so called the La Rambla fault and the Mina Salomé fault (Fig. 1C). These faults maintain much of their extensional displacement

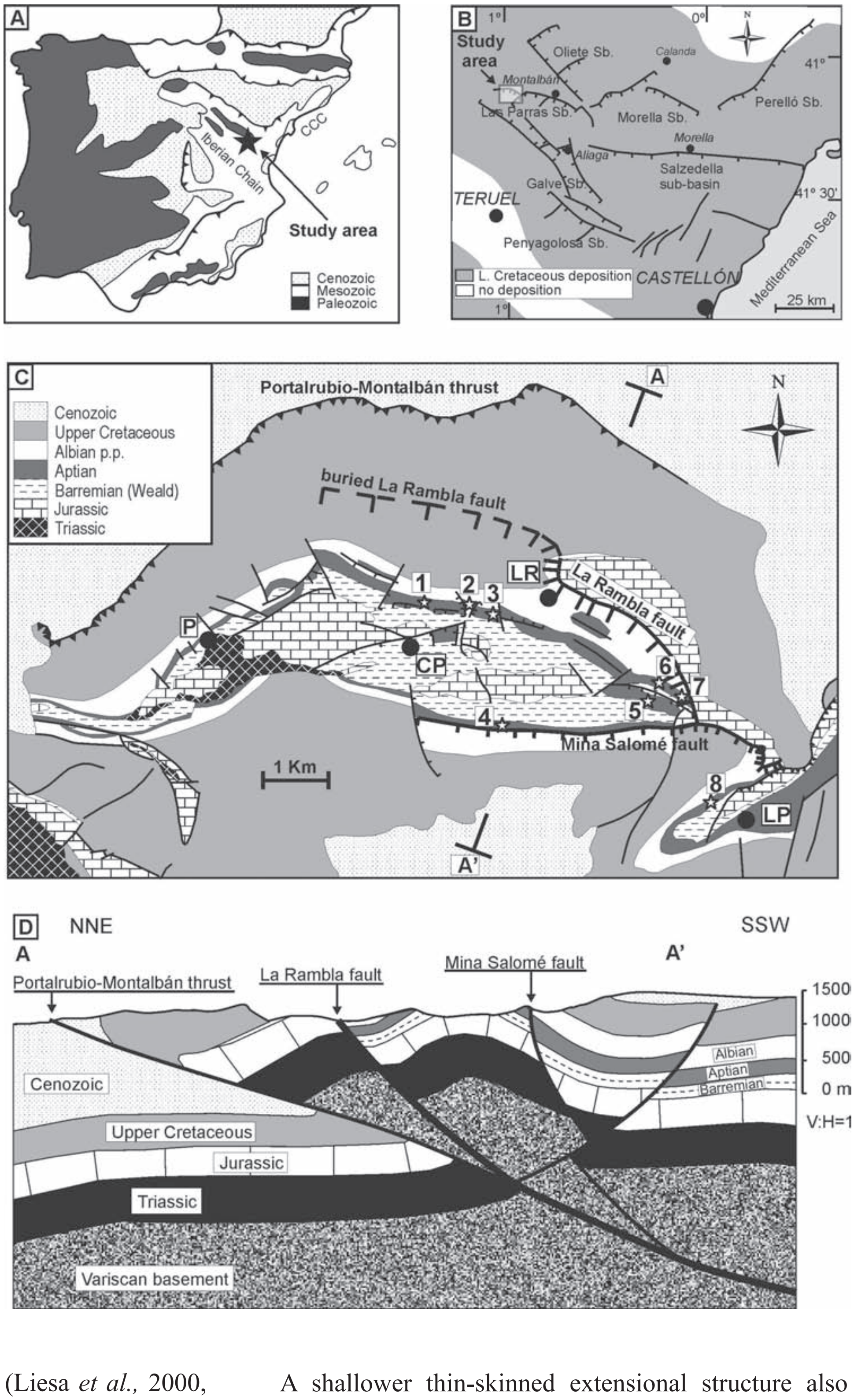


Fig. 1.- A) Geographic and geological context of the studied area. CCC Catalonian Coastal Chain. B) Main structural features of the Maestrazgo basin and subbasins (Sb) during the lower Cretaceous. Modified after Liesa *et al.* (2004). C) Geological map of the studied area. Modified after Martín Fernández (1979) and Soria (1997). Localities: P, Portalrubio; CP, Cuevas de Portalrubio; LR, La Rambla de Martín; LP, Las Parras del Martín. Numbers 1 to 8 correspond to measured sections. D) Geological cross section representative of the studied area. Without vertical exaggeration. Location is indicated in Fig. 1C. Modified after Liesa *et al.* (2000).

Fig. 1.- A) Contexto geológico y geográfico del área estudiada. CCC Cordillera Costero Catalana. B) Principales características estructurales de la Cuenca del Maestrazgo y sus subcuencas (Sb). Modificado de Liesa *et al.* (2004). C) Mapa geológico simplificado de la zona estudiada. Modificado de Martín Fernández (1979) and Soria (1997). Localidades: P, Portalrubio; CP, Cuevas de Portalrubio; LR, La Rambla de Martín; LP, Las Parras del Martín. Los números del 1 al 8 indican las secciones estudiadas. D) Corte geológico simplificado, representativo de la zona estudiada. Sin exageración vertical. Su localización está indicada en la Fig. 1C. Modificado de Liesa *et al.* (2000).

in spite of their Cenozoic inversion (Liesa *et al.,* 2000, 2004). They are synthetic structures with general dip toward the south and they define two blocks with a similar structural hierarchy. La Rambla fault can be considered a basin bounding fault for all of its length while the Mina Salomé fault is basin bounding for its easternmost segment and intrabasinal for the western one (Fig. 1C).

A shallower thin-skinned extensional structure also occurs and is particularly noticeable along the Aptian outcrops. It consists of synthetic faults, more subsiding outward from the main fault, and rare antithetic and transversal faults (Fig. 1C). They accommodate the extensional deformation and result on the fragmentation of the larger scale blocks (Fig. 1C). This fragmentation accounts for a considerable thickness variability of the Aptian deposits in the studied area.

1.2. Stratigraphy

The Aptian of the Las Parras sub-basin overlays Barremian siliciclastic and carbonated deposits (the Artoles Formation), mainly of continental origin (Soria, 1997). It is overlaid by the Albian transitional and marine siliciclastic and coal deposits belonging to the Escucha Formation. The lithostratigraphic framework of the Las Parras sub-basin is composed of four formations named from base to top (Fig. 2): the Morella clays, the Chert limestones and marls, the Forcall marls and the Villarroya de los Pinares limestones (Canérot *et al.*,1982). In the studied area the Aptian lithostratigraphy departs to some degree of this arrangement (Fig. 3), so that the Morella clays are overlaid by a siliciclastic informal unit, which is overlaid by the Villaroya de los Pinares limestones. Neither the Chert nor the Forcall formations are identifiable by their original lithological features in this sector. Nevertheless, recent works by Clariana (1999) and Vennin and Aurell (2001) showed that the Chert limestones Formation passes to sandstone facies toward proximal areas. Our ongoing basin-scale investigations of the region allow us to advance in this paper that the siliciclastic unit studied here probably represents the marginal facies of both Chert and Forcall formations, this advance will be discussed in a future publication.

The siliciclastic unit was firstly described by Canérot (1974), who cosidered this unit around the Bedoulian – Gargasian (lower – middle Aptian) boundary. Clariana (1999) and Clariana *et al.* (2000) described the siliciclastic unit as a wedge-shaped body deposited in the western part of the Las Parras sub-basin and thinning toward the east and southeast. These authors also presented some sedimentological features of the siliciclastic unit. They founded the siliciclastic unit overlaying the Forcall Formation and proposed that the base of the siliciclastic unit constitutes a regional unconformity and that it is laterally related with the Villarroya de los Pinares Formation. However, outcrops covered by our investigation were not included in the previously cited works. To date, the siliciclastic unit has not been formally included into the stratigraphic framework of the Maestrazgo basin (Canérot *et al.*, 1982).

Biostratigraphic data by Aguilar *et al.* (1971) and Canérot (1974) of the overlying limestones, and our own sampled material from the siliciclastic unit (J-P. Masse, personal communication, 2004), return a lower Aptian age due to the presence of *Choffatella decipiens* and

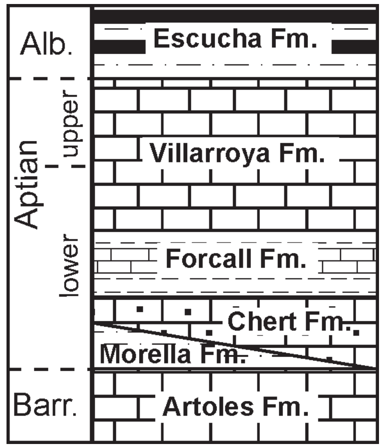


Fig. 2.- Stratigraphic framework of the Las Parras sub-basin. Modified after Canérot *et al.* (1982) and Salas *et al.* (1995).

Fig. 2.- Estratigrafía de la Subcuenca de Las Parras. Modificada de Canérot *et al.* (1982) y Salas *et al.* (1995).

Palorbitolina lenticularis (see Masse, 2003 for biostratigraphic ranges).

This age suggests that the siliciclastic unit should be correlated with the K1.8 (lower Aptian) sequence of Salas *et al.* (1995, 2001).

2. The siliciclastic unit

Eight closely spaced stratigraphic sections (Fig. 1C) were studied to characterise the record of the siliciclastic unit. Their thickness varies between 60 metres (section 5) and 20 metres (section 7), these variations can be linked to faults related to the previously mentioned thin-skinned extensional structure. Additionally, the siliciclastic unit shows noticeable variations on its lithological features across the studied area (Figs. 4 and 5). The siliciclastic unit consist of sandstones (mainly coarse-grained), mudstones and considerable amounts of quartzose limestones. Facies and sedimentology of the whole siliciclastic unit are out of the scope of this work, however the arrangement of lithologies and basic facial attributes have been depicted in figure 4. The siliciciclastic unit represents a variety of coastal marine environments as it is indicated by its shallow marine to freshwater fossil content (Figs. 3 and 4).

Preliminary sedimentological analysis of the siliciclastic unit allowed to divide it in four coarsening upwards sequences (S1, S2, S3 and S4), which are useful for correlation purposes (Fig. 4). Sequence S4 departs of a true coarsening upwards tendency because up to 10 metres of clayey mudstones, sandy limestones and rare sands have been included at the top of this sequence. This was done because the outcrop quality of sequence S4 (dominantly

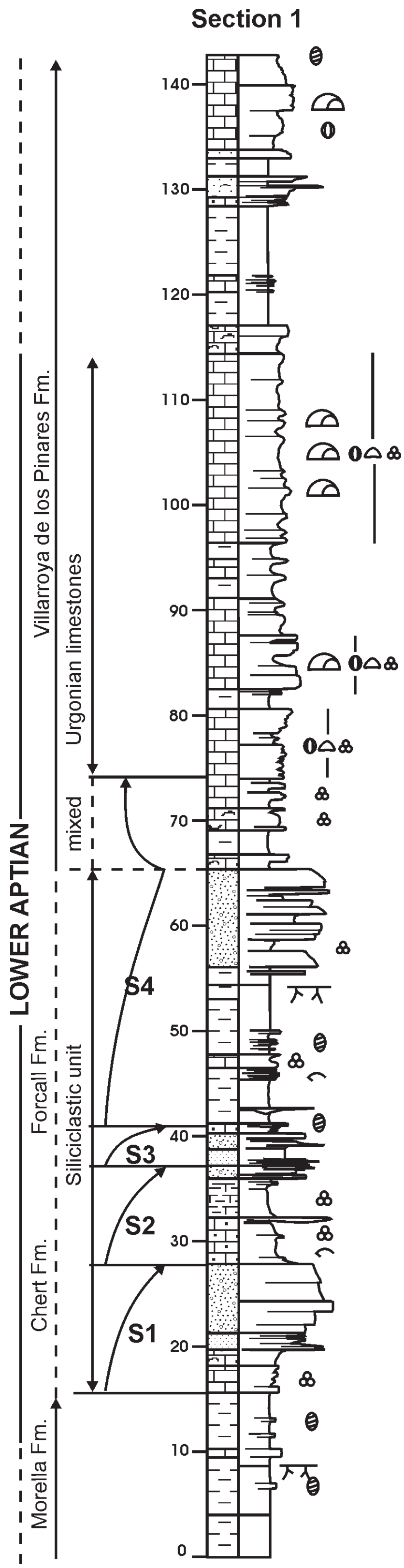


Fig. 3.- Selected stratigraphic section of the Aptian of the studied area (section 1, Fig. 1C). Stratigraphic units and coarsening upward sequences S1-S4 are indicated. Key to fossil content in Figure 4.

Fig. 3.- Columna estratigráfica seleccionada del Aptiense de la zona estudiada (sección 1, Fig. 1C). Se indican las unidades estratigráficas y las secuencias granocrecientes S1 a S4. La leyenda del contenido fosilífero se encuentra en la Figura 4.

muddy) is generally poor and complicates a precise location of the top of the coarsening upward sequence. For correlation simplicity, we have extended the top of this sequence up to the first urgonian limestone package of the Villarroya de los Pinares Formation.

From a lithological point of view, and according to the correlation sketch of figure 4, coarsening upward sequences of the siliciclasctic unit can be grouped as being homogeneously thick and lacking muddy facies (sequences S1 and S3) or as being heterogeneously thick and containing muddy facies (sequences S2 and S4). In spite of this grouping, facies are quite different for each sequence recording a variety of backshore to offshore marine coastal environments.

In this paper we focus in sequence S3, which is featured by the unique occurrence of storm deposits, and therefore having a high correlation potential. Sedimentological features of this sequence are also treated in detail bellow because they bear important information relative to palaeogeography and support the proposed correlation, on which further stratigraphic interpretations rely.

2.1. Facies analysis of sequence S3

The coarsening upward sequence S3 consists of 2.5 to 8 metres of sandstones but most commonly it oscillates about 4 metres thick. It overlays coarse-grained sandstones of the top of the sequence S2, and is locally overlaid by a thin bed of charophyte limestone deposited over an irregular (decimetric relief) erosive surface representing the base of the sequence S4. The sequence S3 is generally arranged in two terms (Fig. 6): a dominantly finer lower term, and a sharply overlaying coarser upper term. Four facies were found to characterise S3, facies F1 to F3 build up the lower term and facies F4 appears in the upper term.

Facies F1. Fine and very fine-grained quartz-sandstones with mica. The colour is white, yellow or ochre depending on the presence of ferruginous cements. In some sections it shows the following upward evolution: parallel-horizontal or slightly undulated (large wavelength) lamination, hummocky cross-stratification (HCS) of decimetric to metric apparent wavelenght and wave ripple cross stratification (Fig. 7A), climbing ripples have been rarely found. Locally, millimetric to decimetric fluid escape structures occur (Fig. 7B). This facies build up 0.5 to less than 1 metre thick tabular beds. Outcrop availability did not allow measuring its lateral extension, nevertheless the facies correlation of the two main packages indicates a kilometric extension. They are interpreted as deposited in a lower shoreface dominated by storm processes (Cheel and Leckie, 1993).

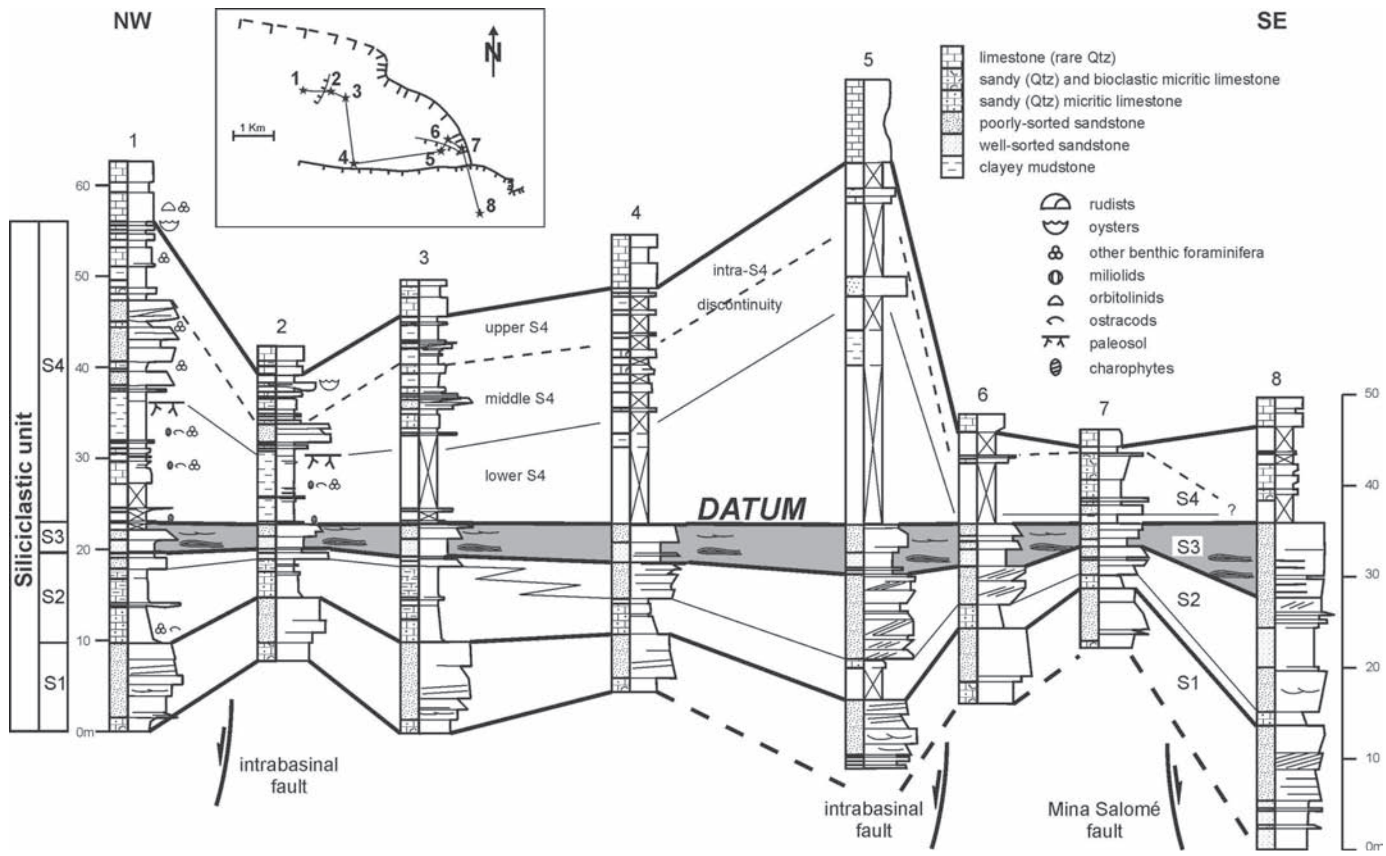


Fig. 4.- Correlation sketch of the siliciclastic unit. The top of coarsening upward sequence S3 is used as Datum surface. Note large thickness variations especially above the Datum. Dashed line represents the approximate position of the intra-S4 discontinuity, see text for explanation.

Fig. 4.- Panel de correlación de la unidad siliciclástica. El techo de la secuencia granocreciente S3 se usa como *Datum* de correlación. Destacan las grandes variaciones de espesor particularmente por encima del *Datum*. La línea discontinua marca la posición aproximada de la discontinuidad intra-S4, explicación en el texto.

Facies F2. Medium and coarse-grained cross-bedded sandstones. It is ochre to reddish in colour and consists of metric to decametric wide lenses, some centimetres to few decimetres thick beds (Fig. 7C). Sometimes they have erosive base and/or undulated tops. Fining upward beds with bioclastic basal lag also appear. This facies is intercalated in facies F1, and commonly, single laminas of this facies interfinger with the surrounding fine storm related facies (F1). Therefore, both facies F1 and F2 are deposited under the same storm conditions. In some sections facies F2 loose its lensoidal character, it thickens and intercalates finer facies (Fig. 8, section 7). Additionally, undulated tops suggest that F2 could be formed by storm related coarse-grained ripples as those described by Leckie (1988). A lower shoreface is also interpreted as the sedimentary environment of this facies.

Facies F3. Fine and very fine-grained mica-rich quartz sandstones. They are white coloured. It builds up a few decimetres thick beds with lensoidal shape (decametric in scale) and sometimes with erosive bases. The main internal structure is horizontal or slightly-undulated parallel lamination, nevertheless, HCS is also present. Beds with this facies appear intercalated in coarser sandstone (F4 or thickened F2 facies). Commonly thin layers or single laminas of this facies interfinger within the coarser surrounding facies (Fig. 7D). This facies is also interpreted to represent a storm dominated lower shoreface environment.

Facies F4. Coarse to very coarse-grained and medium-grained cross-bedded bioclastic quartz-sandstones. Colour is white, but it is commonly dark in exposed surfaces. It consists of a single metric bed with a sharp plane erosive base. It is tabular with kilometric extension. Fining upward or massive sets, gently erosive, a few decimetres thick, with trough cross-bedding are the main internal features (Fig. 7E). In some outcrops cross-bedding can be related to megaripples up to one metre high (Fig. 7F). Thin bioclastic (gastropods, bivalves) layers or laminas also occur. Although paleocurrent data is not available considerable divergence is observable in some outcrops. Some megaripples (the larger) show sigmoid cosets related to reactivation surfaces. In some outcrops, megaripples show coarser foresets grading laterally to finer bottomsets. This facies is interpreted to represent an upper shoreface environment, probably influenced by tidal processes.

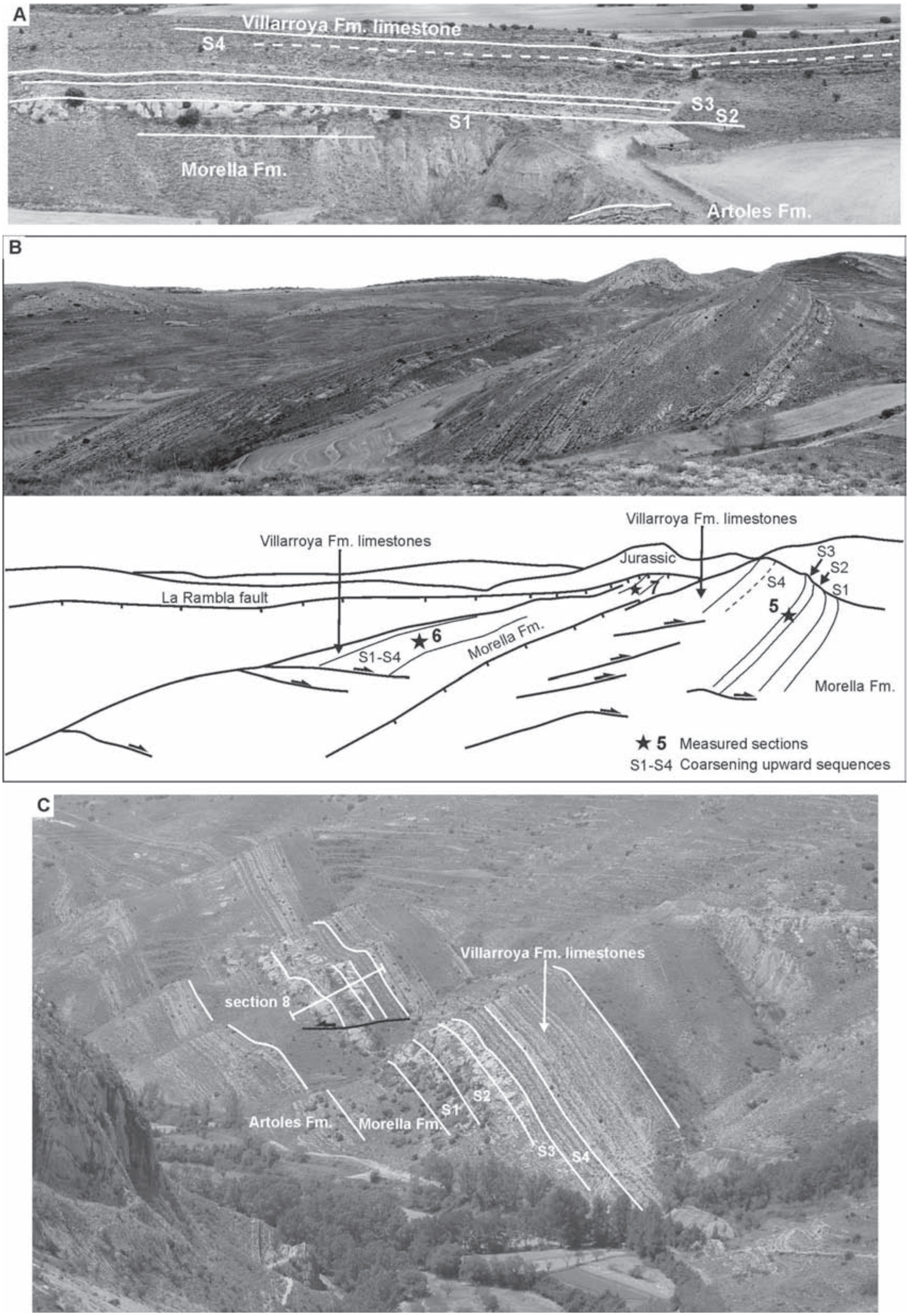


Fig. 5.- Outcrop views of the siliciclastic unit. From A (northwest) to C (southeast) note the increasing proportion of sandy facies in the siliciclastic unit. A) Section 1 viewed from the south. B) Sections 5, 6 and 7; note the thickness difference between sections 5 and 6 and also the thin-skinned extensional faulting. View from the west. C) section 8 viewed from the northeast. See Figures 1C for location and 4 for measured sections.

Fig. 5.- Afloramientos de la unidad siliciclástica. Desde A (al noroeste) a C (al sureste) se verifica un claro aumento de la proporción de facies arenosas en la unidad siliciclástica. A) Columna 1 vista desde el sur. B) Columnas 5, 6 y 7; se observa una gran diferencia de espesor entre las columnas 5 y 6; además se observan fallas normales que resultan en una extensión de piel fina. Vista desde el oeste. C) columna 8 vista desde el nordeste. Véanse las Figuras 1C para localización y 4 para las columnas estratigráficas.

Fig. 6.- Field view of the coarsening upward sequence S3 eastwards of section 3 (Fig. 1C for location). S3a is the fine-grained lower term related to storm events, S3b is the coarse-grained upper term. Hammer for scale.

Fig. 6.- Aspecto de campo de la secuencia granocreciente S3 hacia el este de la columna 3 (localización en la Fig. 1C). S3a corresponde al término inferior de grano fino relacionado con procesos de tormenta, S3b es el término superior de grano grueso. Martillo como escala.

4. Discussion

As stated above facies F1, F2 and F3 represent a lower shoreface sediments deposited under the same storm conditions, they characterize the lower term of the coarsening upward sequence S3; facies F4 represents upper shoreface sediments that characterize the upper term of this sequence (Fig. 8). Such a vertical facies evolution from lower to upper shoreface environments represents a shallowing upward sequence. The erosive top followed by charophyte limestones of sequence S4 is interpreted as further shallowing that produced a sedimentation break; this allows us to consider the top of sequence S3 with storm deposits as a valuable cronostratigraphic *datum* (Fig. 4).

Direct correlation between sections 1 to 7 is easily done because of the almost complete physical continuity of outcrops (Fig. 1C); however, correlation of those sections with section 8 (which is dominantly sandy) is not straightforward and has been done using genetic criteria. Since no other sequence but S3 shows fine-grained storm related sandy facies, the presence in section 8 of intercalations of storm related facies F3 between coarser facies F2 or F4 (distinction cannot be done in section 8 because of the massive character of the sandstone) provide the criterion for correlation. The following discussion on lateral facies association provides additional supportive criteria for genetic correlation of the basal S3 storm deposits.

4.1. Facies associations and spatial variability

The finer lower term of sequence S3 is particularly interesting for the analysis of its lateral facies associations (Fig. 8) since it shows a clear enrichment in coarse-grained facies from north-west (sections 1 to 3, 0-10% of the total volume) to south-east (section 8, 86%) (Fig. 9). This enrichment in coarser grain-sizes may be related to a closer location of the south-eastern sections to a siliciclastic discharge system feeding the Las Parras de Martin sector. The intersection of two basin bounding faults (La Rambla and Mina Salomé faults; Fig 1C) at a nearby area northward of section 8 suggests the possibility that this discharge system could be entering into the basin at this precise location (Fig. 9). A relay fault zone may have existed at this intersection during earlier stages of rift development favouring the catchment of a footwall drainage system similar to those described by Gupta *et al*. (1999) and Gawthorpe and Leeder (2000). These palaeogeographical features provide the mechanism for the facies change between section 8 and the other sections. The source of coarse materials from the discharge system, nearby section 8, to the surrounding areas is expected to have been favoured under storm conditions, which is supported by the synchronicity relationship between fine and coarse grained facies (F1, F2, F3). Evidence of fair-weather sedimentation is lacking in sections 1 to 7. Differently, near the discharge system (section 8) sedimentation was probably a common process under fair-weather conditions. Consequently, fine-grained storm deposits (facies F3) are generally thin and lensoidal in this location, probably representing the residual record of the storm events.

The proximity of a discharge system is not only supported by the lateral changes of the storm related facies of sequence S3, but also by the more sandy character of the whole siliciclastic unit in section 8. Note particularly the lateral facies change due to the advance of sand from the south-east to the north-west in the coarsening upward sequence S2 (Figs. 4 and 5).

4.2. Stratigraphic implications and extensional dynamics

Interesting stratigraphic features arise once the correlation of coarsening upward sequence S3 is set. The most noticeable feature is that sequence S4 is greatly reduced in section 8 (Fig. 4). Sequence S4 can be vertically subdivided in three parts (Figs. 3 and 4): a lower green mudstone package with some intercalated limestones and rarely sandstone, and a red mottled interval at the top;

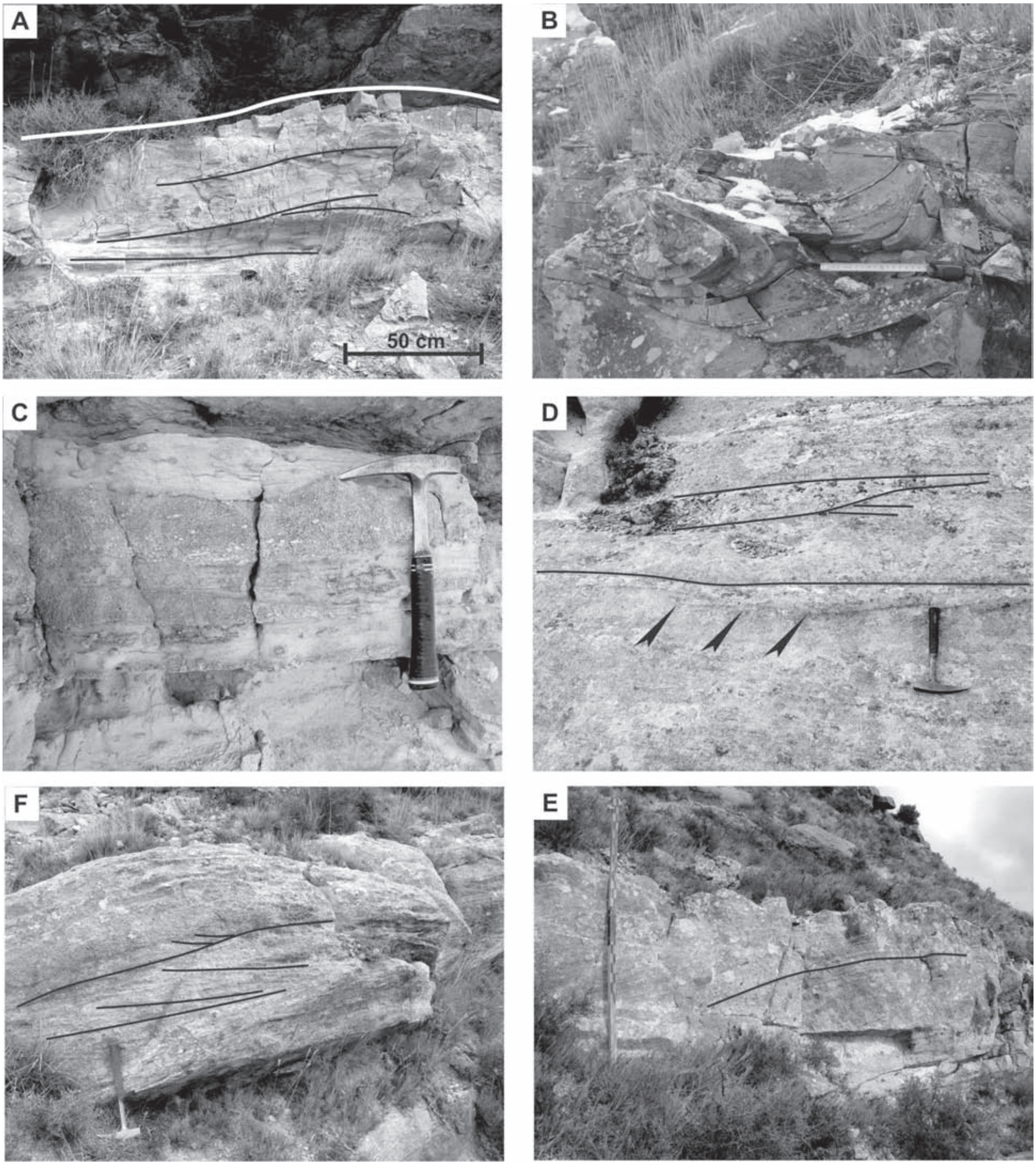


Fig. 7.- Facies of the coarsening upward sequence S3. A) Facies F1, slightly-undulated parallel lamination erosively overlaid by metric scale strongly aggradational HCS fine sandstones. B) Facies F1, fluid escape structure in fine sandstones with HCS. C) Facies F2, thin lensoidal beds of coarse sandstone intercalated in finer sandstones. The lower intercalation shows single laminas interfingering with the finer facies. The upper intercalation shows normal grading. D) Facies F3, fine mica rich sandstone beds intercalated in coarse sandstone. Interfingering of fine and coarse facies are arrowed; a bed with erosive base is also outlined. E) Facies F4, coarse sandstones with trough cross-bedding and low relief erosive troughs. Hammer for scale. F) Facies F4, coarse and medium grained sandstones, a megaripple 1m high is outlined, Jacob staff is 1.5 meters long.

Fig. 7.- Facies de secuencia granocreciente S3. A) Facies F1, areniscas con laminación paralela suavemente ondulada, sobre ellas con base erosiva, areniscas finas con HCS de dimensiones métricas y fuertemente agradante. B) Facies F1, estructura de escape de fluidos en areniscas finas con HCS. C) Facies F2, capas lenticulares y delgadas de areniscas gruesas intercaladas entre areniscas finas. La intercalación inferior muestra láminas individuales que se interdigitan con la facies fina. La intercalación superior presenta gradación normal. D) Facies F3, arenisca de grano fino con mica intercalada entre areniscas gruesas. Algunas interdigitaciones de facies finas y gruesas se marcan con flechas; también se señala una capa con base erosiva. E) Facies F4, areniscas gruesas con estratificación cruzada de surco y surcos de bajo relieve. Martillo como escala. F) Facies F4, areniscas de grano grueso y medio, se ha señalado un *megarriple* de altura métrica, la vara de Jacob mide 1,5 metros.

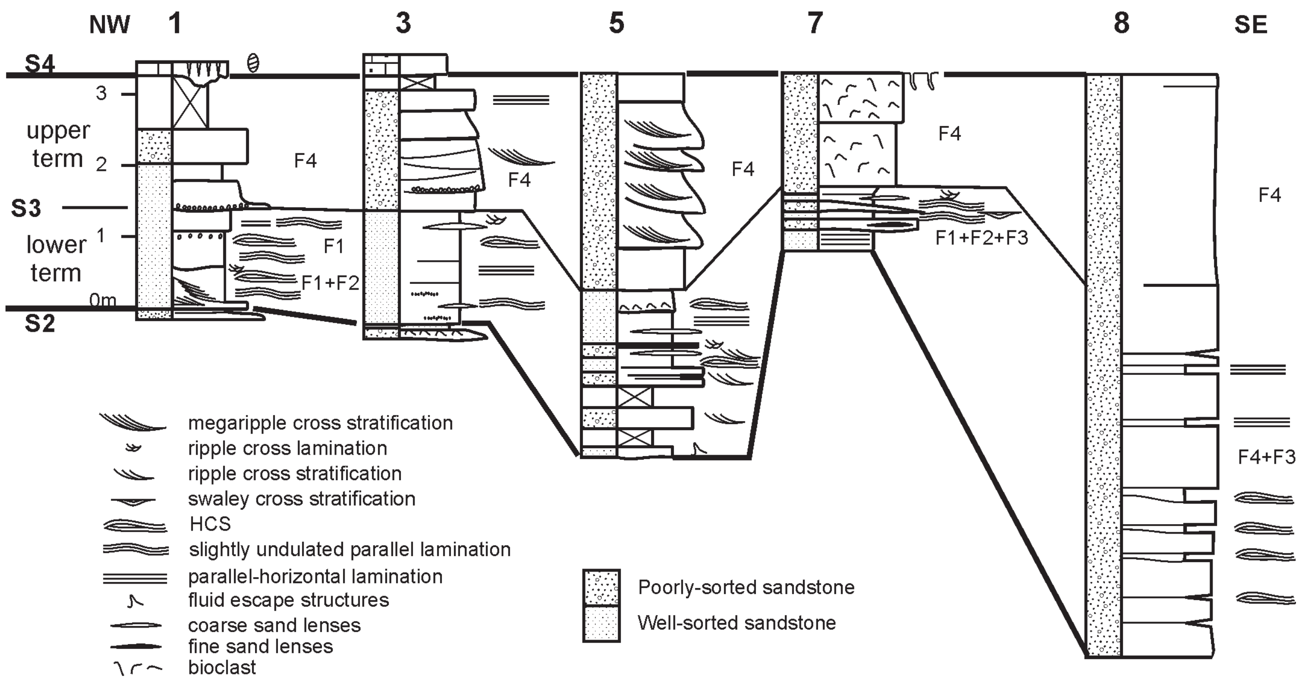


Fig. 8.- Selected stratigraphic sections of coarsening upward section S3, showing facies associations of fine-grained lower term (F1, F2 and F3) and coarse-grained upper term (F4). Note the increasing number of intercalations of coarse sandstones toward the southeast.

Fig. 8.- Columnas estratigráficas seleccionadas de la secuencia granocreciente S3, mostrando las asociaciones de facies del término inferior de grano fino (F1, F2 y F3) y del término superior de grano grueso (F4). Se aprecia el aumento de intercalaciones de areniscas gruesas hacia el sureste.

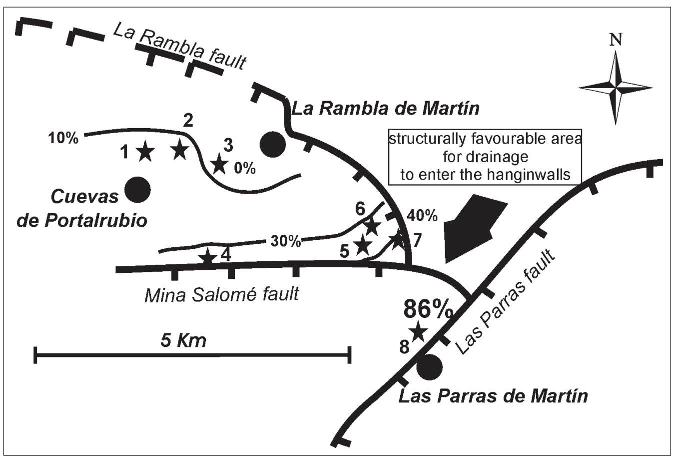


Fig. 9.- Map of coarse sandstone percentage for the fine lower term (storm related) of sequence S3. Main palaeo-structural features (after Soria, 1997) are indicated.

Fig. 9.- Mapa de porcentaje de facies de arena gruesa contenida en el término inferior de grano fino (relacionado con tormentas) de la secuencia S3. Los principales elementos paleoestructurales (de Soria, 1997) han sido indicados.

an heterolithic, laterally variable middle part built up of sandstones (section 1), quartz rich limestones (section 7), and minor mudstones; the upper part is composed of moderately quartzose bio-foraminiferal limestones and green mudstones. In section 8 (Fig. 4) overlaying the sequence S3, 3 metres of covered terrain occur and over them 3 metres of limestones (bioclastic-quartzose at the base and less quartzose upward); with some uncertainty that some of the lower and middle parts of sequence S4 could be represented in the covered terrain, we interpret that only the upper part of sequence S4 is recorded in section 8. Thus, an intra-S4 discontinuity is interpreted based on the correlation of the storm deposits of sequence S3. This discontinuity was previously described between sections 2 and 3 (Peropadre *et al.,* 2004); in that case, muds and sands of the lower part of S4 were not totally absent but an erosional relationship between them and the overlaying onlapping deposits was deduced (Fig. 10). Although the 5 kilometres extent of our study still maintains this discontinuity within the range of local features, its association with a marked vertical facies change from siliciclastic to carbonate dominated litofacies is suggestive of a possible basin-wide importance of this feature.

Integrating this discontinuity with the palaeo-structural map (Fig. 4), it appears that section 8 could have had a different subsidence history than the other sections because it is located in a different subsiding block (in the hangingwall of the Mina Salomé fault). During the deposition of sequences S1, S2 and S3 both the La Rambla and Mina Salomé fault-blocks were subsiding and recording sedimentation. It is notable that Mina Salomé block (section 8) was significantly more subsiding than any measured section of La Rambla block (sections 1 to 7). After deposition of sequence S3 this dynamic changed, the La

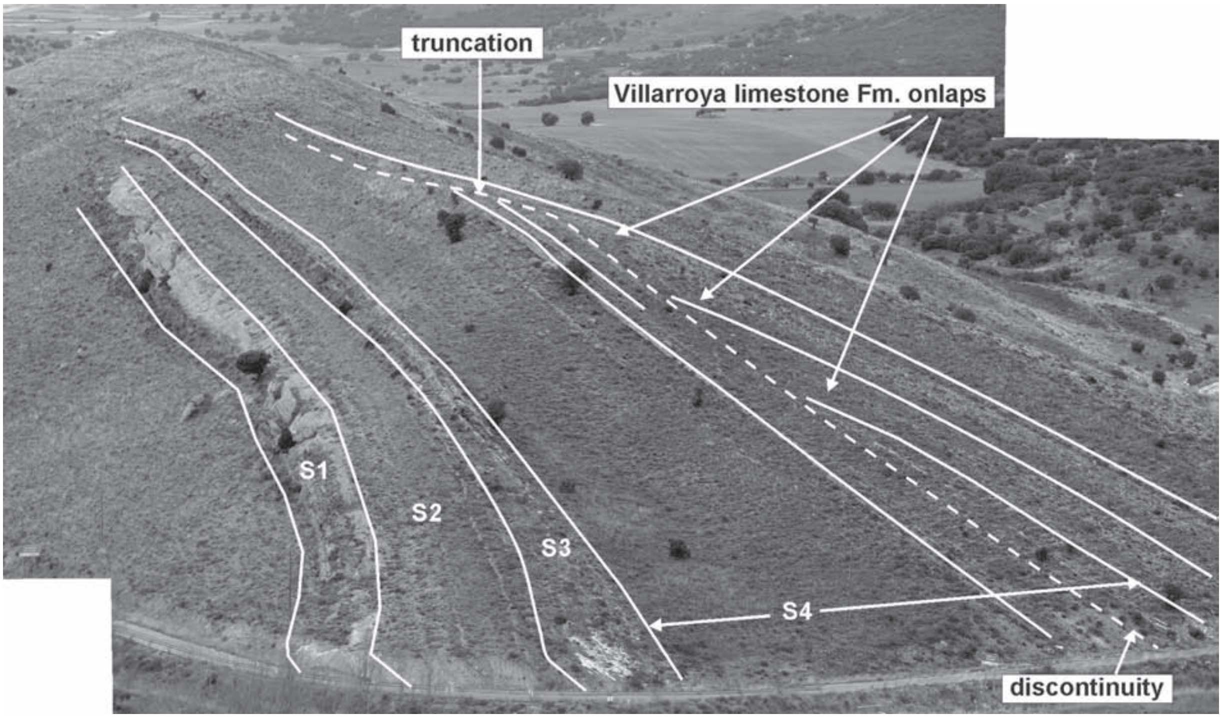


Fig. 10.- Outcrop view of section 3 from the east. The intra-S4 discontinuity is directly observable from stratal terminations.

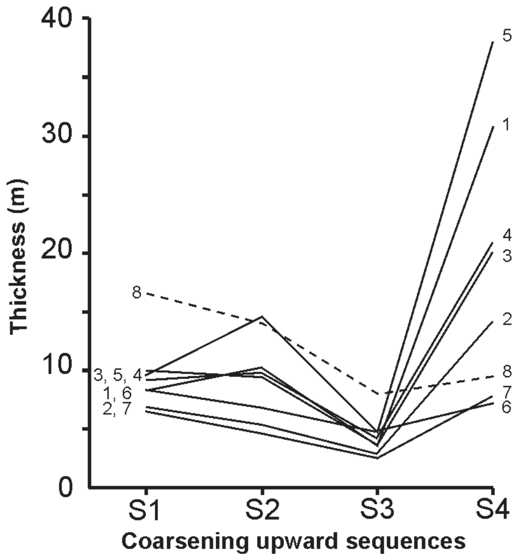
Fig. 10.- Vista del afloramiento de la columna 3 desde el este. La discontinuidad intra-S4 se reconoce directamente a partir de las terminaciones de estratos.

Rambla block continued to subside while the Mina Salomé block did not. The Mina Salomé block is expected to have been a rotating one or being fragmented by a number of transversal faults. Both scenarios resulting in a more subsiding western sector and a relatively uplifted eastern one. Unfortunately, the western sector of Mina Salomé block is buried. Later on, near the end of sequence S4, sedimentation became widespread again, either due to renovated subsidence of the Mina Salomé block or due to higher base level. Therefore, the described intra-S4 discontinuity correlates at the local scale to some degree of extensional readjustment. This readjustment can be easily visualised comparing the thickness evolution of each section along time (Fig. 11). A non-parallel, sharply cutting trend between sequences S3 and S4 of the section 8 with respect to the others is indicative of the change in the subsidence dynamic between the fault-blocks.

It is also noteworthy that the proportion of coarse material contained in the lower storm-related finer term of sequence S3 presents a strong gradient between the Mina Salomé and La Rambla blocks (Fig. 9, compare section 8 with 5 and 7), while the gradient become more gentle inside the La Rambla block. It is also significant that the 30% isoline tends to parallel the Mina Salomé fault. Thus, the coarse sand percentage, somehow a sediment dispersal proxy, also appears to bear information related with the palaeo-structural setting.

At the intra-block scale, an independent feature, which may support the subsidence control on the stratigraphy of the study area, is the differentiation of sequences in two groups according to the spatial variation of their thickness (Fig. 11 and Fig. 4, see sections 1 to 7 of the La Rambla block). The sequences S1 and S3 have homogeneous thickness and muddy facies are lacking, while the sequences S2 and S4 have important lateral thickness variations (heterogeneous thickness) and contain a substantial volume of muddy facies. The presence of muddy lithologies is considered a relevant feature because they have an important impact in the decompacted sediment thickness, which would result in higher thickness heterogeneity.

Focusing in the thickness pattern we may relate homogeneous thickness sequences to reduced differential subsidence. Alternatively, this could be related to a high sedimentation rate that acting over a shorter time-scale may obscure the effects of differential subsidence (presumably working over a longer time-scale). Because differential subsidence has been stated above to be a main factor in the stratigraphic development of the siliciclastic unit, we favour the hypothesis that the lateral homogeneity in thickness is related to homogeneous subsidence. Effects of differential subsidence are particularly marked between sections 1 and 2, 5 and 6, and also between sections 7 and 8 (Fig. 4). In all cases thickness variations



	mean(m)	σ (m)	σ (%)
S1	8.4	1.3	15.6
S2	8.7	3.4	39.3
S3	3.7	0.9	23.2
S4	19.9	11.5	57.8

Fig. 11.- Thickness plot for each coarsening upward sequence (S1 to S4), data for each studied section is linked a line. Lines connecting sections 1 to 7 (numbered) have a similar trend; dashed line is section 8 having a very dissimilar trend. Thickness statistics for sections of La Rambla block (1 to7) are also shown. S1 and S3 show relatively low dispersion with respect to the mean (remarked values) while S2 and S4 are more dispersed (σ, standard deviation).

Fig. 11.- Gráfico que ilustra la variación de espesor de cada secuencia granocreciente (S1 a S4); los datos de cada columna estratigráfica se han unido mediante líneas. Las líneas que conectan las columnas de 1 a 7 (numeradas) presentan una tendencia similar; la línea discontinua corresponde a la columna 8 que presenta una tendencia claramente diferente. Se incluye también la estadística de espesores para las secuencias 1 a 7 del bloque de la rambla. Los espesores de las secuencias S1 y S3 presentan una dispersión respecto a la media relativamente baja (valores subrayados), mientras que S2 y S3 presentan mayor dispersión (σ, desviación típica).

seem to be related to the contemporaneous activity of normal faults. The studied siliciclastic unit could represent an alternation of episodes of homogeneous and heterogeneous subsidence, cycles S1-S2 and S3-S4 (Fig. 11). Such kind of patterns may be of some utility if we expect to understand how the extensional system evolve and its stratigraphic effects when observed over small time-scales.

Basinward extension of the high-resolution sedimentological correlations is expected to clarify the integration of the wedge-shaped siliciclastic unit into the lithostratigraphic organization of the Las Parras sub-basin, and its bearing on sequence stratigraphy. It will also help to determine if homogeneous and heterogeneous subsidence cycles are present at a basin-wide scale, or if the sedimentation rate is the prevailing factor.

5. Conclusions

A storm related coastal marine shallowing upward sequence has been described. It consists of a lower shoreface storm-dominated fine-grained basal term and an overlaying upper shoreface coarse-grained term. This sequence is capped by an erosive surface and is overlaid by fresh-water deposits, which are interpreted to represent a sedimentation break. This allows us to consider the top of the sequence as a valuable correlation datum. Due to the unique apparition of the storm facies along the studied siliciclastic unit it is easily correlatable using genetic criteria.

Genetic relationships of the studied storm deposits point toward the presence of a clastic discharge system located toward the southeast, which fed the north-western localities with coarse siliciclastic sediment. The presence of two extensional basin bounding faults (the NE-SW Las Parras and NW-SE La Rambla fault) intersecting in this sector could have enabled a possible way for coarse material to enter into the basin.

The correlation of the tempestite bearing sequence allows noting a considerable thickness reduction of the topmost coarsening upwards sequence in one location. Further analysis of the reduced interval allows us to establish the presence of a local sedimentary discontinuity, which marks the change from siliciclastic-dominated to carbonate-dominated sedimentation in the studied area, perhaps indicating a larger scale feature.

Thickness patterns and the degree of development of a local discontinuity suggest a considerable variation in the temporal evolution of subsidence when the stratigraphic record of different subsiding blocks is considered. At intra-block scale, alternations of homogeneous and heterogeneous subsidence episodes appear as a possible cyclical trend in subsidence that may be related to extensional dynamics. This hypothesis should be contrasted with similar datasets along other blocks of the basin or in other rift basins.

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