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Cyclically-arranged, storm-controlled, prograding lithosomes in Messinian terrigenous shelves (Bajo Segura Basin, western Mediterranean)

Jesús M. Soria [a,*], Alice Giannetti [a], Paolo Monaco [b], Hugo Corbí [a], Diego García-Ramos [a], César Viseras [c]

[a] Departamento de Ciencias de la Tierra y del Medio Ambiente, Universidad de Alicante, Spain
[b] Dipartimento di Fisica e Geologia, Università degli Studi di Perugia, Italy
[c] Departamento de Estratigrafía y Paleontología, Universidad de Granada, Spain

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ABSTRACT

This work focuses on a Messinian shallow-marine terrigenous unit, termed the La Virgen Formation, which forms part of the sedimentary infill of the Bajo Segura Basin (Betic margin of the western Mediterranean). This formation was deposited during a high sea level phase prior to the onset of the Messinian Salinity Crisis. Stratigraphically, it comprises a prograding stack of sandstone lithosomes alternating with marly intervals (1st-order cyclicity). These lithosomes are characterized by a homoclinal geometry that tapers distally, and interfinger with pelagic sediments rich in planktonic and benthic microfauna (Torremendo Formation). An analysis of sedimentary facies of each lithosome reveals a repetitive succession of sandy storm beds (tempestites), which are separated by thin marly layers (2nd-order cyclicity). Each storm bed contains internal erosional surfaces (3rd-order cyclicity) that delimit sets of laminae. Two categories of storm beds have been differentiated. The first one includes layers formed below storm wave base (SWB), characterized by traction structures associated to unidirectional flows. The second category consists of layers deposited above the SWB, which display typical high regime oscillatory flow structures. The 1st-order cyclicity recorded in the La Virgen Formation corresponds to sapropel/homogeneous marl precessional cycles formed in a pelagic basin context (Torremendo Formation).

1. Introduction

In recent decades, there have been notable advances in our knowledge of palaeoceanographic processes in the Mediterranean during the late Miocene. One of the most studied aspects has been the sedimentary, geochemical, and palaeontological expressions of the climate cycles recorded in pelagic sediments in the deepest sectors of the Mediterranean Basin. The most noteworthy feature of these sediments are the homogeneous marl/sapropel cycles, genetically linked to insolation changes triggered by precession of the Earth's axis (Hilgen and Krijgsman, 1999; Krijgsman et al., 2001; Turco et al., 2001; and many others). These precessional cycles have been critical in interpreting general circulation patterns of water masses, changes in temperature and productivity, deep-water oxygenation and episodes of anoxia (Rossignol-Strick, 1985; Rohling and Hilgen, 1991; Schenau et al., 1999; Sierro et al., 2003). However, in shallow marine sediments on the margins of the Mediterranean, the response to climate cycles is scantily documented and more difficult to recognize. There are examples of prograding patterns associated to astronomical cycles (precession and eccentricity) in the Messinian reef carbonates of the Sorbas Basin (Braga and Martín, 1996) as well as in Tortonian ramp-type shallow marine platforms in the Guadix Basin (García-García et al., 2009). In the case of the Sorbas Basin, the development of reef frameworks and reef slope deposits occurred during thermal maxima within precessional cycles (Sánchez-Almazo et al., 2007). As regards the Guadix Basin, the progradation of huge siliciclastic lithosomes rich in temperate carbonates took place during periods of minimum precession and maximum insolation.

Our study focuses on the shallow-marine platforms dominated by terrigenous sedimentation that developed along the margins of the western Mediterranean during the Messinian, prior to the onset of the Messinian Salinity Crisis. A combined sedimentological and palaeontological analysis of the stratigraphic record of the Bajo Segura Basin reveals the hydrodynamic and palaeoecological conditions reigning along the margins of the Mediterranean during the Messinian. The depositional model illustrates two novel aspects concerning the sedimentary dynamics of the Mediterranean margins: (1) the role of storms as an agent of sediment supply to terrigenous platforms, and (2) the cyclical nature of storms in response to allogenic factors, primarily climate changes. Moreover, from the standpoint of applied geology, our results offer a genetic model for large-scale sandy reservoirs. This

* Corresponding author.
E-mail address: jesus.soria@ua.es (J.M. Soria).

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aspect is a key starting point for future studies on the storage capacity of water resources, hydrocarbons, and greenhouse gases (see www.sedregroup.com).

2. Methods

This work analyses shallow-marine sedimentary bodies from the La Virgen Formation (Montenat et al., 1990). This unit largely consists of sandstones, and some marls and silty marls. The first part of this study aims at reconstructing the large-scale geometry of the La Virgen Formation as well as its relationship with both under- and overlying units by means of subsurface data (seismic lines) and surface data (extensive outcrops). The second part entailed both selecting the most representative stratigraphic section (the Venta de la Virgen section) and focusing on the strata stacking pattern. A bed-by-bed analysis was carried out for the whole section considering four aspects: physical sedimentology, ichnology, micropalaeontology, and marine macroinvertebrate palaeontology.

The physical sedimentology analysis has basically targeted the sandstone beds, characterizing the sedimentary structures both inside and on bed surfaces. In addition, the sandstone layers were studied under the optical microscope to determine four petrological parameters: (1) nature of the components (lithoclasts and bioclasts), (2) grain size, (3) shape of particles, and (4) fabric (framework, cement, and matrix).

Ichnological analysis first of all addressed the taxonomic determination of the trace fossils in order to differentiate ichnoassemblages. Since *Ophiomorpha nodosa* represents a unique trace fossil in most of the study section, for a better characterization of the deposits we also analysed burrow diameter, abundance, grouping of trace fossils, and vertical versus horizontal development, studying their variations throughout the section. These parameters have been evaluated for each bed in a 50 cm × 50 cm grid. For both *Ophiomorpha*-dominated and *Thalassinoides*-dominated ichnoassemblages, a bioturbation index (BI; sensu Droser and Bottjer, 1989) ranging from 0 to 3 has been established. The significance of each BI value in terms of trace-fossil abundance is as follows: 0 = 0–4 traces; 1 = 5–14 traces; 2 = 15–29 traces; and 3 = 30–50 traces.

A micropalaeontological analysis of the marls and silty marls consisted of the study of wet-screened planktonic and benthic foraminifera to recover the fraction over 0.125 mm. Planktonic foraminifera are used to detect biostratigraphic events as well as to characterize the conditions of temperature and trophism of surface waters. Benthic foraminifera are fundamentally used for palaeobathymetric estimates, providing additional information on diversity changes and sea bottom general content of dissolved oxygen and salinity.

Marine invertebrate palaeontology has dealt with molluscs (bivalves and gastropods), which offer information on general bottom conditions as regards substrate oxygenation, salinity, and stress.

3. The Bajo Segura Basin: tectonic and stratigraphic setting

The Bajo Segura Basin lies in the southeastern Iberian Peninsula with an open connection to the western Mediterranean (Fig. 1A). This basin is part of a mosaic of interconnected Neogene–Quaternary basins in the eastern end of the Betic Cordillera (Fig. 1B). The sedimentary infill seals the contact between the two principal geological domains of the Betic Cordillera: the internal zones and the external zones (Fig. 1B). The internal zones are dominantly Palaeozoic and Triassic metamorphic rocks that make up the basement of the southern half of the basin; the external zones are mainly Mesozoic sedimentary rocks that constitute the basement of the northern half of the basin. Montenat et al. (1990) described the general stratigraphic and tectonic features of the basin, reporting an age for its sedimentary infill that encompasses a time span from the Tortonian to the Quaternary. These authors also explained the tectonic evolution of the basin in relation to the so-called Betic segment of the Trans-Alborán Shear Zone (de Larouziére et al., 1988). This is a regional-scale, left-lateral transcurrent structure extending from the provinces of Almería to Alicante (Fig. 1B) that conditioned the genesis of the basins in the eastern Betic Cordillera, including the Bajo Segura Basin. The activity of this major structure lasted from the Tortonian to the Quaternary, forming the folds and faults visible in the Bajo Segura Basin (Fig. 2). The stratigraphy and geometry of the sedimentary infill of the basin can be recognized on the limbs of one of these folds, the Torremendo anticline. Outcrops of Messinian sediments studied herein are well-exposed on the southern limb of this anticline (see below for more details).

The general stratigraphic architecture of the Bajo Segura Basin includes five allostratigraphic units which range from Late Miocene to Pliocene in age (Corbí, 2010): synthems TI (Tortonian I), TII (Tortonian II), T–MI (latest Tortonian–Messinian I), MII (Messinian II), and P (Pliocene). These synthems are closely related to global sea-level changes, and attained their maximum development in coincidence with the stages of eustatic maxima of the curve of Haq et al. (1987) (Fig. 2). Each synthem comprises several lithostratigraphic units which are named in accordance with Soria et al. (2008a). The first two units (TI and TII) are Tortonian in age (planktonic foraminiferal biozones MMi11 and MMi12 pro parte, considering the Astronomically Tuned Neogene Time Scale—ATNTS 2004; Lourens et al., 2004), and the boundary unconformities that delimit these two units are associated with eustatic minima. The Messinian and Pliocene T–MI, MII, and P synthems are limited by two discontinuities closely linked to the Messinian Salinity Crisis (Caracuel et al., 2004, 2011; Soria et al., 2005, 2008a, 2008b; García-García et al., 2011). The T–MI synthem represents the pre-evaporitic (pre-crisis) sedimentation stage. Its age spans the latest Tortonian (upper part of the MMi12 biozone) and the Messinian (MMi13 biozone). According to Soria et al. (2005), this synthem represents a complete highstand sytem tract that comprises continental, coastal, and marine facies. Montenat et al. (1990) distinguished two formations of marine nature: (1) the marginal La Virgen Formation consists of shallow-marine sandstones and reefal carbonates, and grades distally into (2) the Torremendo Formation, which is made up of cyclically arranged marls, sapropels, and diatomites (Soria et al., 2008a) which were deposited in slope and pelagic-basin settings. The T–MI synthem is truncated by an erosional surface termed the intra-Messinian unconformity, overlain by the MII synthem. The MII synthem represents the stage of evaporitic sedimentation in the Bajo Segura Basin, and is late Messinian in age (non distinctive zone; ATNTS 2004). This synthem includes the Lago Mare Unit (Soria et al., 2007), the Terminal Carbonate Complex (Esteban, 1979), and the San Miguel Gypsum Formation (Montenat et al., 1990). The MII synthem is eroded by the end-Messinian unconformity; the most outstanding feature of this unconformity being deeply incised valleys filled with marine sediments from the P synthem. This last synthem, of Zanclean age (from MPL1 to MPL4 biozones), records the reflooding of the Mediterranean after the Messinian Salinity Crisis.

4. The La Virgen Formation: general stratigraphic architecture and age

The La Virgen Formation represents a lithostratigraphic unit dominated by terrigenous sandy facies that lies at the top of the T–MI synthem in most of the Bajo Segura Basin. Minor reef carbonate facies interstratify with the terrigenous facies of the upper part of the formation (Montenat et al., 1990; Reinhold, 1995; Soria et al., 2005). The internal geometry of the T–MI synthem can be recognized in seismic lines as well as in large-scale outcrops. In the first case (Fig. 3A), the seismic reflections reveal homoclinal and sigmoidal prograding clinoforms. The orientation of the clinoforms indicates SE progradation, that is, towards the current Mediterranean. In the second case (Fig. 3B and C), the La Virgen Formation is formed by prograding homoclinal (2–3° dip) lithosomes. These lithosomes are formed of sandstone bodies several metres thick and up to several kilometres wide, which taper towards the basin centre, grading into the Torremendo Formation. As

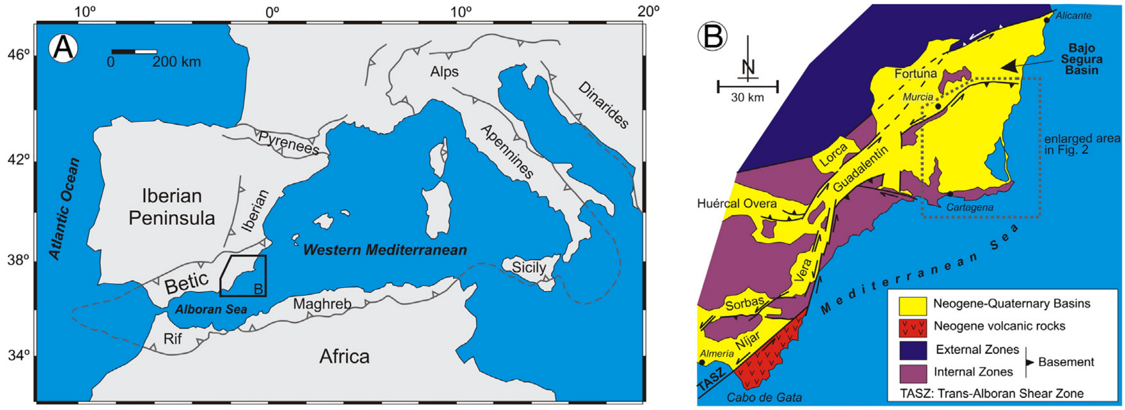

Fig. 1. (A) Location of the Betic Cordillera in the western Mediterranean. And (B) geological map of the eastern end of the Betic Cordillera showing the position of the Bajo Segura Basin (after Montenat et al., 1990).

in the clinoforms recognized in the seismic reflections, the lithosomes dip to the east indicating progradation towards the Mediterranean. Overall in the Bajo Segura Basin, the Torremendo Formation clearly grades vertically towards the La Virgen Formation (Fig. 2), defining a stratal stacking pattern consistent with a thickening- and coarsening-upward sandstone megasequence (Soria et al., 2005, 2008a).

As indicated above, all the Messinian biozones are recorded (Fig. 2) in both marine formations of the T–MI synthem (Torremendo and La Virgen), For the specific case of the Venta de la Virgen section (Fig. 4), two planktonic foraminifera bioevents were documented in the Torremendo Formation (Krijgsman et al., 2006): FCO of *Globorotalia miotumida* group (7.24 Ma) and FO of *Globorotalia nicolae* (6.83 Ma), which define the MMi13a and MMi13b biozones respectively. In addition, our study shows that between the Torremendo and La Virgen Formations the sinistral to dextral coiling change of the *Neogloboquadrina acostaensis* (6.35 Ma) occurs, which allows the assignment of the La Virgen Formation to the MMi13 subzone. Considering the ATNTS 2004 (Lourens et al., 2004), this last subzone extends up to the onset of the non distinctive zone of the late Messinian (5.96 Ma). According to these data, in the studied section La Virgen Formation ranges from 6.35 to 5.96 Ma. These age constraints represent the maximal temporal range possible for the La Virgen Formation in the studied section, given the fact that the top of the formation is truncated by the intra-Messinian unconformity. Additionally, as deduced from the progradational geometry of the La Virgen Formation, the base of the section is progressively younger in the progradation direction. In fact, in the sections located east of the studied section (Garruchal section; Corbí, 2010), the isochrone 6.35 Ma (coiling change of *N. acostaensis*) is within the Torremendo Formation, clearly below the stratigraphic base of the La Virgen Formation.

5. The Venta de La Virgen section

The Venta de la Virgen section is the most complete one in the Bajo Segura Basin and it shows very well preserved sedimentologic features as regards cyclic arrangement and facies typology, representing a perfect case study for the interpretation of depositional processes in Messinian terrigenous platforms. Although other sections in the area show very well preserved sedimentologic structures, they are not complete because of the truncation related to the intra-Messinian unconformity (Soria et al., 2005, 2008a), therefore cannot be considered suitable for this study. At the Venta de La Virgen (Fig. 4) (the reference locale for the La Virgen Formation; Montenat et al., 1990 and previous works by these authors), both the upper part of the Torremendo Formation (dominated by pelagic marine marls) and the La Virgen Formation (dominated by shallow-marine sandstones) are well exposed. La Virgen Formation is limited at the top by the intra-Messinian unconformity, overlain by a unit dominated by lagoonal marls, which is termed the Garruchal Formation (Soria et al., 2008a). The latter represents the MII synthem, which records the Lago Mare-like sedimentation typical of the late Messinian throughout the Mediterranean domain. This section and adjacent sectors display lateral and vertical relationships between the Torremendo and the La Virgen Formations (Fig. 5), which confirm the prograding model (mentioned above) visible throughout the Bajo Segura Basin. Interestingly, the marls of the Torremendo Formation contain a silty marl and sandstone interval (labelled 0 in Figs. 4, 5, 6) which represents the distal end of a sandstone lithosome which belongs to the La Virgen Formation.

5.1. Torremendo formation

This unit is key to unravelling the palaeoenvironmental and palaeobathymetric conditions of the basin during the deposition of the sandy storm beds studied herein, on account of the lateral relationships between the La Virgen and Torremendo formations. The marls of the Torremendo Formation contain abundant planktonic and benthic foraminifera in addition to other biogenic components such as small, thin-shelled bivalves, gastropods, ostracods, carbonate sponge spicules, and plant remains. Lithoclasts, primarily consisting of very fine-grained sand siliciclasts, are extremely scarce. The scanty terrigenous components (extrabasinal) point to the predominantly pelagic nature of the sedimentation. According to Soria et al. (2008a), one of the most significant features of the Torremendo Formation lies on the record of massive grey marls alternating with laminated light brown marls or sapropelic marls, defining precessional cycles.

In the La Venta de la Virgen section, the planktonic foraminifera preserved in the marls of the upper part of the Torremendo Formation (Fig. 6) are dominated by the genera *Globigerina* (*G. bulloides*) and *Neogloboquadrina*, with significantly lower frequencies of the genus *Globigerinoides* (*Globigerinoides obliquus* and *Globigerinoides bulloideus*). In the silty-marls and sandstones of lithosome 0 (which laterally grades into La Virgen Formation sandstones), the *Globigerina* + *Neogloboquadrina* association proportion drops as the *Globigerinoides* proportion rises. According to Sierro et al. (2003), the first association is considered a marker for cold eutrophic waters and the second for warm oligotrophic waters.

The assemblage of benthic foraminifera is characterized by the coexistence of taxa which display different depth ranges. To estimate water depth during sedimentation of the Torremendo Formation marls, we considered the deepest-water species as representative. The joint presence of deep water and shallow water taxa may be accounted for the downslope transport of tests of the shallower taxa. Below lithosome 0, the occurrence of *Uvigerina cylindrica* (120–630 m deep, according to Schweizer, 2006) and of *Valvulineria complanata* (40–110 m deep, according to Wright,

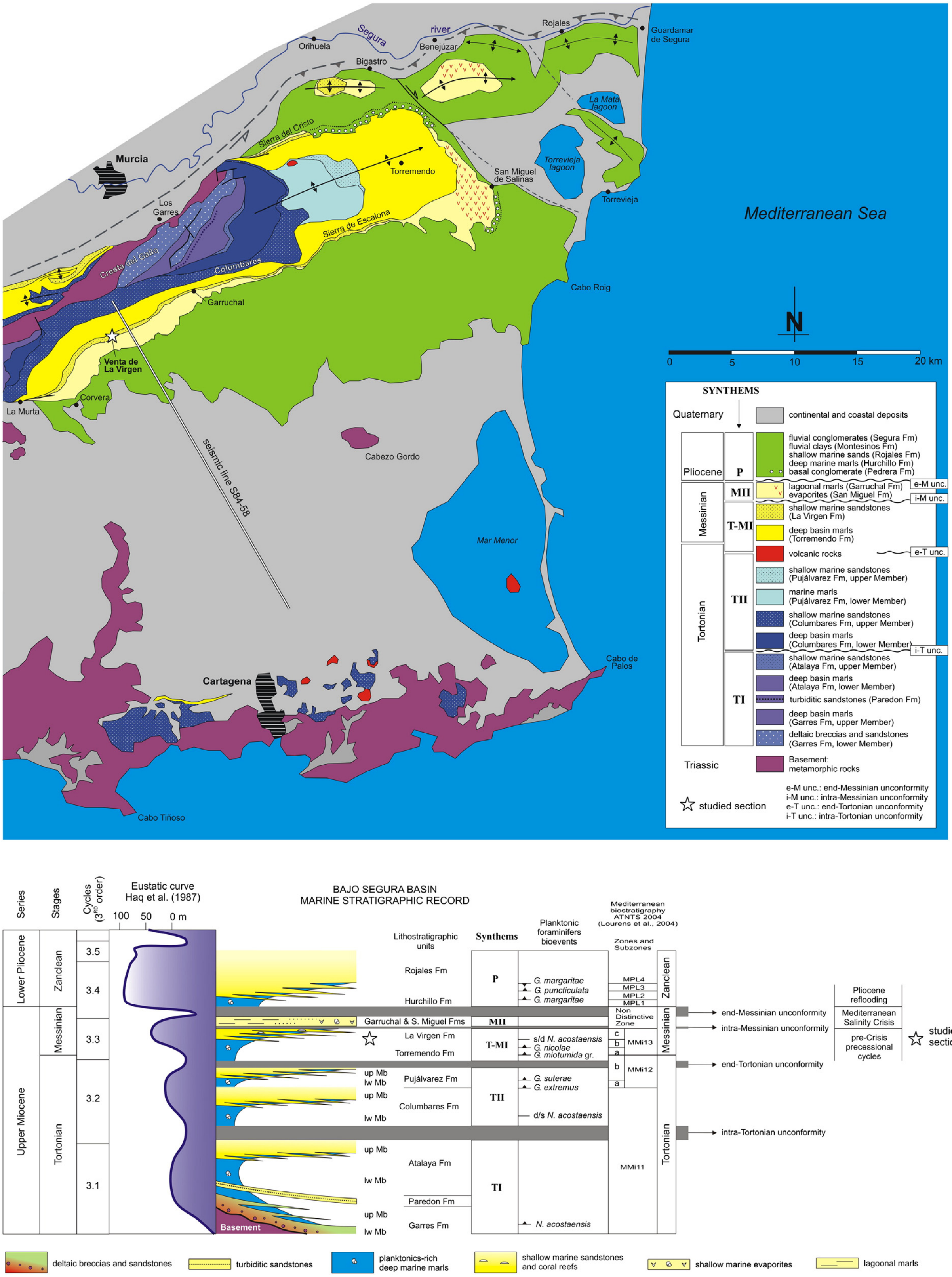

Fig. 2. (Upper) Geological map of the southern Bajo Segura Basin (simplified from Montenat et al., 1990). (Lower) Marine stratigraphic architecture of the basin, with the position of the study section. The curve of Haq et al. (1987) is used to illustrate how the various synthems recorded in the Bajo Segura Basin are coincident with stages of eustatic maxima, and that bounding unconformities correspond with eustatic minima. The age of these synthems has been established through the biostratigraphic study of planktonic foraminifera, referring to biovents and zonal schemes of the Astronomically Tuned Neogene Time Scale (ATNTS 2004; Lourens et al., 2004).

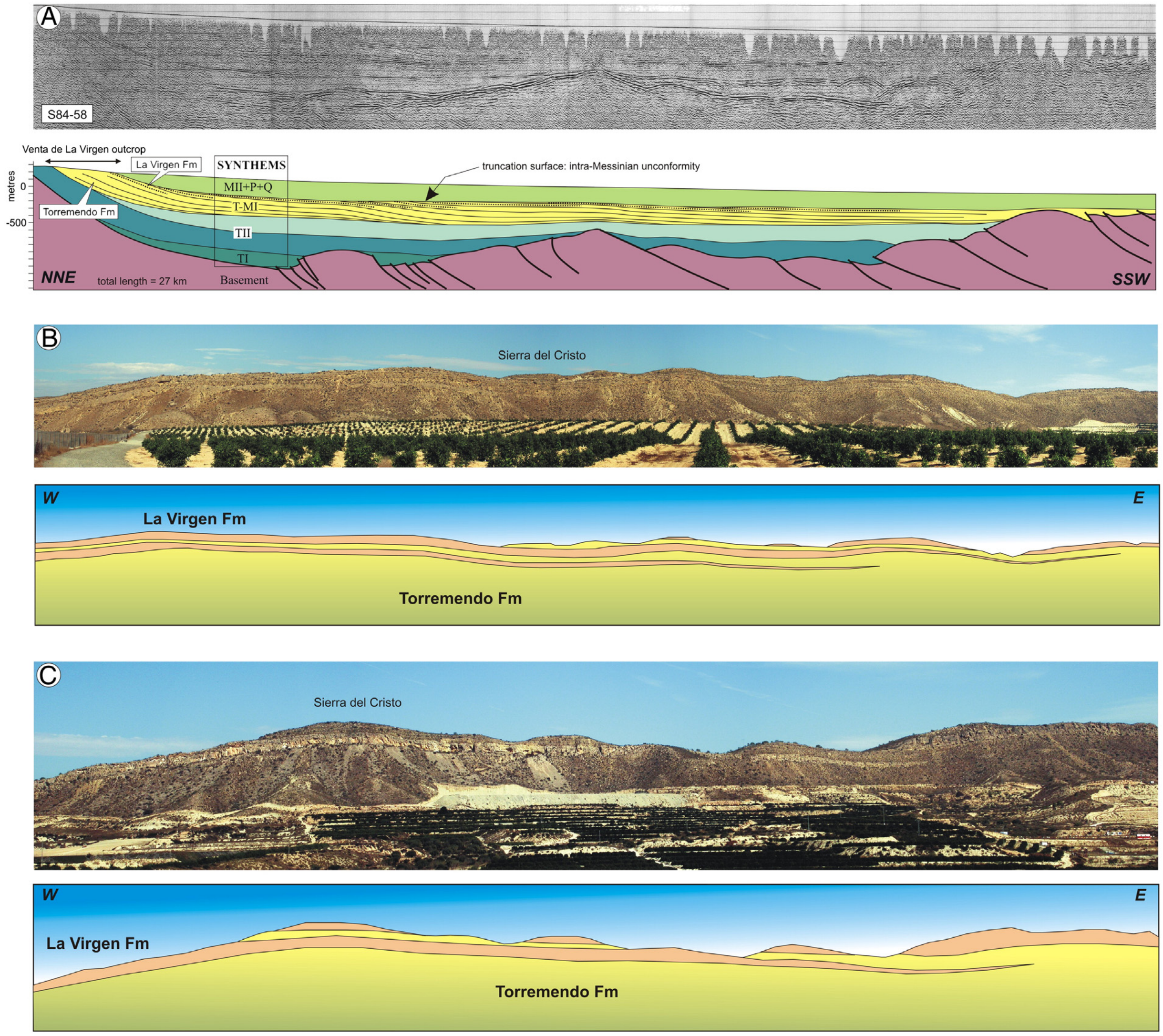

Fig. 3. (A) Sedimentary infill of the basin from subsurface data (see location of seismic line S84-58 in Fig. 2); note the prograding pattern of reflections in Synthem T–MI, defining sigmoidal clinoforms both in the La Virgen Fm. as well as in the Torremendo Fm. (B,C) Panoramic views showing the eastward-prograding homoclinal lithosomes of the La Virgen Fm. over the Torremendo Fm.

Fig. 4. (A) Complete stratigraphic succession of the Venta de La Virgen section, with indication of the planktonic foraminiferal bioevents which allowed for datation of the Torremendo Fm and the La Virgen Fm. The *G. miotumida* gr. and *G. nicolae* bioevents have been adopted from Krijgsman et al. (2006). (B) Panoramic view of the La Virgen Fm (see location on Fig. 2). 0 to VII indicates the sandstone lithosomes comprising this formation, which are the basic focus of this study. The numbers within each lithosome are inserted to identify the sandstone layers that are analyzed in detail in Fig. 7.

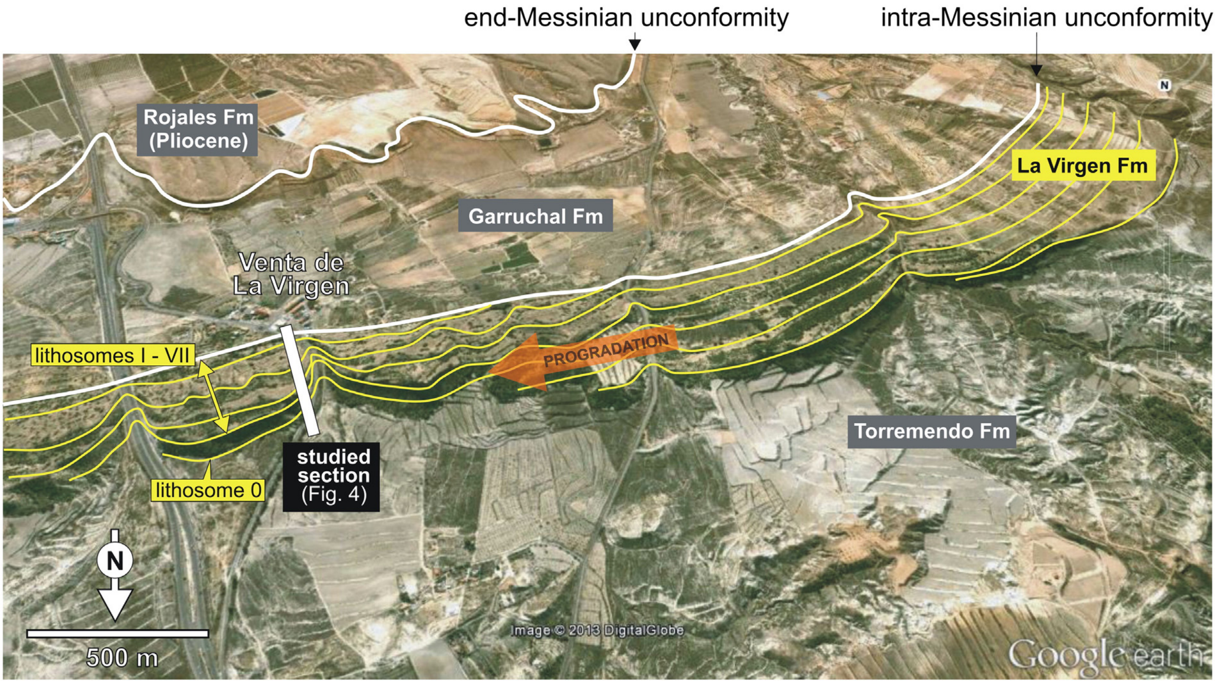

Fig. 5. Oblique satellite photo (Google Earth) of the Venta de la Virgen sector, showing both the stratigraphic relationships between the Torremendo Fm and the La Virgen Fm, and the position of the intra-Messinian unconformity which truncates the latter formation. To be noted how the distal ends of the La Virgen lithosomes correspond to an eastward progradation.

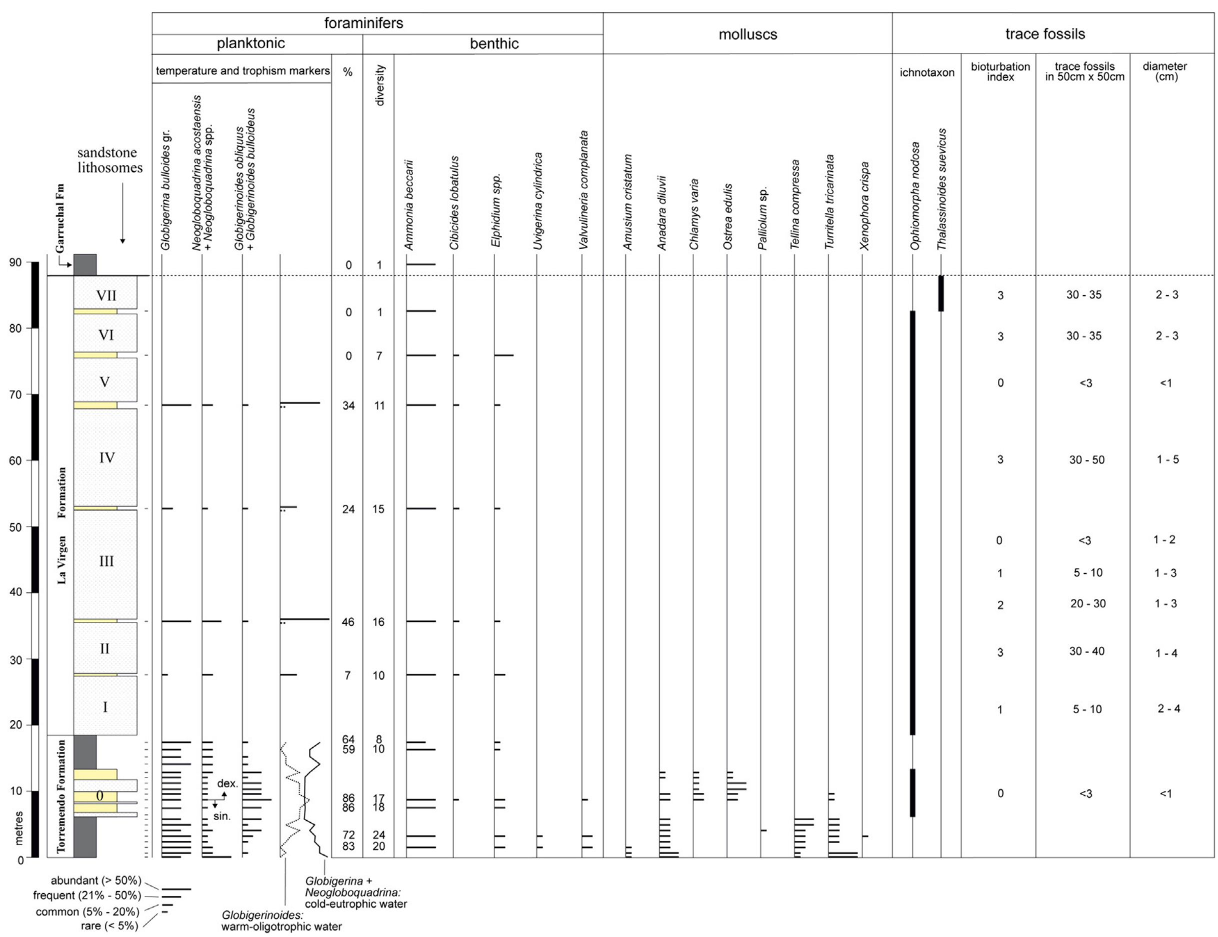

Fig. 6. Simplified stratigraphic succession of the La Virgen Fm., including the main palaeontological features (benthic and planktonic foraminifera, molluscs and trace fossils) used for palaeoenvironmental reconstructions.

1978) suggest a palaeobathymetry of circa 100 m, typical of the outer shelf. Within lithosome 0, the presence of *C. lobatulus* (20–200 m water depth according to van Hinsbergen et al., 2005) and of *Ammonia beccarii* and *Elphidium* spp. (both 0–100 m water depth) point to a middle to outer shelf water depth zone. Above lithosome 0, the benthic foraminifer association is similar, although the absence of *C. lobatulus* indicates slight shallowing towards the inner–middle shelf.

The mollusc assemblage (bivalves and gastropods) recorded in the pelagic marls underlying lithosome 0 is relatively diverse, with *Turritella tricarinata*, *Anadara diluvii*, and *Tellina compressa* as dominant species, whilst *Amusium cristatum*, *Xenophora crispa*, *Thyasira* cf. *flexuosa* and *Palliolum* sp. occur sparsely. The former species are endobenthic deposit-feeders, typical of muddy substrates in the outer shelf (Lozano-Francisco, 1997). This relatively high diversity of molluscs is suggestive of oxic conditions in the sediment–water interface (Borja et al., 2000); an interpretation supported by the occurrence of *Cibicides* spp. In the silty marls of lithosome 0, the mollusc assemblage points out a marked decrease in diversity. It is dominated by *Chlamys varia* and in situ clumps of *Ostrea edulis*, with scattered *A. diluvii*. The occurrence of multicostate morphotypes of *O. edulis* is indicative of high-salinity conditions at the bottom (Lozano-Francisco, 1997). This feature, together with low species diversity, points to a context of benthic stress related to stratification episodes of the water column during the deposition of lithosome 0. This is consistent with the relatively frequent occurrence of *U. cylindrica* (a deep endobenthic species) at the top of the underlying unit, since this species has been reported to tolerate raising salinity conditions (Kouwenhoven et al., 2003).

5.2. La Virgen Formation

In the study section, this formation attains a thickness of 70 m (Fig. 7), with seven sandstone lithosomes (labelled I to VII) interspersed with extensive silty marl intervals. Lithosome thickness ranges between 5 and15 m and their width can extend laterally for several kilometres. In addition to these seven main sandstone units, the lithosome 0 is also included in the La Virgen Formation. This lithosome of 7.5 m thick, isolated in the uppermost part of the Torremendo Formation, is composed of silty marls with thin sandstone levels. Each of these lithosomes comprises sheetlike sandstone beds whose sedimentary analysis and depositional interpretation will be provided in further detail below. From a petrographic point of view (Fig. 8), the most abundant constituents of the La Virgen sandstones are quartz, feldspar, and carbonate lithoclasts, in addition to well-preserved planktonic and benthic foraminiferal tests. Grain size progressively increases from lithosome 0 (silt to very fine sand) to lithosome VII (fine to medium sand). In each of these lithosomes, individual sandstone beds are moderately sorted, and there is no grading. Albeit the microfabric is frequently grain-supported, it displays a variable content in intergranular microsparite cement as well as in muddy matrix; hence three types of microfabrics are differentiated: (1) matrix-filled framework (lithosome 0); (2) cement-filled framework (the dominant type throughout the formation; lithosomes I to V); and (3) mixed matrix/cement-filled framework (lithosomes VI and VII). Quartz grains are predominantly angular, but feldspar and carbonate grains are mainly subrounded. The poor sorting of the sandstone components, in addition to the angularity of the quartz grains, point to an immature original sediment in the source area.

The silty marl intervals separating the seven sandstone lithosomes are characterized by a scant, variable content in terrigenous particles (very fine-grained sand). The most abundant biogenic constituents of the sediment are planktonic and benthic foraminifera. Overall, both the proportion of plankton and the benthic diversity decrease upward in the section. In fact, the last two intervals (V–VI and VI–VII) are barren of plankton, whilst benthic diversity is notably lower in comparison with that of underlying intervals (Fig. 6). As regards the planktonic foraminifera, the *Globigerina* + *Neogloboquadrina* association prevails over the *Globigerinoides* association in the first four intervals (I–II, II–III, III–IV, and IV–V). This is consistent with the results from the pelagic marls of the Torremendo Formation, indicating that the inter-lithosome intervals of the La Virgen Formation correspond to cold-eutrophic surface waters.

The final configuration (geometry and internal structure) of the individual sandstone beds forming the seven lithosomes of the La Virgen Formation is a result of the interaction of processes linked to physical sedimentology and ichnology. These two aspects will be treated separately below.

6. Physical sedimentology

6.1. Typology and vertical arrangement of sandstone beds

The aforementioned eight lithosomes comprise a stack of sandstone layers of variable thickness; ranging from a few centimetres to 1 m. These layers predominantly form cosets limited by internal erosional surfaces. In some cases, they regularly alternate with thin silty marl levels. In other cases, the sandstone layers are amalgamated, as it happens with lithosomes 4 and 5. The typology and vertical distribution of internal sedimentary structures are quite varied. Based on these two features, the following types of beds have been differentiated (Fig. 9).

m: massive, or lacking internal structure (Fig. 9A). This type presents a scoured base and a flat top. The best and most abundant examples are found in lithosome 0.

p: planar lamination from base to top of the bed, with parting lineation, very thin mud partings, and frequent internal erosion surfaces (Fig. 9B). This type has two variants: one with a massive interval at the base and faint, small-scale, hummocky cross-lamination very close to the top (Fig. 9C), and the other with mud clasts in the basal lamimae (Fig. 9D). Both types have a scoured base and a flat or erosional (uneven) top. The palaeocurrents measured on flute marks in sandstone beds from lithosome I indicate N75–90E directed flows. This direction points towards the current position of the Mediterranean and coincides with the general dip of the lithosomes observable in large-scale outcrops (see Section 3 and Fig. 3B and C).

h: hummocky cross-lamination dominates throughout the layer. Swales are lacking. The most significant case is characterized by a flat base and a convex-up sandstone lens with the typical morphology of isolated hummocks (Fig. 9E). Hummocks are relatively flat, over 4 m in wavelength and 30 cm in height.

sw: swaley cross-lamination (Fig. 9 F). In this type, very well-developed concave-up laminae (high relief) are laterally connected with planar laminae or with relatively flat (low relief) hummocks. Internal erosional surfaces separate various sets within a single bed. Mud clasts appear in isolated cases. The beds are bounded by amalgamation surfaces. Typically, swales are 2–3 m in wavelength and 25–30 cm in height.

sw + h, h + sw: layers in which both swaley cross-lamination and hummocky-cross lamination are laterally and vertically connected (Fig. 9G to K). Swales dominate in sw + h, and hummocky-cross lamination dominates in h + sw. Mud clasts are common in both cases, especially in the bottom part of layers or the base of internal sets limited by erosional surfaces. Basal bounding surfaces are undulated, according to the morphology of the basal laminae. Erosional or amalgamated tops dominate. Swale and hummock wavelength and height vary from one lithosome to another. In lithosomes IV and V, they are 2–3 m and 20–30 cm, respectively, whereas in lithosomes VI and VII, they are smaller, ranging from 1 m to 10 cm, respectively.

(p) → sw: diffuse planar lamination grading upwards into swaley cross-lamination with mud clasts (Fig. 9L). Scoured base of beds. These bed types are characteristic of lithosome III. Swales in the upper parts of beds have a wavelength of 5 m and a height of 50 cm.

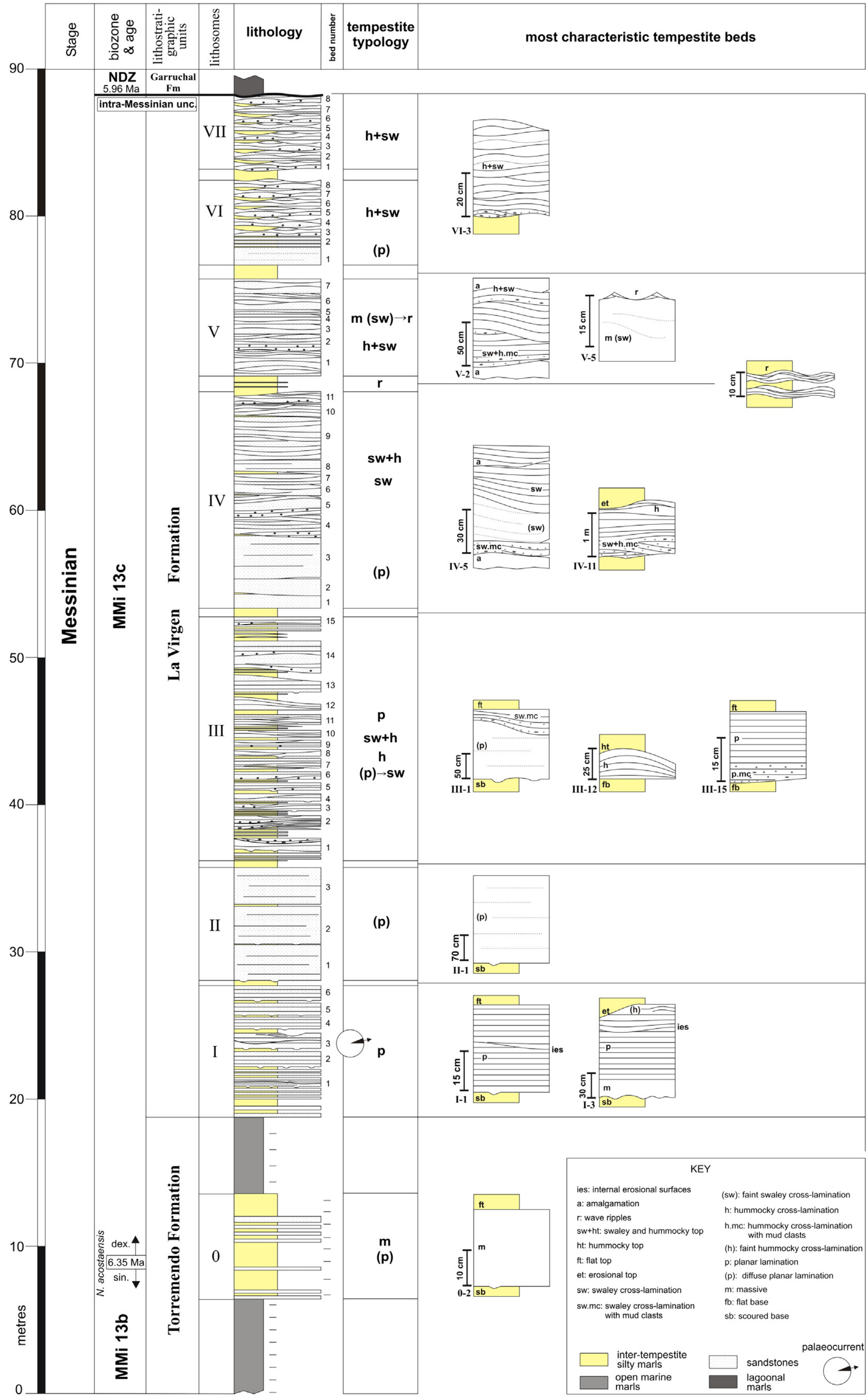

Fig. 7. Detailed sedimentological succession showing the different types of tempestite beds comprised by each of the eight sandstone lithosomes of the La Virgen Fm at the Venta de la Virgen section.

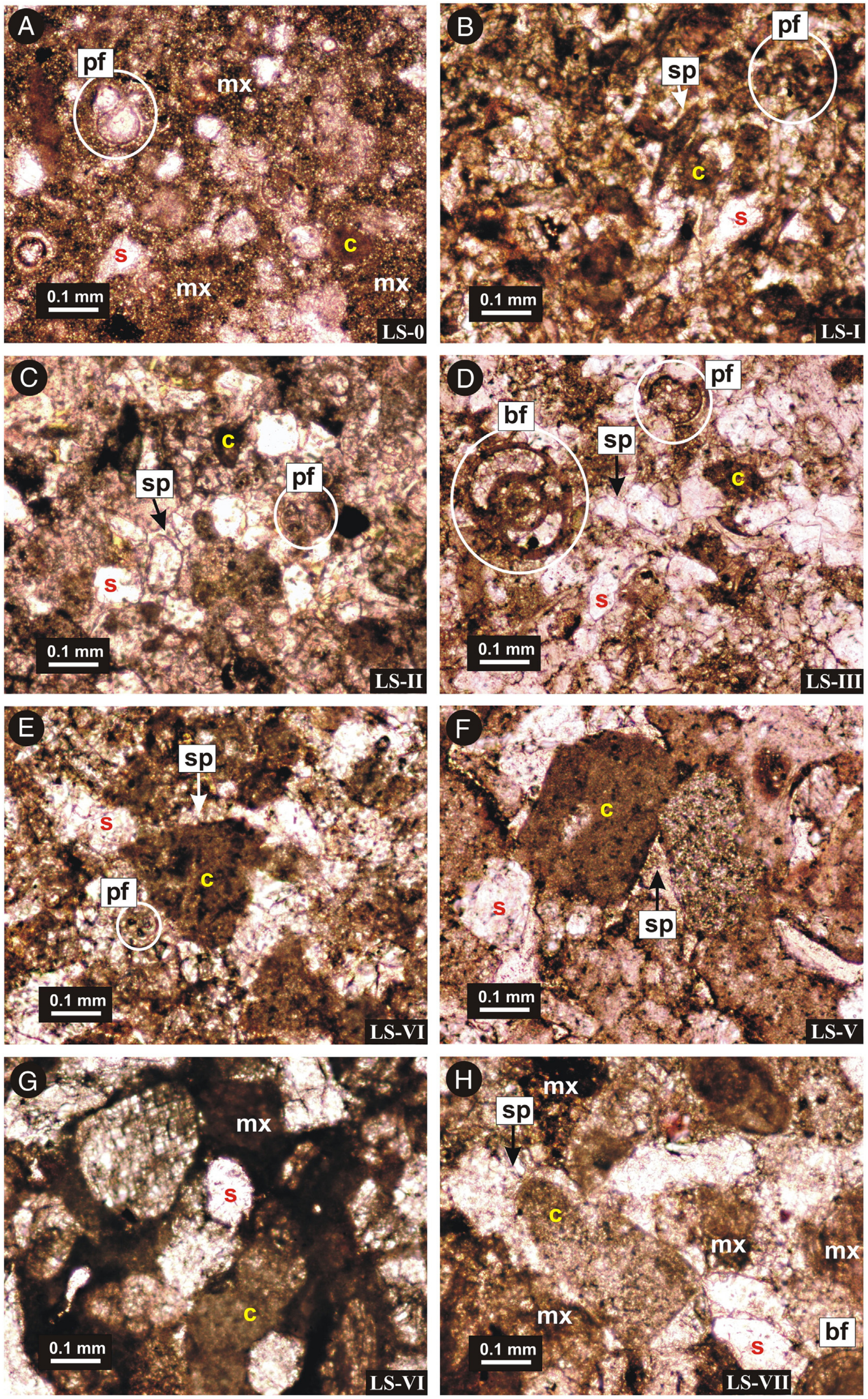

Fig. 8. Petrology of the sandstones forming the La Virgen Fm. The lithosome corresponding to each image is labelled as LS in the lower-righthand corner. Note the progressive increase in grain size from LS-0 to LS-VII. Key for components: s, siliciliclastic (quartz and feldspar) clasts; c, carbonate clasts; pf, planktonic foraminifers; bf, benthic foraminifers; sp., sparite cement; mx, muddy matrix.

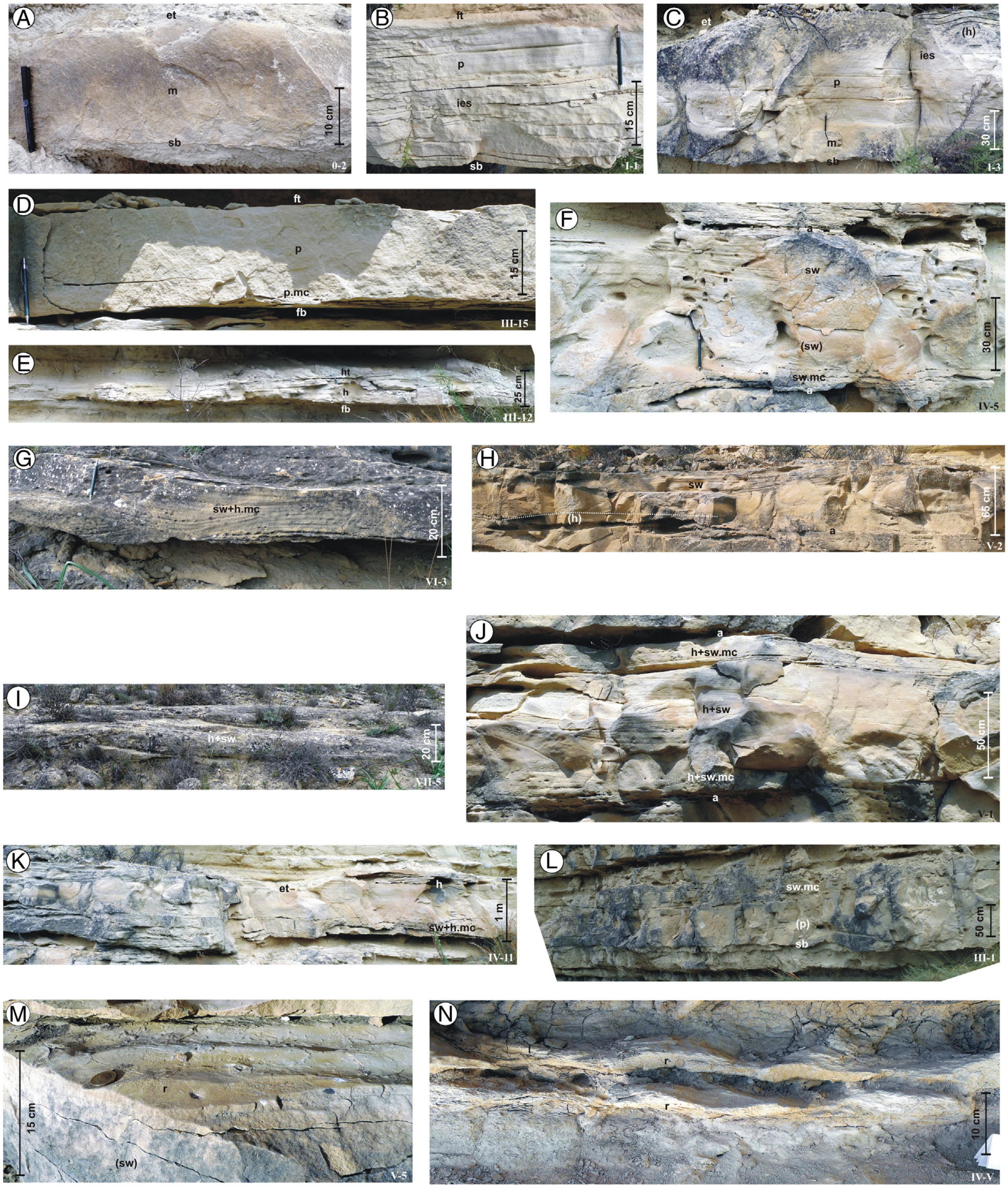

Fig. 9. Close-up view of the most characteristic tempestite beds recognized in the La Virgen Fm. For the key to the sedimentary structures, see Fig. 7. The lithosome and bed numbers are labelled in the lower-righthand corner. Close-up view of the most characteristic tempestite beds recognized in the La Virgen Fm. Image N corresponds to the wave-rippled sandstones in the silty marl interval separating lithosomes IV and V.

(m, sw) → r: massive or diffuse swaley cross-lamination grading upwards into straight-crested (2D or chevron-like) symmetrical wave ripples (Fig. 9M). Ripple wavelength is 5 cm and height is 1.5 cm.

r: this type comprises thin, wavy layers with internal wave ripple (off-shooting) cross-lamination (Fig. 9N). They appear only in the silty marl intervals separating sandstone lithosomes. These ripples, with gentle crests and troughs, have a wavelength of 15 cm and a height of 3 cm.

As a whole, in the La Virgen Formation the sandstone bed types described above indicate a progressive upward change of beds formed under a regime of unidirectional currents (planar lamination) towards beds formed under an oscillatory regime (hummocky and swaley cross-laminations).

In lithosomes 0, I, and II, type p beds (planar lamination) dominate. The massive nature of these layers in lithosome 0 is likely a result of the similar grain size of the sediment components, which hamper laminae segregation during unidirectional flow. A common feature is scour marks, evidencing the highly effective traction in the flows. Internal erosional surfaces within the beds suggest that they were formed by several reworking events.

In lithosomes III and IV, type-p beds are superceded by dominant type sw and h layers and, to a lesser extent, type sw + h. Some p–sw layers reflect evolution over time during a period of simple deposition from unidirectional flows to oscillatory flows. For the first time, mud clasts have been recognized in the swale laminae, indicating that the turbulent oscillatory flow laden with sand is partially fed by the silty marl interbeds. Layers are commonly amalgamated (especially in lithosome IV) as a result of consecutive high-energy depositional events.

In lithosomes V, VI, and VII, most beds are h + sw with mud clasts in the basal laminae. In contrast to the other lithosomes, there are no beds dominated by swales and hummocks. These h + sw beds indicate that the entire sand deposit is modelled by oscillatory flows. An exception are the (sw)–r beds, which indicate a gradual loss of energy, from high to low regime, of the oscillatory flows.

The large-scale geometry of the sandstone lithosomes of the La Virgen Formation is suggestive of a depositional setting that may be interpreted as a gently dipping (2–3º) homoclinal ramp. The background sedimentation of this ramp is represented by silty marls separating both the lithosomes and the sandstone beds that form each of them. All of the sandstone bed types that make up the La Virgen Formation can be interpreted as depositional events genetically related to the emplacement of storm ebb surges; their sedimentary record can be referred to as a storm bed or simply as a tempestite. The cases represented in this formation are similar to those described by Dott and Bourgeois (1982), Walker et al. (1983), Hobday and Morton (1984), Cheel (1991), Brenchley et al. (1993), and others. We have used the model illustrated by Cheel (1991), in which a tempestite is formed under combined flow, that is, with unidirectional and oscillatory components. The unidirectional gravity component (excess-weight forces) caused the downslope transport of sediment-laden water. The oscillatory component consists of a bipolar movement over the seafloor related to storm waves. The Cheel model considers that a storm ebb surge is emplaced during the gradual fall in energy of a storm, beginning with a strong unidirectional flow (first erosional and then depositional) followed by an oscillatory flow, where energy decreases from high to low regime.

The tempestites in the La Virgen Formation are classified into two categories. The first one includes those beds deposited under the storm wave base level, which only record unidirectional flow. This class contains types p and m, in which bed soles often bear scour marks. They primarily occur in lithosomes 0, I, and II, characterizing the distalmost tempestites throughout the La Virgen Formation (outer-middle shelf based on the benthic foraminiferal associations). The second category includes tempestites deposited above the storm wave base level, recording the effects of oscillatory flows. This second class contains the types with swaley and/or hummocky cross-lamination, always from lithosome III upwards (middle-inner shelf). There are varied cases. In the p–sw type, the ebb surge emplaced by unidirectional flow is shaped in its upper part by storm waves. Types sw and h (including the case where the two coexist, sw + h) are thought to be a result of the complete remodelling of the ebb surge (initially emplaced by unidirectional flow) by storm waves. Finally, the sw–r type records the gradual decrease in energy of the storm waves, from high to low regime. Apart from the types described, which always form part of the sandstone lithosomes, the silty marl intervals contain sporadic type r tempestites. They are similar to the type sw + h, but their thinness and small size indicate sporadic, short-lived, low-energy storm.

6.2. Depositional model and provenance analysis

The huge extensions of the sandstone lithosomes and of the individual storm beds suggest that the tempestites (storm ebb surge deposits) forming the La Virgen Formation derive from the erosion of long and wide segments of sandy coastlines well nourished by local river discharge. The large extent of the sandy bodies, together with their sheet-like geometry, discards a shallow-water turbiditic flow depositional model (cf. wave-modified turbidites model, by Myrrow et al., 2002). Such a model would have smaller, lens-like bodies corresponding to hyperpycnal flow lobes generated directly at river mouths. In addition, the sedimentary sequences from the wave-modified turbidites contain Bouma-like sequences and abundant climbing combined-flow ripples, and neither of these features has been observed in the sandstone beds of the Venta de la Virgen section. Sandstone beds with hummocky cross stratification could be interpreted also as part of flood-dominated fluvio-deltaic systems (Mutti et al., 1996, 2003). These authors introduce the term “shelfal sandstone lobes with HCS” to refer to sediments deposited by high and low density turbidity currents during catastrophic events of fluvial discharge. We consider that Mutti's model biggest problem is related to the genesis of the oscillation needed to form HCS, which would be induced by the hyperpycnal flow when entering the sea-water body. Mutti et al. (1996, 2003) suggest that internal waves generated by hyperpycnal flows can actually cause the set in motion of the shallow sea water and explain the common presence of HCS in shelfal sandstone lobes. Nevertheless, it is to point out that the internal wave sedimentary record is still subjected to debate. According to Pomar et al. (2012), internal wave deposits (internalites) are highly variable and definitive criteria for recognition are still to be developed. More critically, Shanmugam (2013) states: “there are absolutely no core-based studies by sedimentologists on the origin of primary sedimentary structures formed by baroclinic currents associated with internal waves and internal tides in modern marine environments”. Amid this state of knowledge, we prefer to adopt the storm ebb surge model for the beds with HCS forming the sandstone lihosomes of the La Virgen Formation.

Based on the sandstone bed petrology, the storm ebb surges incorporate two types of sedimentary components: (1) terrigenous clasts from the source area, and (2) bioclasts (planktonic and benthic foraminifers) and mud clasts, both intrabasinal. The moderately sorted character of the terrigenous components, in addition to the angularity of the quartz grains, point to an immature original sediment in the source area. This is in accordance with river sand supplies, rapidly redistributed by coastal agents, and with a short time of residence in the foreshore and shoreface before being reworked during the storm climax. Consequently, wave motion has neither substantially sorted the original fluvial sediment nor modified the original quartz grain morphology to rounder shapes characteristic of long-time-residence sediments along the coastline.

The variable content in sparite cement and muddy matrix (see Section 5.2) is related to turbulence and downslope transport during tempestite deposition. Fine-grained and relatively deep (outer shelf) tempestites, such as lithosome 0, have high matrix contents. This indicates that scant sediment is suspended under conditions of diminished turbulence whether due to energy loss of the ebb surge or to the inefficiency of the oscillatory flow. In somewhat shallower tempestites characterized by coarser grains (most of the lithosomes—I to V), muddy matrix lacks and the sandy sediment pores are infilled with microsparite cement. In these cases, high turbulence combined flows, with a very effective downslope unidirectional (tractive) flow, cause complete dispersion of fine-grained sediment by winnowing. The original high porosity of this well-washed sediment favours the subsequent precipitation of sparite in the intergranular spaces. The shallowest tempestites (inner shelf), with larger grain sizes (such as lithosomes VI and VII), have a variable content in matrix and cement. These tempestites are shaped by oscillatory flows alone. As a result of a scarce downslope displacement, most of the fine fraction is retained in the wave motion turbulence zone. In this position, incomplete sand washing results in partial porosity and less intergranular cements.

7. Ichnology

7.1. Trace fossils throughout the La Virgen Formation

The La Virgen Formation is characterized by an oligotypic ichnological association of *O. nodosa* (Figs. 6, 10). Very rare and small *Thalassinoides suevicus*, *Teichichnus* isp., and *Rosselia* isp. are found in the lower part of the section (lithosome III). *T. suevicus* is very abundant in lithosome VII, where it represents a monotypic assemblage.

Fine-grained sandy pellets make up the *Ophiomorpha* burrow lining, which in several cases has been completely eroded and can be observed only as an external mould in the host rock. Pellets are subspherical to slightly discoidal, and they completely cover the surface of the burrow. Their size is constant in the same trace fossil, although it can vary between burrows. Burrows are passively filled with the same sand as the overlying bed, usually coarser than that of the burrow lining. The geometry includes well-developed vertical or slightly inclined shafts and horizontal mazes. Horizontal burrows are Y-branched and 1–5 cm in diameter; mazes can extend laterally for several metres. *T. suevicus* in lithosome VII is represented by small Y-shaped forms with a diameter of about 2–3 cm.

In lithosomes 0 and I, *O. nodosa* is very scarce and small in diameter. It begins to be more abundant and larger in lithosome II, where it reaches a bioturbation index of 3 and a diameter of 1–4 cm.

Lithosomes III and IV strongly differ, although the ichnoassemblage is represented exclusively by *O. nodosa* in both of them. In lithosome III, trace fossils are very scarce (bioturbation indices 0–1) and very small. In contrast, in lithosome IV, burrows reach the highest concentration (up to 50 burrows in a 50 cm × 50 cm square) and the largest size, both considering burrow diameter (up to 5 cm) and shaft length (up to 1 m).

In lithosomes V and VI, there is once again a decrease in both the bioturbation index and burrow size, with horizontal mazes almost completely absent. From an ichnological standpoint, lithosome VII completely differs from the others since *O. nodosa* is absent, replaced by *T. suevicus*. Horizontal mazes are very well developed, whereas vertical shafts, although abundant, are very short; burrow entrances are usually quite visible on the bed surfaces.

7.2. Trace fossils as proxies for the palaeoecology and hydrodynamics during tempestite deposition

In the study section, *Ophiomorpha* commonly forms three-dimensional mazes, a feature that has been considered typical for *Ophiomorpha* ichnofabrics in storm beds (Anderson and Droser, 1998). Several genetic models of highly bioturbated *Ophiomorpha* ichnofabrics in storm beds focus on the role of allochthonous tracemakers (Föllmi and Grimm, 1990; Savrda, 2007) as the cause for this intense bioturbation. These crustaceans are assumed to be transported during the storm together with the sediment, beginning to burrow immediately after deposition. At this new site, according to the number of organisms transported and the ecological conditions of the new environment, these crustaceans will (or will not) establish a real community (Föllmi and Grimm, 1990). Rather than by the abundance of *Ophiomorpha*, the peculiarity of the Venta de La Virgen section is given by the extremely low diversity of the ichnoassemblage, which, in the entire section, is represented almost exclusively by crustacean-related trace fossils (*Ophiomorpha* and *Thalassinoides*). Preservation of these burrows would be enhanced by the absence of substrate mixing by a well-established autochthonous community in the final depositional environment, probably due to unfavourable environmental conditions (Savrda, 2007). In fact, in the study section, there is no type of bioturbation other than *Ophiomorpha*

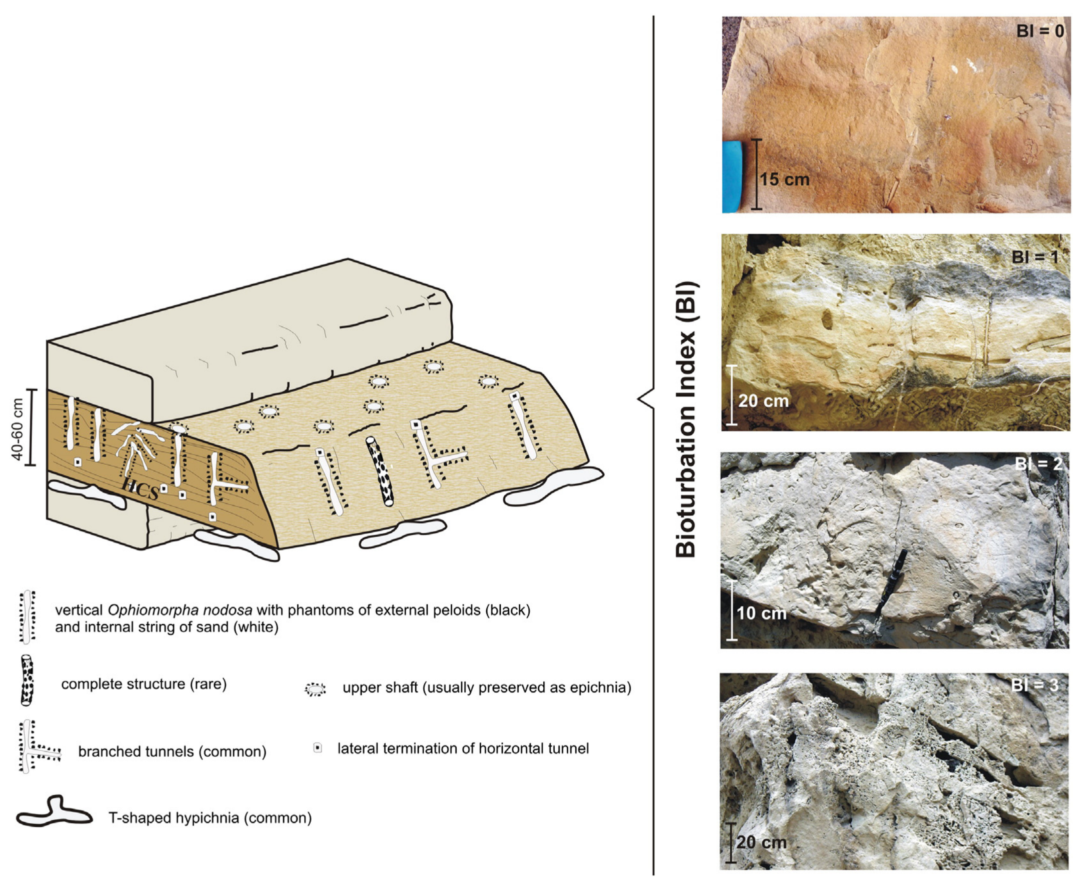

Fig. 10. *Ophiomorpha nodosa*: the most typical trace fossil in the La Virgen Fm.

either in the uppermost part of the storm beds or in the marly beds representing the autochthonous material, even though burrows related to soft ground conditions would be expected (Belaústegui and de Gibert, 2013). We considered the possibility that the lack of trace fossils in the marls could be related to preservation problems rather than to the absence of the trace makers. However, thin lamination is usually very well preserved in the marls, and this would be possible only in the case of very scarce to absent bioturbation. The abrupt change from *Ophiomorpha* to *Thalassinoides* would appear to follow a change in sediment composition. In fact, *Thalassinoides* only appears in the last lithosome (VII), which is the richest in muddy matrix. *Ophiomorpha*, by contrast, is related to clean sandy beds, representing the loose substrate typical for these burrows (Anderson and Droser, 1998; Rotnicka, 2005).

8. Depositional and tempestite cyclicity

The grouping of sandstone and marl units in the La Virgen Formation indicates three hierarchical cyclicity orders.

The 1st-order cyclicity consists of alternating lithosomes (0–VII) and silty marl intervals separating them (Fig. 11). Out of these eight pairs, lithosome 0 and its underlying marls offer the key to its climate control and frequency. As mentioned in Section 5.1, the fossil content in the marls (foraminifera and molluscs) reflect shallow, cold-eutrophic waters with oxic conditions at the sediment–water interface. In contrast, the fine-grained sediments in lithosome 0 are typical of warm-oligotrophic surface waters with enhancing high-salinity, stressful conditions on the seabed. This change in surface temperature indicates that sand input in the basin by river discharge and its immediate transport by storms occurs during warm climate periods, in correspondence with maximum insolation in the Mediterranean domain. In addition, the marls were deposited in a context of a mixture of surface and deep waters, and lithosome 0 corresponds to episodes of water-column stratification. In the other lithosomes (I–VII), the silty marl intervals defining 1st-order cycles have foraminiferal assemblages coinciding with those of the aforementioned marls. The terrigenous nature of the lithosomes prevents the determination of their original biogenic content. Nevertheless, on account of stratigraphic relationships, it can be envisaged that they may reflect a similar palaeoenvironmental context as that of lithosome 0. Overall, the 1st-order cyclicity in the La Virgen Formation can be interpreted as a different lithological expression of the same repetitive process controlling the homogeneous marl/sapropel pairs in the underlying Torremendo Formation. These lithological pairs (or sedimentary cycles) are ubiquitous throughout the Mediterranean basins prior to the Messinian Salinity Crisis (e.g. Betics, Apennines, Sicily, Greece and Cyprus). Detailed cyclostratigraphic studies correlate the homogeneous marl/sapropel pairs with precessional orbital cycles (20–23 ka; Hilgen and Krijgsman, 1999; Krijgsman et al., 1999; Hüsing et al., 2009). Concerning the palaeoclimatic significance of these sedimentary cycles, Turco et al. (2001) argue that the homogeneous marls correspond to the times of maximum precession and minimal insolation and that, in contrast, the sapropels were deposited in periods of precession minima and insolation maxima.

In short, we hold that the generation of the sandy lithosomes of the La Virgen Formation from the combined effect of river supply and storm is related to precessional climate cycles. According to Rohling and Hilgen (1991), on the Mediterranean coastline, storms associated with Atlantic-derived atmospheric depressions are more intense and frequent during minimum precession and maximum insolation orbital cycles. In the same vein, river discharge on the coastline associated to intense precipitation (a key factor for sandy coastline development) is also more intense in such orbital configurations (Rossignol-Strick, 1985).

The 2nd-order cyclicity is recorded within each lithosome by alternating cosets of sandstone beds and silty marls. This order also includes amalgamated sandstone beds since the inter-bed fine-grained sediment is easily dispersed in suspension during storm wave-generated turbulence. If partially consolidated, part of this sediment can be incorporated as mud clasts in the overlying tempestite. This cyclicity reflects alternating periods dominated by either storms or by good weather. The frequency is difficult to accurately establish. For lithosomes with more cycles (III and IV), storm-dominated periods fall within a precessional semi-cycle, indicating that each storm period lasts about 1 ka. This value should not be confused with the duration of a single storm event since only major storm events at intervals of a few thousand years have left recognizable imprints in the geological record (Banerjee, 2000). The average preservation interval of a single storm bed ranges between 6 and 250 years (Tamura and Masuda, 2005).

The 3rd-order cyclicity is characterized by internal laminae and lamina packets (sets) within individual beds (cosets). Each lamina represents a pulse of varying storm intensity. Well-developed lamination, including very thin mud partings, indicate flow pulses with alternate periods of slack water within an event of storm deposition (Chakraborty and Bose, 1992).

9. Discussion: towards a basin-scale scenario

The La Virgen Formation constitutes a record of a basin margin oversupplied by terrigenous sediments that has no comparable examples in Mediterranean margins during the Messinian. Coetaneously with the progradation of the extensive terrigenous lithosomes characterizing the La Virgen Formation, most of the margins of the Mediterranean developed tropical carbonates represented by prograding coral reefs. Exceptional examples of the latter are documented in other Betic Cordillera basins neighbouring the Bajo Segura Basin, such as the basins of Sorbas, Vera, Níjar, Cabo de Gata, Tabernas, and Mallorca (Esteban et al., 1996; Riding et al., 1998). Other examples of prograding reefs are found in the Melilla Basin (Maghreb Chain), of Messinian age and correlating with the Betic Cordillera reefs established by Benson et al. (1997) and van Assen et al. (2006). Other parts of the western Mediterranean also preserve Messinian reefal carbonates of equivalent age to those mentioned above. Such is the case in the Maltese Islands and Lampedusa (Pedley, 1988) and on the Salento Peninsula (Bosellini et al., 2002), both in southern Italy; and in Monferrato and Emilia (Bosellini et al., 2003), both in the northern Apennines.

Based on their study of reefs in the Sorbas Basin, Martín et al. (1999) concluded that tropical carbonates formed in warm periods during rising and high sea levels in the Mediterranean during the Messinian. According to these authors, these favourable periods for reef development coincide with Haq's eustatic maxima. This eustatic context is in agreement with the highstand sea-level model put forth by Soria et al. (2008a, 2008b) for T–MI synthem in the Bajo Segura Basin, to which the La Virgen Formation belongs. In fact, this formation includes local coral reefs (Montenat et al., 1990; Reinhold, 1995; Feldmann and McKenzie, 1997; Soria et al., 2005) with similar characteristics to those of time-equivalent reefs documented from other parts of the margins of the Mediterranean. The factor differentiating the Bajo Segura Basin margin from the rest of the Mediterranean, on which the unique sedimentary features of the La Virgen Formation stems, is the excess in clastic supply deriving from the erosion of the reliefs in the Betic Cordillera. Parallel traits in the prograding model of this formation with regard to purely reefal units can also be seen in the distal or basinal pelagic sediments. As illustrated by the Sorbas and Níjar basins, the fringing reefs interfinger with cyclically arranged marls, sapropels, and diatomites that together form a unit so-called the Upper Abad marls (Sierro et al., 2003). The fringing reefs and the Upper Abad marls are equivalent to the La Virgen Formation and the Torremendo Formation (upper part), respectively. To be recalled is the fact that the latter formation, as mentioned above, shows a characteristic stacking pattern of marl/sapropel cycles, with its upper part having intercalated distal ends of the sandy lithosomes formed in a storm-dominated marine platform.

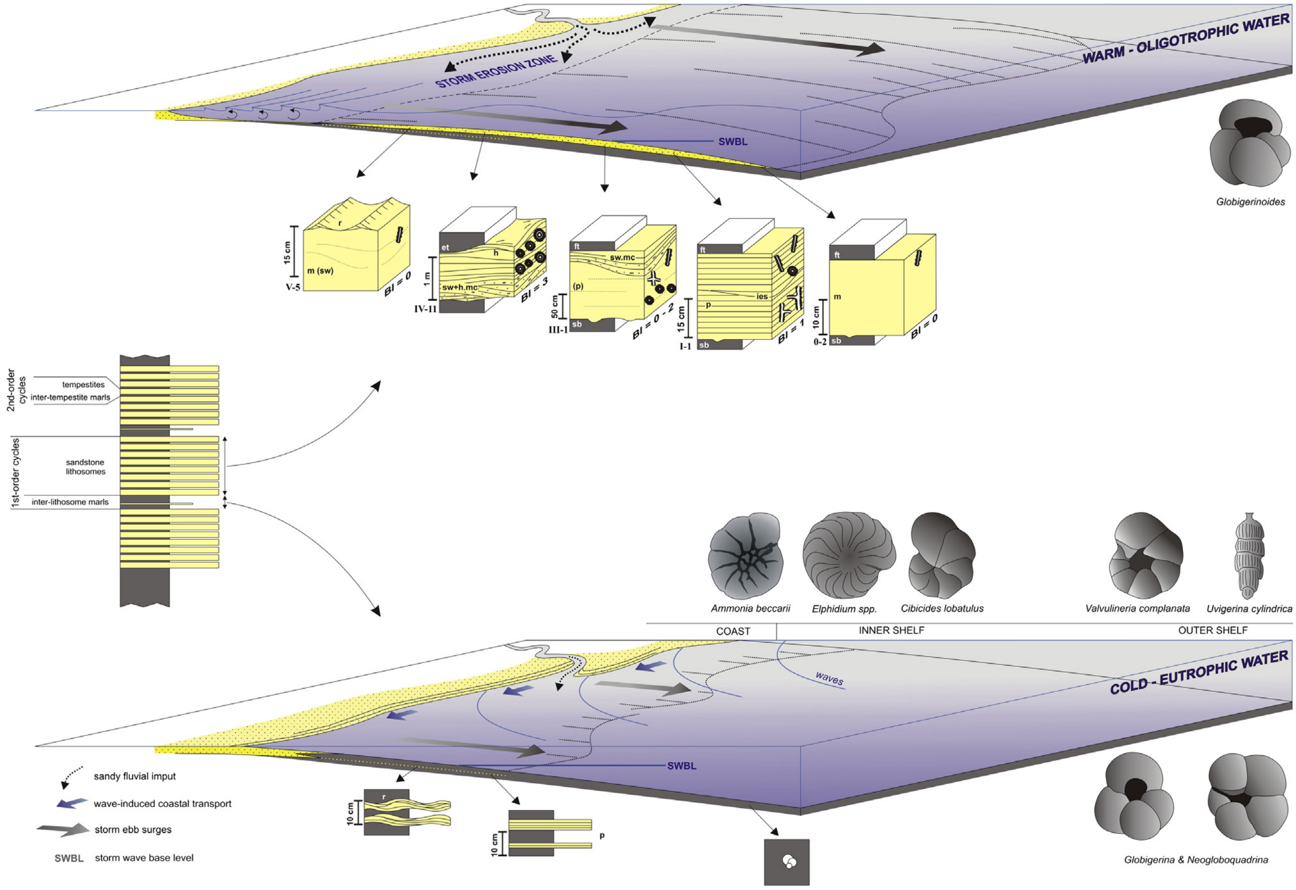

Fig. 11. Depositional interpretation, tempestite distribution, and cyclicity model for the shallow-marine terrigenous shelf in relation to climate changes. (Lower) During cold-eutrophic water episodes the shelf is starved, and pelagic sedimentation dominates (plankton-rich silty marls); the only terrigenous supply is produced by sporadic and low energy storm ebb surges. (upper) During warm-oligotrophic water episodes, generation of the sandy lithosomes of the La Virgen Formation results from frequent and high energy storm ebb surges. Large amount of sand in well nourished coastal zones (from enhanced river supply) is eroded by major storms.

10. Conclusions

The La Virgen Formation turns out as an exceptional example of a storm-dominated prograding marine platform formed during the Messinian prior to the onset of the Mediterranean Salinity Crisis. The terrigenous nature of the platform is typical of a well-nourished Mediterranean margin, which differentiates it from time-equivalent and widely documented reef-dominated carbonate margins. The unique sedimentary nature of the La Virgen Formation lies in four basic features that help to fill in our knowledge of the dynamics of the ancient Mediterranean Sea.

First, the La Virgen Formation illustrates prograding large-scale sandy lithosomes during a high sea level context. Petrologic data indicate that the source area for these lithosomes consist of extensive sandy coastlines locally nourished by river discharge.

Second, this formation displays the response of shallow-marine deposit systems to global climate changes. The successive prograding lithosomes, together with the marly intervals separating them, define 1st-order sedimentary cycles corresponding to precessional climate cycles.

Third, the La Virgen Formation documents that storm ebb surges were the main operative depositional mechanism, transporting sediment from coastal zones to the outer shelf. The sedimentary record of the storms (tempestites) is repetitive, forming 2nd-order (cosets) and 3rd-order cycles (sets and internal laminae). The tempestite beds formed over a wide range of depths, both below and above the storm wave base level.

And fourth, on the scale of the entire Mediterranean basin, this formation is characterized by the scant presence of coral reefs, which are generally ubiquitous throughout the Messinian. Even though the water temperature and the bathymetry would have favoured reef development, the high supply of terrigenous sediment was likely the factor inhibiting the formation of reefal buildups. This formation thus serves as an example to illustrate a genetic model of a large-scale sandy reservoir with quite unique characteristics in the circum-Mediterranean area during the Messinian.

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