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SEDIMENTOLOGY

The ichnoassemblages of the Abad Member (Tortonian–Messinian), Vera Basin, SE Spain: implications for the regional tectonic and palaeogeographical evolution

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Abstract – The Vera Basin is one of a series of interconnected Neogene–Quaternary-age basins located within the Betic Cordillera in SE Spain. The initial marine phase in the basin is represented by the sedimentary succession of the Abad Member (Tortonian–Messinian) and comprises mainly marls with varying amounts of intercalated siliciclastic–calcareous turbidites. The succession contains a rich ichnofauna comprising 12 ichnogenera (21 ichnospecies), which can be subdivided into a number of distinct ichnoassemblages. Detailed analysis of the distribution of these ichnoassemblages reveals that deposition occurred within the Nereites ichnofacies, more specifically, the Paleodictyon subichnofacies, presumably in a lobe-type setting, and at epi- to mesobathyal depths (i.e. 200–1000 m). Changes within the ichnofacies suggest that there is a clear deep-through-to-shallow trend within the succession extending from the older (i.e. Almocáizar Corridor) to the younger (i.e. centre of the Vera Basin) parts of the succession. These changes coincide with the onset of the Messinian Salinity Crisis (MSC) across the region, and correlate well with the pre-MSC through to Lago Mare deposits.

Keywords: ichnofossils, turbidite, deep marine, Messinian Salinity Crisis.

1. Introduction

The Betic Cordillera (SE Spain) is part of the European Alpine Belt, which formed as a result of the relative movements of the African, Iberian and European plates (Weijermars, 1987*a*, 1991; Vergés, Fernàndez & Martínez, 2002; Fernández-Fernández *et al.* 2007). Uplift of the Betic Cordillera is related to the collision of the African and Iberian plates in Santonian/Campanian times (De Jong, 1990; Weijermars, 1991; Vergés, Fernàndez & Martínez, 2002; Reicherter & Peters, 2005). The NNE–SSW-elongated orogen can be subdivided into an External Zone (N), an Internal Zone (SE) and a Flysch Zone (SW; Fig. 1; Huibregtse *et al.* 1998; Braga, Martín & Quesada, 2003; Reicherter & Peters, 2005; Fernández-Fernández *et al.* 2007; Jabaloy-Sánchez, Fernández-Fernández & González-Lodeiro, 2007). In consequence of the ongoing uplift of the Betic Cordillera during Neogene times, intermontane pull-apart basins developed in the External Zone (with occasional linkage to the Atlantic Ocean) and the Internal Zone (linked to the Mediterranean Sea; Fig. 1b and Fig. 2; Krijgsman *et al.* 2001; Braga, Martín & Quesada, 2003; Puga-Bernabéu *et al.* 2014). The Neogene- to Quaternary-age basins of the Betic Cordillera include the Sorbas, Nijar and Vera basins (Sanz de Galdeano & Vera, 1992; Martin & Braga, 1996; Martín *et al.* 1996; Martín, Braga & Riding, 1997; Krijgsman *et al.* 2001; Braga, Martín & Quesada, 2003; Fortuin & Krijgsman, 2003; Puga-Bernabéu *et al.* 2014; Do Couto *et al.* 2015) separated by metamorphic domes (c.f. Augier *et al.* 2005; Pedrera *et al.* 2009; Fig. 2) as well as by normal and strike-slip faults (e.g. the Palomares Fault Zone (PFZ) in the Vera Basin; Fig. 1b; Egeler & Simon, 1969; Bousquet, 1979; García-Hernández *et al.* 1980; Weijermars, 1987*b*; Huibregtse *et al.* 1998; Jonk & Biermann, 2002; Faulkner, Lewis & Rutter, 2003; Booth-Rea *et al.* 2004; Martínez-Díaz & Hernández-Enrile, 2004; Krijgsman *et al.* 2006). The tectonostratigraphic histories of the basins are broadly similar, while their evolution parallels that of the Alboran Sea (Banks & Warburton, 1991; Braga *et al.* 2006; Giaconia *et al.* 2014; Mancilla *et al.* 2015).

The Vera Basin, located in the eastern part of the Betic Orogen, is connected to the south (via the Almocáizar Corridor) with the Sorbas Basin, and to the north (via the Pulpí Corridor) with the Lorca Basin. The sedimentary succession of the Vera Basin, comprises > 1 km of Burdigalian- to Pliocene-age deposits and consequently includes evidence of the Messinian Salinity Crisis (MSC) (Montenat *et al.* 1976; Bellón *et al.* 1994; Fortuin, Kelling & Roep, 1995; Braga, Martín & Wood, 2001; Booth-Rea *et al.* 2003; Stokes, 2008). The succession can thus be broadly subdivided into pre- and post-MSC units (Völk & Rondeel, 1964;

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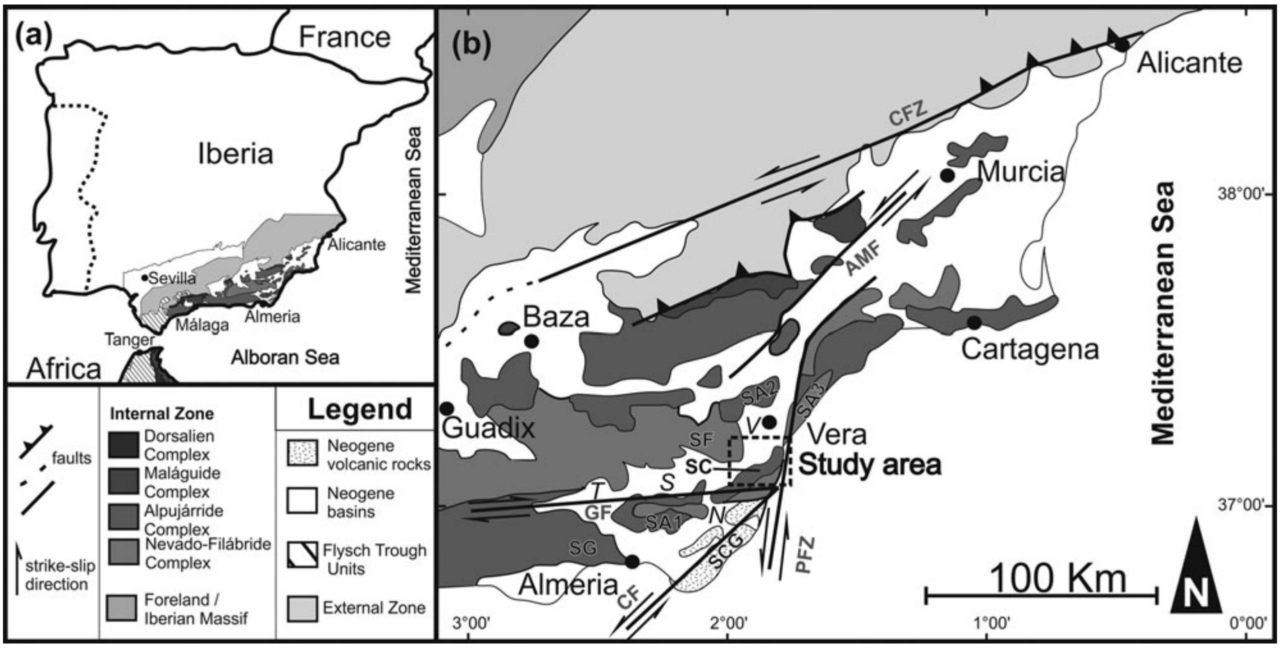

Figure 1. Geological overview of the Betic Cordillera: (a) location and orientation on the Iberian peninsula, including the main structural units of the orogen (e.g. External Zone, Internal Zone, Flysch Trough Units) and the Neogene-age basins (Atlantic or Mediterranean-linked basins); (b) detailed view of the western part of the Betic Cordillera, showing the main fault systems (CFZ – Crevillente Fault Zone; GF – Gafariollos Fault; PFZ – Palomares Fault Zone; CF – Carboneras Fault) and the Mediterranean-linked Neogene-age basins (from west to east): T – Tabernas Basin; N – Nijar Basin; S – Sorbas Basin; and V – Vera Basin. The sierras surrounding the basins are (from west to east): SG – Sierra Gador; SA1 – Sierra Alhamilla; SF – Sierra de los Filabres; SCG – Sierra del Cabo de Gata; SC – Sierra Cabrera; SA2 – Sierra Almagro; and SA3 – Sierra Almagrera (modified after Huibregtse *et al.* 1998; Faulkner, Lewis & Rutter, 2003; Fortuin & Krijgsman, 2003; Jabaloy-Sánchez, Fernández-Fernández & González-Lodeiro, 2007; Mancilla *et al.* 2015).

Braga, Martín & Wood, 2001; Booth-Rea *et al.* 2003; Stokes, 2008). The succession records a dramatic deepening event (continental to deep marine) relatively early during the basin evolution. The aim of the present study is to investigate, in detail, the evidence for such a deepening event, via sedimentological fieldwork, and including detailed ichnological analysis, which has, to date, not yet been carried out within this area. Focusing on the corridor area (i.e. Almocáizar Corridor; Montenat *et al.* 1976) between the Sorbas and Vera basins, as well as the central area of the Vera Basin (located immediately to the north-east; Fig. 3a) allows the closely related histories of the basin successions (Vera, Sorbas) to be compared and contrasted, while also investigating the possible reasons why this event appears to be restricted to the Vera Basin.

2. Pre-Messinian stratigraphy of the Vera, Sorbas & Nijar basins

As noted above, the Vera Basin is one of several Neogene-age basins in the Almeria area of SE Spain (Fig. 1b) which were closely linked during the early stages of their formation, to the extent that some of them (e.g. Vera, Nijar and Sorbas basins) could at this initial stage be considered as a single basin (albeit with localized sub-depocentres; Fig. 2a). Successive uplift of the Betic Cordillera led to increasing restriction, in terms of sediment movement and transport, between the Neogene-age basins, particularly from late Messinian times onwards (Fig. 2a–c; Völk & Rondeel, 1964; Sanz de Galdeano, 1987; Benson & Bied, 1991; Bellón *et al.* 1994; Fortuin, Kelling & Roep, 1995; Braga, Martín & Wood, 2001; Booth-Rea *et al.* 2003; Braga, Martín & Quesada, 2003; Fortuin & Krijgsman, 2003). Owing to this level of interconnection, stratigraphic correlation (especially between the Sorbas, Nijar and Vera basins) of the older (Burdigalian – upper Messinian) sediments is possible. Subsequent uplift, however, resulted in increasing basin isolation leading to the development of considerable variations in the post-late Messinian sedimentary successions within the various basins (Fig. 2b, c; Sanz de Galdeano & Vera, 1992; Soria, Fernández & Viseras, 1999; Baggley, 2000; Stokes & Mather, 2000; Fortuin & Krijgsman, 2003; Puga-Bernabéu *et al.* 2014; Do Couto *et al.* 2015).

The pre-Messinian stratigraphy of the Sorbas, Vera and Nijar basins is summarized in Figure 4. The succession comprises five formations, namely, from base to top (i.e. the onset of the MSC succession): the Alamo, Gomara, Umbria, Chozas and Turre formations. The oldest described sediments (i.e. Alamo, Gomara and Umbria formations of Völk & Rondeel, 1964) are found in the Sorbas and Vera basins (Sanz de Galdeano & Vera, 1992; Braga, Martín & Wood, 2001; Booth-Rea *et al.* 2003; Braga *et al.* 2006; Do Couto *et al.* 2015). These comprise deformed continental conglomerates as well as shallow-marine

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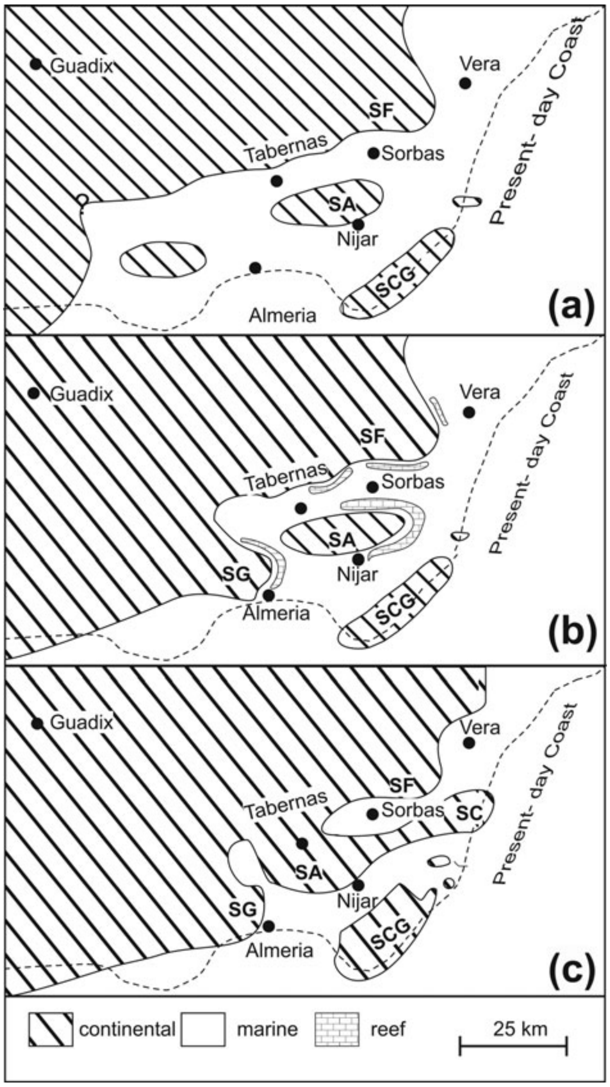

Figure 2. Palaeogeography of SE Spain, showing the development of the connection between the Neogene-age basins and the progressive uplift of the surrounding sierras during the deposition of the Abad Member: (a) latest Tortonian to earliest Messinian times, representing the setting during the accumulation of the older Abad Member deposits; (b) early Messinian times, including the middle to late Messinian-aged reefs; and (c) the end of the Messinian, i.e. subsequent to the reflooding at the end of the Messinian Salinity Crisis. Modified after Braga, Martín & Quesada (2003) and Fortuin & Krijgsman (2003). Abbreviations: SF – Sierra de los Filabres; SA – Sierra Alhamilla; SG – Sierra Gador; SCG – Sierra del Cabo de Gata; SC – Sierra Cabrera

conglomerates, sandstones and marls and are of Burdigallian – early Tortonian age. The continental conglomerates are locally derived and concentrated along the basin margins where they prograde into the marine areas where they become shallow-marine conglomerates. In contrast, the shallow-marine marls are widespread across the basinal areas, extending from the Sorbas Basin into the Vera Basin (Fig. 4; Jonk & Biermann, 2002). Whether these sediments are also present within the Nijar Basin is unclear owing to a lack of outcrop.

The basal sedimentary succession is unconformably overlain by the lower Tortonian-age Chozas Fm (Fig. 4; Völk & Rondeel, 1964; Braga, Martín & Wood, 2001; Booth-Rea *et al.* 2004), which comprises marls, limestones and sandstones and represents a deepening sequence within the Neogene-age basin infill (Martín *et al.* 1996; Braga, Martín & Wood, 2001; Jonk & Biermann, 2002). The unconformably overlying upper Tortonian to upper Messinian-age Turre Fm (Fig. 4; Martín *et al.* 1996; Braga & Martín, 2000; Braga, Martín & Wood, 2001; Krijgsman *et al.* 2001; Sierro *et al.* 2001; Jonk & Biermann, 2002; Booth-Rea *et al.* 2004) comprises three members. The first two of these are the Azagador Member, a proximal, shallow-marine unit containing siliciclastic and carbonate sediments, and the closely related reef complex (Cantera Member), which is best developed in late Messinian times, and is particularly well exposed in the Sorbas and Nijar basins (Fig. 4; Sanz de Galdeano & Vera, 1992; Martin & Braga, 1996; Martín *et al.* 1996; Martín, Braga & Riding, 1997; Krijgsman *et al.* 2001; Fortuin & Krijgsman, 2003; Puga-Bernabéu *et al.* 2014). Within the Vera Basin, the Cantera member is only exposed in a restricted area in the northwest (Fig. 3). These two members (Azagador and Cantera Member) interdigitate with the distal marls and intercalated sandstones of the Abad Member.

The development of transgressive successions in the upper part of the Turre Fm was related to sea-level variations, which commenced at the Tortonian–Messinian boundary, coupled with a coeval increase in tectonic activity (Fig. 4). This latter event was related to uplift of the sierras surrounding the basins in the region (Fig. 2c; Braga, Martín & Quesada, 2003; Booth-Rea *et al.* 2004) as well as increased activity along the strike-slip fault systems. The end result was a phase of rapid basin subsidence as well as increasing isolation of the Sorbas and Nijar basins, both from the Mediterranean Sea as well as from the Vera Basin. As a consequence of these changes, the Azagador and Abad members became increasingly lithologically disparate between the Sorbas/Nijar and Vera basins (Cloetingh, 1991; Baggley, 2000; Krijgsman *et al.* 2001; Fortuin & Krijgsman, 2003; Braga *et al.* 2006).

The sediments of the Abad Member (Vera Basin) form the basis for this study. Within the basin, the succession comprises 200–300 m of grey silty marls intercalated with sandstone beds (Fig. 4–6). The percentage of sandstone beds increases upwards, thus roughly subdividing the member into a sand-poor lower part (sandstone:marl = 1:10) and a sand-rich upper part (1:2). This lithological subdivision of the Abad Member correlates broadly with the foraminiferal assemblages present, with *Globorotalia mediterranea* and *Globorotalia multiloba* present in the lower part, and *Neogloborotalia acostaensis* in the upper part (Sierro *et al.* 1999; Baggley, 2000). Booth-Rea *et al.* (2004) have suggested that there is an unconformity (related to tectonic activity) present within the member (although the precise location of this, if present, is unclear).

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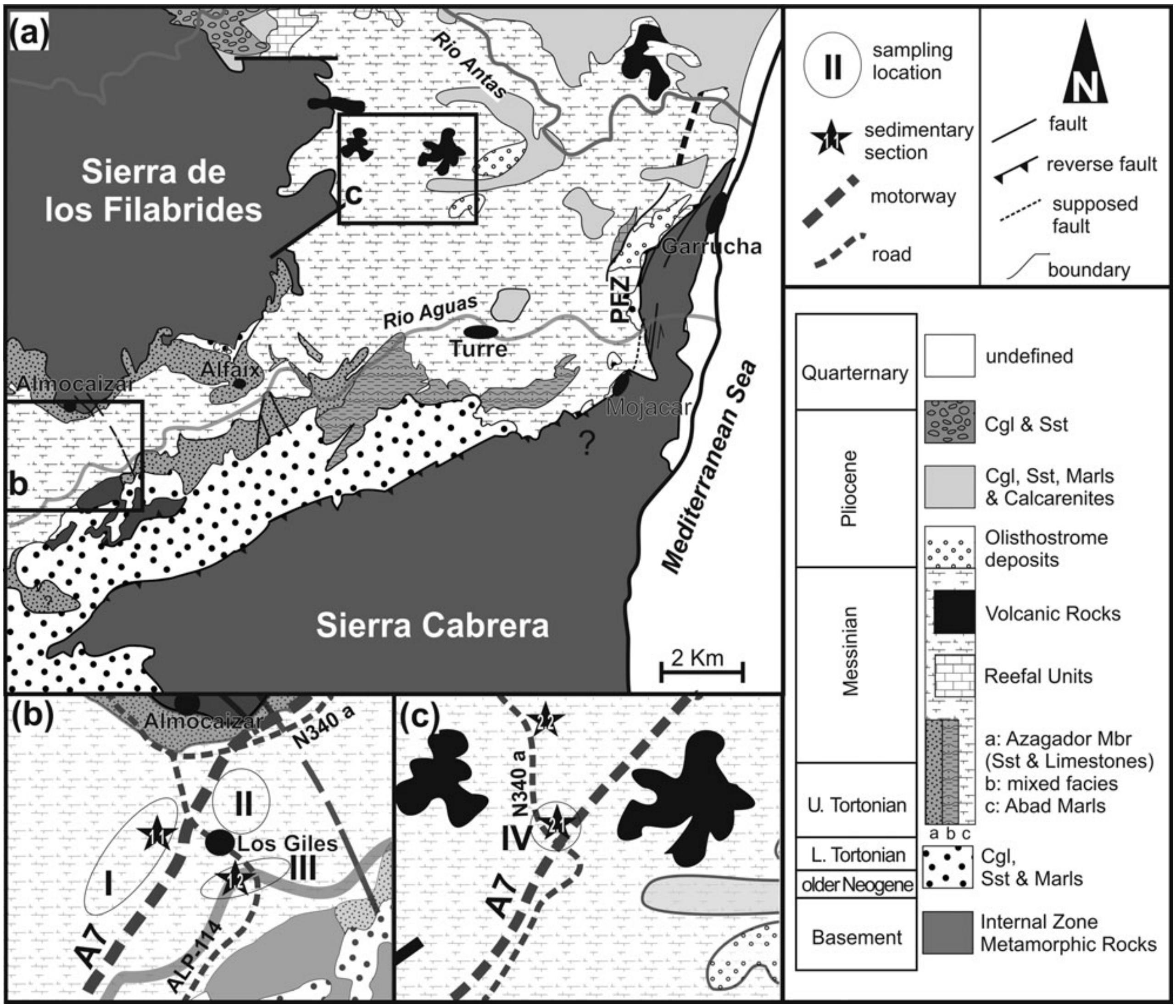

Figure 3. (a) Geological map of the central and southern parts of the Vera Basin showing the main stratigraphic units (Burdigallian–Pleistocene) within the basin (modified after Bellón *et al.* 1994; Braga, Martín & Wood, 2001; Braga *et al.* 2006; Fortuin & Krijgsman, 2003; Stokes, 2008; Booth-Rea *et al.* 2004 and including the results of new fieldwork carried out as part of this study). (b, c) Detailed views of the sampling locations (I/II/III/IV). Broad sampling areas are marked by circles while the locations of the sedimentological profiles are marked by stars. Section coordinates: GPS – UTM European 1950, 30S, (1.1) 586677/4109472; (1.2) 588331/410947; (2.1) 596200/4116972; (2.2) 595914/4118305. PFZ – Palomares Fault Zone.

The sand-rich part of the Abad Member (i.e. Santiago Beds; Völk & Rondeel, 1964; Benson & Bied, 1991; Fortuin, Kelling & Roep, 1995) is considered to represent a marker unit deposited prior to the onset of the MSC. In the Vera Basin, the Santiago Beds are interpreted as turbidites based largely on the presence of Bouma sequences (Völk & Rondeel, 1964; Fortuin, Kelling & Roep, 1995; Huibregtse *et al.* 1998) as well as the ichnofossil *Paleodictyon.*

In the Sorbas and Nijar basins, the Abad Member can also be subdivided into two units based on foraminiferal biostratigraphy as well as sedimentary characteristics (Martín *et al.* 1996; Krijgsman *et al.* 2001; Sierro *et al.* 2001; Braga, Martín & Quesada, 2003; Fortuin & Krijgsman, 2003). During the deposition of the Abad Member, palaeoenvironmental conditions were stable with the relatively low energy system (Krijgsman *et al.* 1999, 2001; Baggley, 2000; Sierro *et al.* 2001; Fortuin & Krijgsman, 2003). In contrast, the deposition of the Upper Abad Member occurred during a period of fluctuating salinity accompanied by the deposition of sapropels and slump activity all of which suggest ongoing restriction between the basins (i.e. Sorbas/Nijar and Vera) and the Mediterranean Sea (Fig. 4, Krijgsman *et al*. 1999, 2001; Sierro *et al*. 1999, 2001).

The subsequent phase of deposition, which included the MSC, differs markedly between the Sorbas/Nijar and Vera basins as a result of their increasing separation Fig. 2c and the development of individual palaeogeographical settings (e.g. Riding *et al.* 1998; Krijgsman *et al.* 1999; Sierro *et al.* 1999, 2001; Fortuin & Krijgsman, 2003; Augier, Jolivet & Robin, 2005; Braga *et al.* 2006; Manzi *et al.* 2013). In the Vera

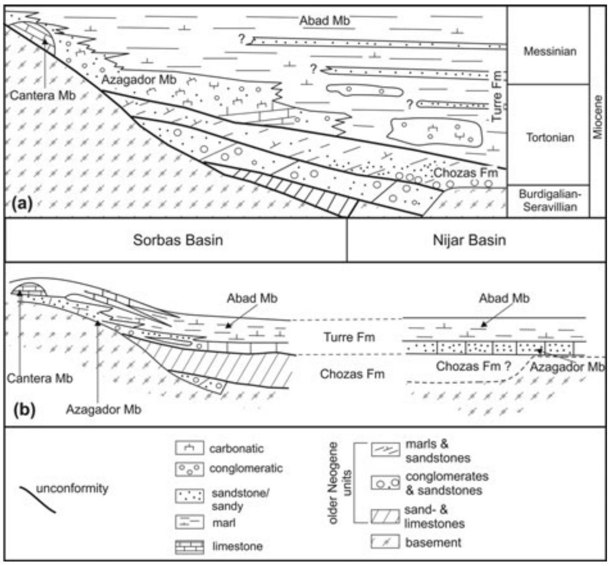

Figure 4. (a) Schematic stratigraphic overview for the sedimentary succession of the pre-Messinian Salinity Crisis (Burdigalian to the end of Messinian times) sedimentary succession of the Vera Basin, showing the relationship between the individual formations and, in detail, the correlation of the three members of the Turre Formation (i.e. Azagador, Abad and Cantera members). (b) Comparison of the stratigraphy of the Vera Basin with the adjacent Sorbas and Nijar basins. Note the occurrence of the same formations/members within these adjoining basins. Modified after Montenat *et al.* (1976), Braga, Martín & Wood (2001), Fortuin & Krijgsman (2003), Puga-Bernabéu *et al.* (2014) and including the results of field mapping from this study.

Basin, the MSC is mainly preserved as an erosional hiatus (Benson & Bied, 1991; Bellón *et al.* 1994; Fortuin, Kelling & Roep, 1995), while in the Sorbas and Nijar basins the period is represented by the deposition of extensive gypsum units (Yesares Member; Martín, Braga & Riding, 1997; Conesa & Babinot, 1999; Krijgsman *et al.* 1999, 2001; Jonk & Biermann, 2002; Fortuin & Krijgsman, 2003; Braga *et al.* 2006; Do Couto *et al*. 2015).

3. Description of the studied succession

The uppermost Tortonian- to Messinian-aged Abad Member crops out in the southern and central parts of the Vera Basin (Fig. 3a). The sediments in the southern part of the basin are stratigraphically older than those in the central parts. Four representative sedimentary profiles, two from each area, were selected for detailed study (Fig. 3b, c). The sediments of the Abad Member comprise marls with interbedded sandstones. The former is the dominant lithology within the member, while the coarser-grained sandstones are present throughout, although there are marked changes both in frequency and bed thickness. In general, the stratigraphically younger part of the succession contains relatively greater amounts of sandstone (i.e. Santiago Beds, see above).

3.a. Lithologies

3.a.1. Marl

As noted above, marls are the dominant lithofacies of the Abad Member (up to 70 %). This lithofacies comprises a grey-coloured, apparently homogenous, and well-sorted mixture of carbonate and siliciclastic material, with individual beds ranging in thickness from 0.5–20 cm. The grain size ranges from clay to silt (classified after Wentworth, 1922). In addition, the marls in the southern part of the Vera Basin are coarser (mainly silt) than in the central part (dominantly clay). The siliciclastic fraction (*c.* 50 %) comprises quartz and clay minerals as well as up to 10 % of mica (dominantly muscovite), while the carbonate fraction consists mainly of micrite and microfossils. The latter are predominantly foraminifera, such as *Globorotalia mediterranea* (Benson & Bied, 1991; Baggley, 2000; Braga, Martín & Wood, 2001). Furthermore, isolated brachiopods (e.g. *Maltaja pajaudi*) and fragments of red algae were noted. Internally, rare parallel and wavy lamination was observed (< 10 % of the entire succession). However, the presence of diffuse microbioturbation in some areas would suggest that primary sedimentary structures were originally present but destroyed as a result of biological activity. Occasionally, the marls show a darker grey-coloured amorphous pattern, which is made up of concentrations of several dark-grey spots (*c.* 1 mm in diameter), suggesting an enrichment in organic material.

3.a.2. Sandstone

Light-grey to beige-coloured beds of coarse- to fine-grained sandstones, ranging in thickness from 0.5–20 cm, are interbedded within the marls. The coarse- to medium-grained sandstones tend to crop out more frequently in the southern part of the Vera Basin, while the central part of the basin is characterized more by the medium- to fine-grained sandstones. The sandstones comprise a mixture of siliciclastic and carbonate material.

The coarser-grained sandstone beds are light grey in colour and graded with the grain size ranging from coarse grained (10 %) through to medium grained (60 %) and on to fine grained (30 %). In addition to the internal grading, cross- and parallel-lamination were also observed. These internal structures can be classified according to the scheme of Bouma (1962). Thus, the sandstones are predominantly Tbc (*c.* 40 %) and Tab (*c.* 30 %), while Tac (*c.* 20 %), Tad (*c.* 5 %) and Ta (*c.* 5 %) were also recognized. Bed bases show evidence of loading and flute casts (270°, n = 7). Bed tops show evidence of current ripples (Tc). The coarse- to medium-grained sandstones are dominated by the siliciclastic fraction (up to 65 %), mainly quartz, mica, lithic fragments (dominantly mica schist and carbonates) and clay minerals. The remaining 35 % of the sandstones comprises micrite, shell fragments and foraminifera.

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The finer-grained sandstone beds are light grey to beige in colour and graded, ranging from medium grained (60 %) through to fine grained (40 %). Bed thickness varies from 1–15 cm. Internal grading as well as cross- and parallel-lamination were observed. The sandstones are predominantly Tac (*c.* 30 %), while Ta (15 %), Tad (*c.* 10 %), Tbc (10 %) and Tcd (5 %) were also recognized. Bed bases show evidence of loading while the bed tops are often rippled (Tc). The finer- and coarser-grained beds are lithologically similar, although the former show higher percentages of carbonate content (up to 50 %), as well as an enrichment of clay within the clastic fraction, resulting in the beige colour of the sediments.

3.b. Sedimentary profiles

Four representative sedimentary sections were measured in the deposits of the Abad Member within the study area. Two of these are older, cf from a stratigraphically lower location in the Almocáizar Corridor area (Fig. 5), while two sections from the basin centre are younger, cf from a stratigraphically higher position (Fig. 6).

3.b.1. Sections 1.1 and 1.2 (Fig. 5)

The older profiles (Figs 4a,b; 5) are characterized by thick beds (ranging from 0.07–8 m, but predominantly *c.* 0.7 m) of silt-rich marl, alternating with coarser-grained sandstone beds. These latter vary in thickness, from 5–20 cm (generally *c.* 8 cm; *c.* 60 %). The boundaries (bases and tops) with the intercalated marls are very sharp and slightly wavy to straight. The frequency of the sandstone beds varies, and this can be related to the thickness of the marl beds, varying from several metres (e.g. 3.8 m thick bed in Fig. 5) to tens of centimetres.

3.b.2. Sections 2.1 and 2.2 (Fig. 6)

The marls and sandstone sediments of the younger profiles (Figs 4a,c; 6) in the central part of the basin comprise mainly finer-grained material. In addition, the marls in this area are more beige in colour as a result of the higher content of clay minerals. In section 2.1, the frequency of the interbedded sandstone beds is higher than in the older profiles (Fig. 5; 1.1 and 1.2). Marl thickness is generally *c.* 30 cm (range 1–90 cm). The boundaries of the medium- to fine-grained, normally graded sandstones are very sharp and slightly wavy and, occasionally (*c.* 10 %), the tops grade into the overlying marl. Trace fossils are mainly preserved on the bases of the sandstone beds.

In section 2.2, there is an increase in the sandstone bed frequency, while the marl beds are mainly *c.* 20 cm thick (ranging from 5–55 cm). Additionally, the sandstones are generally finer grained than in the other measured profiles in the region. In this section no ichnofossils were observed, nor were any ichnofossils noted in the surrounding area (e.g. weathered outcrops).

4. Systematic ichnology

The ichnofossil assemblage of the Vera Basin is presented in the following section in alphabetical order. Preservational terminology follows that adopted by Ekdale (1984) and Knaust (2012), while the internal structures of sandstone beds use the terminology of Bouma (1962), Collinson, Mountney & Thompson (2006) and McCann & Manchego (2015).

The ichnofossils were observed and collected from two main outcrop areas in the Vera Basin: the older one in the southern part of the basin (Almocáizar Corridor) and the younger one in the central part (Fig. 3). In the stratigraphically lower area (i.e. Almocáizar Corridor, three locations (I, II and III in Fig. 3b) were examined in detail, while in the younger, area (i.e. Basin Centre) work was concentrated in one location (section 2.1 in Fig. 3c). In all four of these locations, suites of ichnofossils were collected for subsequent examination. Uncollectable samples were examined and photographed in the field.

Ichnogenus *Circulichnis* Vialov, 1971

Circulichnis montanus Vialov, 1971 by original designation

Figures 7e, 8c

Material. Five specimens and numerous observations in the field.

Description. Smooth ellipsoidal traces (both partial and complete ellipses) preserved in convex hyporelief on the soles of 1.5–1.8 cm thick, medium-grained sandstone beds with internal cross-lamination (Tac). Burrows are cylindrical, unlined. Infill is identical to that of the host rock. Diameters of the long axes vary between 10.7 and 14.6 mm and of the short axes between 0.5 and 10.3 mm.

Remarks. The samples of the Vera Basin conform well to those of McCann (1993) and Fillion & Pickerill (1984), who discussed the original description of Vialov (1971) in detail and suggested that *C. montanus* is a post-depositional burrow.

Ichnogenus *Desmograpton* Fuchs, 1895

Desmograpton dertonensis Sacco, 1888

Figure 7b, c

Material. Three specimens and rarely noted in the field.

Description. Narrow J-shaped semi-meanders (1.2–1.5 mm in diameter of the meander) with parallel to sub-parallel connecting bars. Burrows are up to 0.8 mm wide. The ichnofossils are preserved on the bases of up to 2.5 cm thick, medium-grained sandstones with internal grading and parallel-lamination (Tab).

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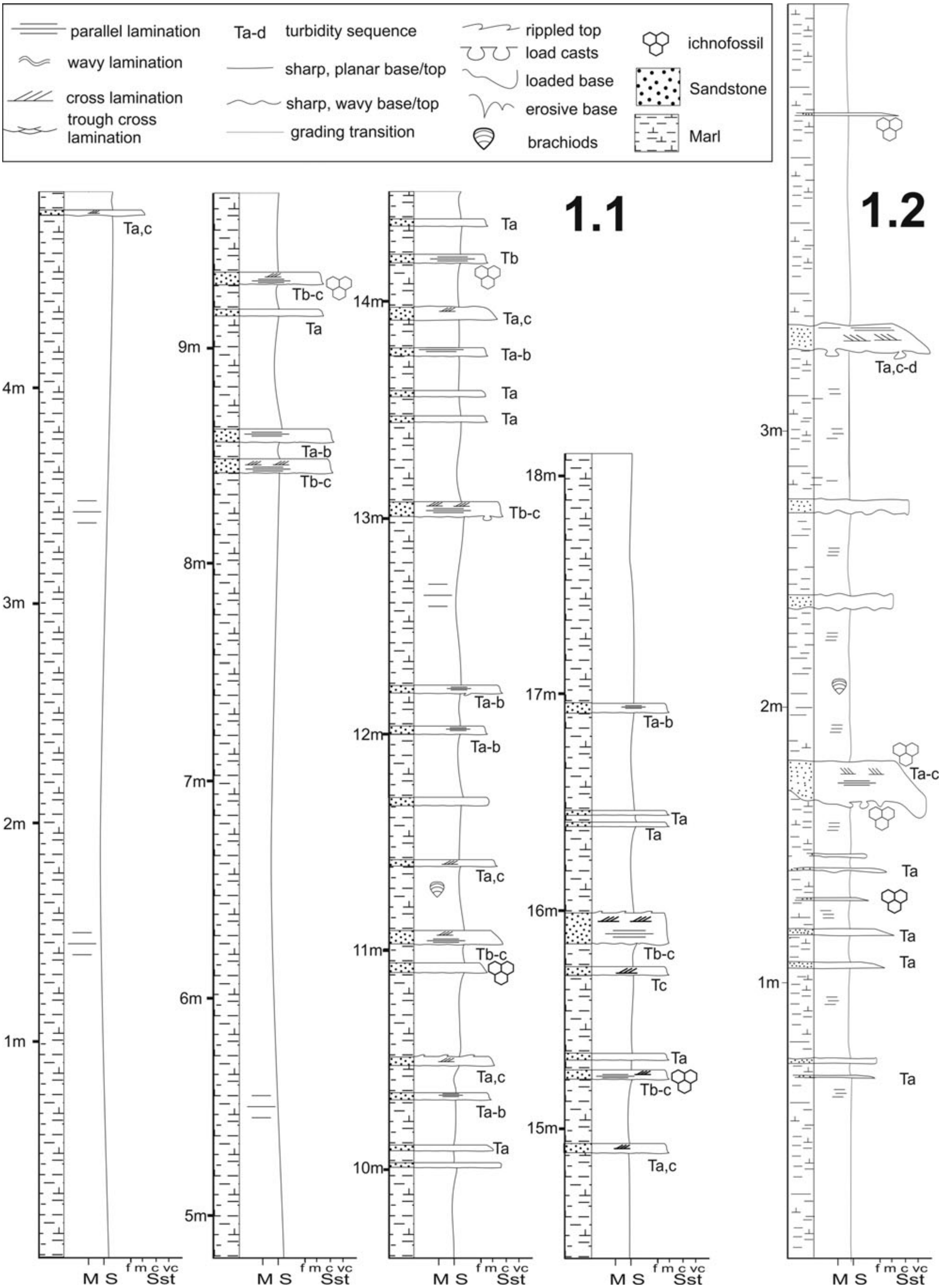

Figure 5. Measured sections of the Abad Member succession. 1.1 and 1.2 – sections within the Almocáizar Corridor (i.e. older Abad deposits). Grain size: M – mud; S – silt; Sst – sandstone (f – fine; m – medium; c – coarse; vc – very coarse). For locations see Figure 3.

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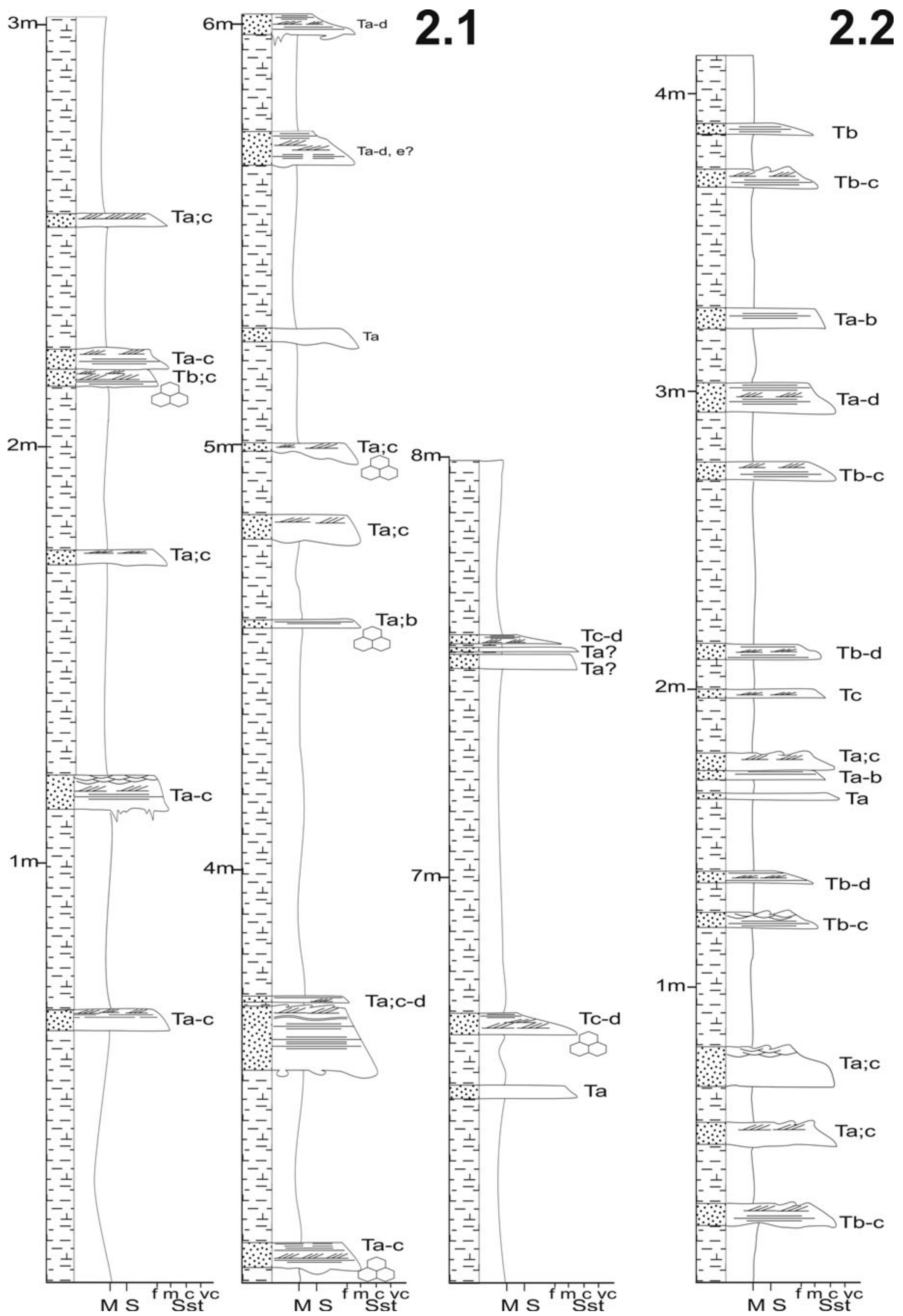

Figure 6. Measured sections of the Abad Member succession. 2.1 and 2.2 – sections from the basin centre (i.e. 2.1 younger Abad deposits and 2.2 Lago Mare deposits). Grain size: M – mud; S – silt; Sst – sandstone (f – fine; m – medium; c – coarse; vc – very coarse). For locations see Figure 3.

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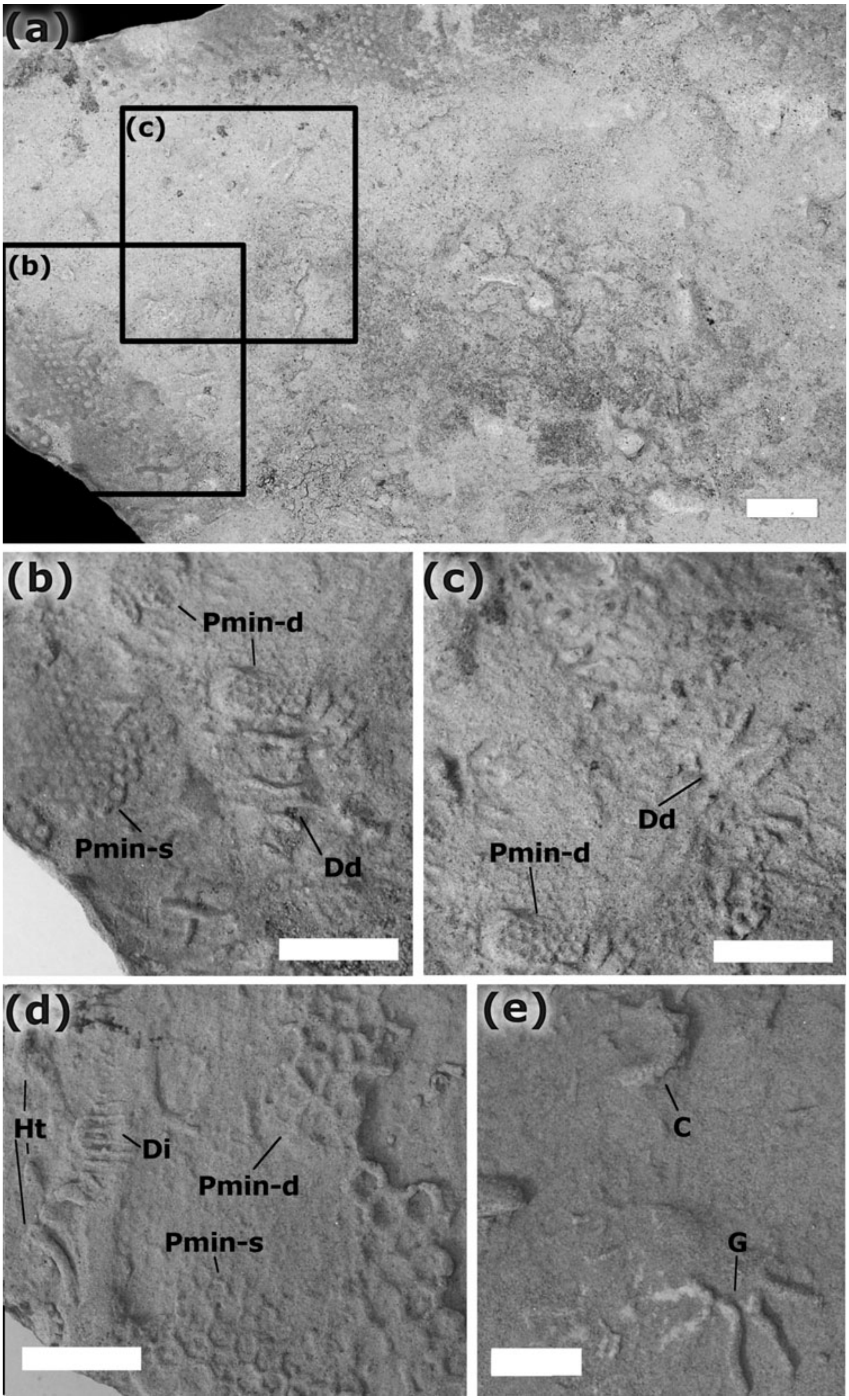

Figure 7. Ichnofossils from the Abad Member, Vera Basin. (a) View of the base of a 2 cm thick, medium-grained sandstone bed showing a variety of ichnofossils preserved in convex hyporelief. These are viewed in more detail in (b) and (c). (b) *Desmograpton dertonensis* (Dd) and *Paleodictyon minimum*, showing both the deep (Pmin-d) and shallow (Pmin-s) forms; (c) deep form of *Paleodictyon minimum* (Pmin-d) and *D. dertonensis* (Dd). (d) *D. ichthyforme* (Di), *Helminthopsis tenuis* (Ht) and *Paleodictyon minimum* preserved as shallow (Pmin-s) and deep (Pmin-d) form in convex hyporelief on the base of a 2 cm thick, medium-grained sandstone. (e) *Glockerichnus alata* (G) and an incomplete specimen of *Circulichnis montanus* (C) preserved in convex hyporelief on the base on the base of a 1.8 cm thick, medium-grained sandstone. Scale bar = 1 cm.

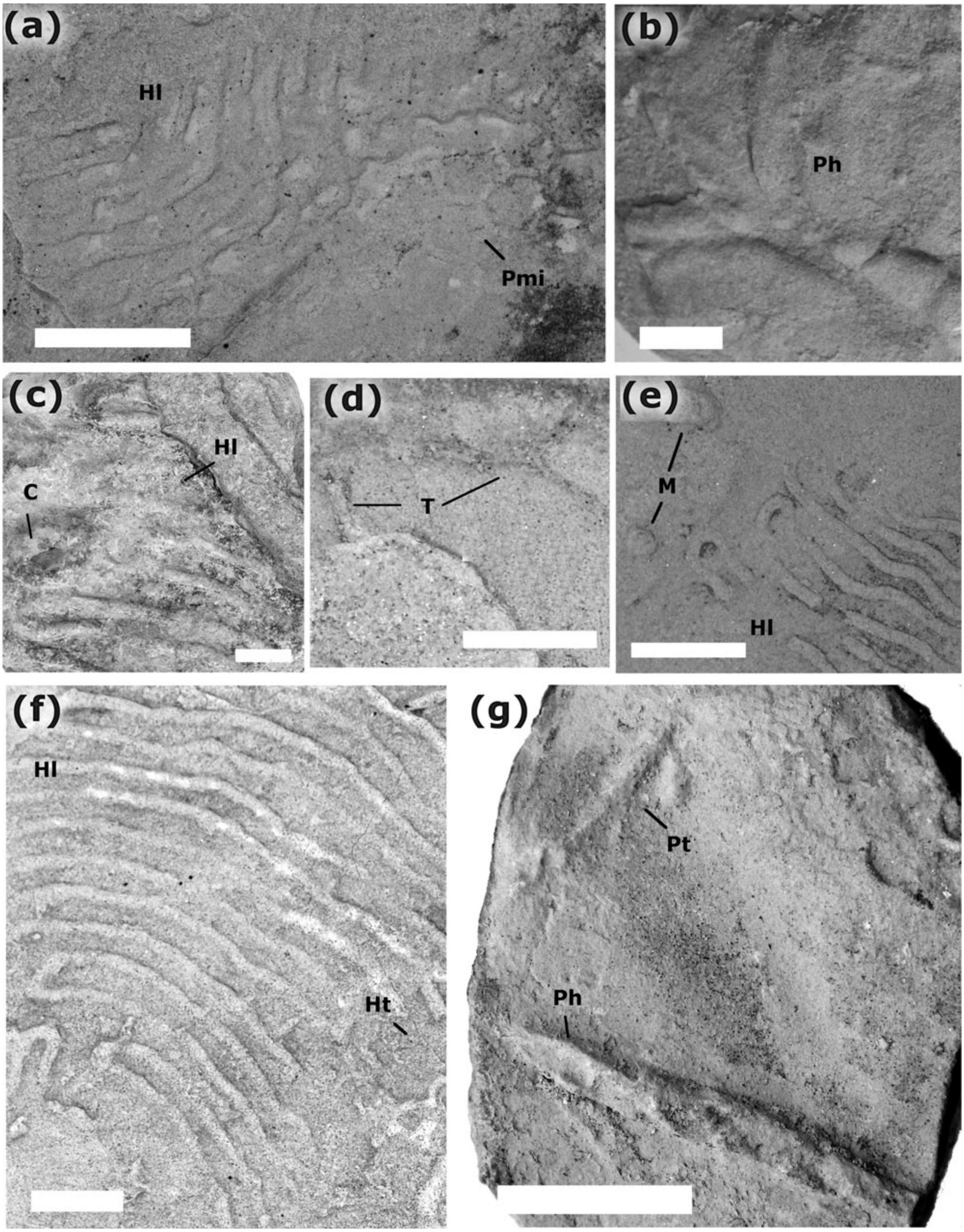

Figure 8. Ichnofossils from the Abad Member, Vera Basin. (a) *Helminthoida labyrinthica* (Hl) and *Paleodictyon miocenicum* (Pmi) preserved in convex hyporelief on the base of a 1.8 cm thick, medium-grained sandstone. (b) *Phycodes bilix* (Ph) and *Palaeophycus tabularis* preserved in convex hyporelief on the base of a 1.1 cm thick, medium-grained sandstone. (c) *Circulichnis montanus* (C) and *Helminthoida labyrinthica* (Hl) preserved in convex hyporelief on the base of a 1.8 cm thick, medium-grained sandstone. (d) *Thalassinoides suevicus* (T) preserved in convex hyporelief on the base of a 3 cm thick, medium-grained sandstone. (e) *Helminthoida labyrinthica* (Hl) and *Mammillichnis aggeris*? (M) preserved in convex hyporelief on the base of a 2.9 cm thick, medium-grained sandstone. (f) *Helminthoida labyrinthica* (Hl) and *Helminthopsis tenuis* (Ht) preserved in convex hyporelief on the base of a 3.4 cm thick, medium-grained sandstone. (g) *Palaeophycus herberti* (Ph) and *Palaeophycus tabularis* (Pt) preserved in convex hyporelief on the base of a 2 cm thick, medium-grained sandstone. Scale bar = 1 cm.

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Remarks. As noted by Uchman (1995, 1998), the ichnotaxonomic and ichnospecies revisions of *Desmograpton* are problematic. His revisions helped to clarify some of the extant problems, but have also resulted in new ones. For example, both *Desmograpton dertonensis* and *D. alternum* contain U- or J-shaped semi-meanders according to the descriptions of Uchman (1998). Indeed, the only difference between them is the presence of the connecting bars, which according to Uchman (1995) are parallel or sub-parallel in *D. dertonensis*, while in *D. alternum* (= *D. geometricum* of Książkiewicz, 1977) they are oblique and form a zig-zag pattern (Uchman, 1995, 1998). However, the illustrations provided by Uchman (1998) of both ichnospecies differ from those illustrated by Seilacher (1977) whose *D. geometricum* (= *D. alternum* of Uchman, 1998, see his fig. 97) appears to be quite different. Seilacher's (1977) *D. inversum* most closely resembles the current sample, termed *D. dertonensis* by Uchman (1998) after the original illustration by Sacco (1888). Thus, while the ichnogenus is still clearly in need of taxonomic revision, the current designation as *D. dertonensis* fits best with the observed features of the samples.

Desmograpton ichthyforme Macsotay, 1967

Figures 7d, 9f, 10c

Material. Five specimens and rarely noted in the field.

Description. Smooth burrow system preserved in convex hyporelief at the base of 1–2.5 cm thick, fine- and medium-grained sandstones which are internally parallel- and cross-laminated (Tab, Tbc, Tcd). Length of the structures range from 1–2.5 cm, with burrow diameters ranging from 0.2–1.5 mm. The narrow, roughly straight and sub-parallel closely spaced (1 mm) string-sized burrows show a clear swelling in the median zone of the individual strings. Occasional transverse links (0.2–1 mm in length) were observed.

Remarks. The samples of the Vera Basin conform to the description of *Desmograpton fuchsi* as described by Książkiewicz (1977) and McCann (1989), and classified as *D. ichthyforme* by Seilacher (1977). The latter author noted the pronounced length of the transverse elements, although this need not be the case (McCann, 1989). The partial review of *Desmograpton* undertaken by Uchman (1995) noted that the name *D. ichthyforme* takes preference over *D. fuchsi*. Although, the transverse links between the burrows in the current examples are barely preserved, the characteristic swelling of the medial zone is present allowing the specimen to be clearly classified as *D. ichthyforme* (cf. Książkiewicz, 1977)

Ichnogenus *Glockerichnus* Pickerill, 1982

Glockerichnus alata Seilacher, 1977

Figure 7e

Material. One specimen.

Description. The 18.1 mm bilateral structure is made up of radially elongated ridges (1.2–1.9 mm in diameter). These ridges are made up of 6 mm wide U-shaped burrows. The smooth burrows are preserved in convex hyporelief on the base of a 1.8 cm thick, medium-grained and internally cross-laminated (Tc) sandstone bed with a rippled top.

Remarks. As noted by Weber *et al.* (2012), several *Glockerichnus* ichnospecies have been described (e.g. Książkiewicz, 1968, 1977; Seilacher, 1977). All of these ichnospecies show the characteristic stellate morphology of *Glockerichnus* where numerous ribs run radially from a diffuse central field, often with dichotomous branching along the distal parts of some of the larger main ribs (Uchman, 1998). Specimens of *Glockerichnus* range from *c*. 15 cm (some of the larger Carpathian examples, e.g. *Glockerichnus glockeri*, Książkiewicz, 1977) down to 2–3 cm (e.g. '*Glockeria*' *parvula* = *Glockerichnus parvula*, Książkiewicz, 1968). The current example, however, contains distinct loops in the central part of the trace, thus more closely resembling *Glockerichnus alata* (= *Glockeria alata* Seilacher, 1977). The main problem, however, is the relative size of the specimens described by Seilacher (1977) and figured in Seilacher (2007). In detail, the ribs are described as having diameters of up to 7 mm, with the entire burrow system having a diameter of up to 50 cm. The current example is considerably smaller. Thus, the assignation may represent an ontogenetic variation of the specimens described by Seilacher (1977) or another ichnospecies. At the present time, however, we choose to suggest that the recorded ichnospecies belongs to *G. alata*.

Ichnogenus *Helminthoid*a Schaufhäutl, 1851

Helminthoida labyrinthica Heer, 1865

Figure 8a, c, e, f

Material. Three specimens and numerous observations in the field.

Description. Smooth meandering burrow preserved in convex hyporelief on the base of 1.9–3.2 cm thick, medium- and fine-grained sandstones, which are internally graded and parallel-laminated (Ta, Tb). The burrow diameters range from 1.3–1.5 mm, and loop separation is 1–3 mm. The burrows show evidence of weak coiling.

Remarks. Helminthoida is a variable ichnogenus (Książkiewicz, 1977) with closely spaced and parallel burrows (Crimes & Anderson, 1985), although they can be extremely variable (Häntzschel, 1975). The observed variety led Książkiewicz (1977) to subdivide the ichnogenus into two groups, although it is doubtful whether such a subdivision is necessary. Additionally, Seilacher (1977) erected the new ichnogenus *Helminthorhaphe* to separate *Helminthoida crassa* Schafhäutl, 1851 from *H. labyrinthica*, which he considered to be preservational variations. Both Crimes, Goldring

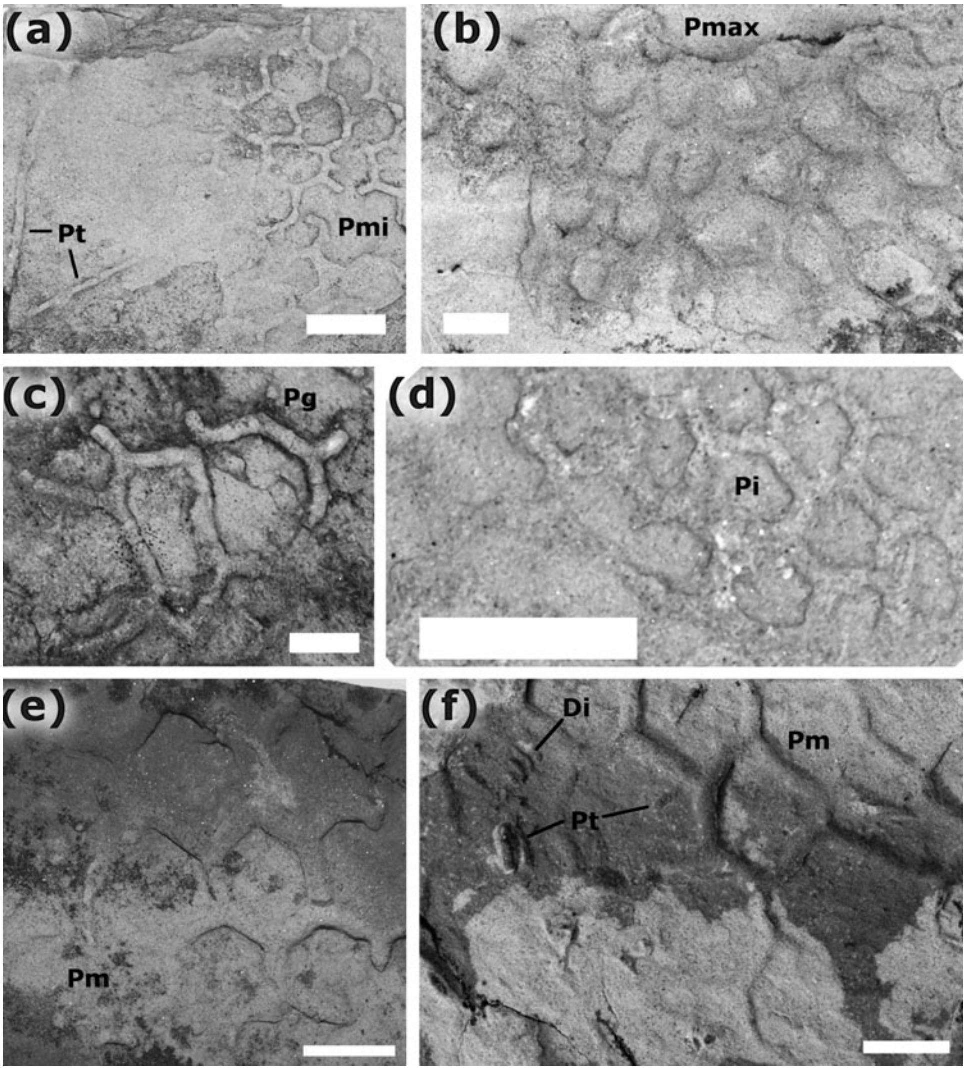

Figure 9. Ichnofossils from the Abad Member, Vera Basin. (a) *Palaeophycus tabularis* (Pt) and *Paleodictyon* (*Glenodictyon*) *miocenicum* (Pmi) preserved in convex hyporelief on the base of a 2.5 cm thick, medium-grained sandstone. (b) *Paleodictyon* (*Glenodictyon*) *maximum* (Pmax) preserved in convex hyporelief on the base of a 3.4 cm thick, medium-grained sandstone. (c) *Paleodictyon* (*Glenodictyon*) *gomezi* (Pg) preserved in convex hyporelief on the base of a 1.5 cm thick, medium-grained sandstone. (d) *Paleodictyon intermedium* (Pi) preserved in convex hyporelief on the base of a 2.4 cm thick, medium-grained sandstone. (e) *Paleodictyon* (*Glenodictyon*) *majus* (Pm) preserved in convex hyporelief on the base of a 1.1 cm thick, medium-grained sandstone. (f) *Desmograpton ichthyforme* (Di), *Palaeophycus tabularis* (Pt) and *Paleodictyon* (*Glenodictyon*) *majus* (Pm) preserved in convex hyporelief on the base of a 2 cm thick, medium-grained sandstone. Scale bar = 1 cm.

& Homewood (1981) and Crimes & Anderson (1985) have discussed this new ichnogenus and deemed it unnecessary. Uchman (1998), in a detailed revision of the collection of Marian Książkiewicz, also noted the problematic nature of the ichnogenus, and assigned *H. labyrintica* to *Nereites irregularis* Schafhäutl, 1851. However, *Nereites* is clearly defined as having a median, back-filled tunnel (core) enveloped by an even to lobate zone of reworked sediment, with commonly only the external part of the mantle being preserved as a densely packed chain of uni- or multi-serial depressions or pustules (Uchman, 1995, 1998). A close reading of the description of *Nereites irregularis* Schafhäutl, 1851 reveals that the burrow comprises a light-coloured core and an indistinct backfill feature, both of which are clearly absent in the present samples, suggesting that the smooth meandering trace of *Helminthoida* is clearly not a *Nereites*. Additionally, Uchman (1998) notes that *Nereites irregularis* occurs mainly in deep-marine, often calcareous planktonic sediments (Seilacher, 1986), which is clearly not the case in the present samples, which are demonstrably turbiditic and siliciclastic. The problematic nature of the ichnogenus, however, remains. In the absence of any real synonymy with *Nereites* and the absence of any real reason to use *Helminthorhaphe*, we prefer to use the general term *Helminthoida* until such time as the genus can be fully revised.

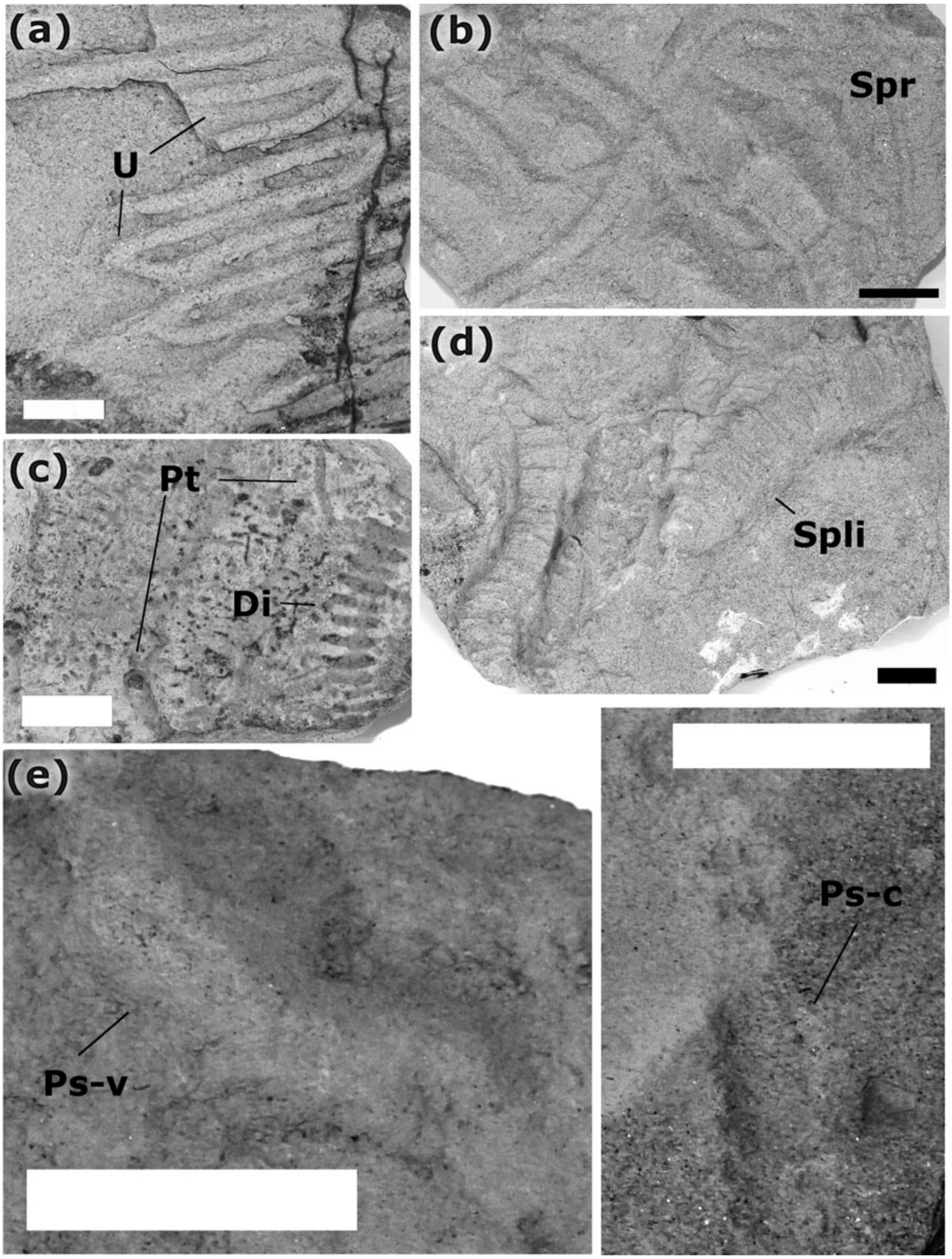

Figure 10. Ichnofossils from the Abad Member, Vera Basin. (a) *Urohelminthoida dertonensis* (U) preserved in convex hyporelief on the base of a 2.2 cm thick, medium-grained sandstone. (b) *Scolicia prisca* (Spr) preserved in convex hyporelief on the base of a 2 cm thick, medium-grained sandstone. (c) *Palaeophycus tabularis* (Pt) and *Desmograpton ichthyforme* (Di) preserved in convex hyporelief on the base of a 1 cm thick, medium-grained sandstone. (d) *Scolicia plana* (Spli) preserved in convex hyporelief on the base of a 2.2 cm thick, medium-grained sandstone. (e) *Palaeophycus serratus* preserved in convex (Ps-v) and concave (Ps-c) hyporelief on the base of a 1.7 cm thick, medium-grained sandstone. Scale bar = 1 cm.

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Ichnogenus *Helminthopsis* Heer, 1877

Helminthopsis tenuis Książkiewicz, 1968

Figures 7d, 8f

Material. Two specimens and rarely noted in the field.

Description. Simple, unbranched, elongate simple tubes (0.9 mm in diameter) with wide, shallow meanders up to 1 cm wide, and narrow but obtuse meanders, up to 4 cm wide. The burrow depth varies from 0.1–0.3 mm. The narrow meanders are slightly deeper than the wider ones.

Remarks. Distinguishing between the two ichnospecies *Helminthopsis tenuis* and *H. abeli* is difficult. Han & Pickerill (1995) considered them synonyms, and in their emended diagnosis noted that the winding style should be considered the main distinguishing feature between ichnospecies of *Helminthopsis*. Uchman (1998) has noted that specimens of *H. tenuis* generally display wide, shallow meanders and deeper, narrow but obtuse meanders, in comparison to the bulging, horseshoe-shaped meanders exhibited by *H. abeli*. The variations in meander form exhibited by the present specimens suggest that they should be classified as *H. tenuis*.

Ichnogenus *Mammillichnis* Chamberlain, 1971

Mammillichnis aggeris? Chamberlain, 1971

Figure 8e

Material. Four specimens and rarely noted in the field.

Description. Hypichnial elliptical mound with a depression in its centre preserved in hypichnial relief on the bases of 1.5–2.0 cm thick laminated sandstones (Ta, Tab, Tb). The structures are 2.8–3.0 mm wide and 2 mm in height.

Remarks. According to Uchman (1998) *Mammillichnis aggeris* is the upper part of a thin vertical or sub-vertical cylindrical burrow. While the elliptical structure, including a central depression, of the samples within the Vera Basin coincides well with the description of Książkiewicz (1977) and Uchman (1998), the size seems to be more problematic. The present specimens are markedly smaller in size than those described by the aforementioned authors, who describe specimens of *Mammillichnis aggeris* ranging from 8–10 mm in diameter and 3–4 mm in height. The present specimens are thus smaller than those described by Książkiewicz (1977) and Uchman (1998), but in terms of their morphology, they conform well with both the ichnogenus and ichnospecies.

Ichnogenus *Palaeophycus* Hall, 1847

Palaeophycus herberti Saporta, 1872

Figure 8g

Material. One specimen and rarely noted in the field.

Description. Smooth cylindrical burrow preserved in full relief on top of a 2 cm thick graded, medium-grained sandstone, with internal parallel- and cross-lamination (Tbc). The burrow, which is straight, is 2.9 mm in height and 4.2 mm in diameter, with the cylindrical inner part eroded and partly collapsed; the central tube is 1.9 mm in diameter

Remarks. The specimen corresponds well with the description of Pemberton & Frey (1982) and Blissett & Pickerill (2004); the internal tube of the specimen is, as noted above, partly collapsed and owing to the poor preservation difficult to distinguish.

Palaeophycus serratus McCann, 1993

Figure 10e

Material. Two specimens and rarely noted in the field.

Description. Straight to slightly winding, lined burrows preserved in convex and concave hyporelief on the base of a 1.7 cm thick, medium-grained sandstone, with internal grading, cross-lamination and with ripples preserved at the top (Tac). The burrows are 4.5–5.3 mm in diameter with an annulation of a maximum 2 per millimetre.

Remarks. The present specimen corresponds well with the description of McCann (1993), who distinguished *P. serratus* from other ichnospecies of *Palaeophycus*. Characteristic for this ichnospecies is the presence of a transverse annulation, which is clearly and consistently observable in both specimens from the Vera Basin.

Palaeophycus tabularis Hall, 1847

Figures 8g, 9a, 10c

Material. Thirty-eight specimens and numerous observations in the field.

Description. Straight to slightly winding, unbranched and smooth burrows on the base of 1.0–2.9 cm thick sandstones, which are medium to very fine grained and internally parallel- and cross-laminated (Tab, Tac, Tacd, Tbc, Tc). The burrows, which are preserved in convex hyporelief, range from 0.7–2.9 mm in diameter and from 0.37 cm to 4.3 cm in length. The burrow fill is identical to that of the host rock; no internal structures are observable.

Remarks: According to Pemberton & Frey (1982), burrows of *Palaeophycus tabularis* can be characterized as branched or unbranched, smooth or ornamented, lined, cylindrical and mainly horizontal trace fossils. This rather broad description demonstrates the diversity of this particular ichnofossil, and is consistent with a variety of specimens in the samples collected from the Vera Basin. *Palaeophycus* is a eurybathic facies-crossing ichnogenus, produced probably by polychaetes (after Pemberton & Frey, 1982).

Ichnogenus *Paleodictyon* Meneghini *in* Savi & Meneghini, 1851

Subichnogenus *Glenodictyon* van der Marck, 1863

Diagnosis. Three-dimensional network ichnofossil consisting of a horizontal net composed of regular to irregular hexagonal meshes and vertical outlets (after Uchman, 1995, 1998).

Paleodictyon (*Glenodictyon*) *gomezi* Azpeitia Moros, 1933

Figure 9c

Material. Three specimens and numerous observations in the field.

Description. Smooth, irregular hexagonal (sometimes pentagonal), very large network preserved in convex hyporelief on the bases of 1.6–2.75 cm thick and internally graded medium- to fine-grained, structureless, parallel- and cross-laminated (Tab, Tac, Tbc) sandstone beds. The strings are 2.0–2.8 mm in diameter and the mesh size ranges from 10.5–20.5 cm.

Remarks. The specimens correspond well with the description of *P. gomezi* of Wetzel (2000), Uchman (1998) and Crimes & McCall (1995) and, in addition, are very similar to the specimens described by Crimes (1977; e.g. his pl. 4c, e, p. 85). According to Wetzel (2000) the penetration depth of this very large type of *Paleodictyon* is distinctly deeper than the normal shallow burrowing depth of *Paleodictyon,* suggesting a positive correlation between the size and the penetration depth of this ichnogenus. This trend corresponds well with the present samples, since *P. gomezi* represents the highest relief in comparison with other traces on the same slab. The maximum depth of *P. gomezi* of the collected samples is 0.58 mm and hence, noticeably greater than any other collected *Paleodictyon* specimens from the Abad Member.

Paleodictyon (*Glenodictyon*) *intermedium* Książkiewicz, 1970

Figure 9d

Material. Eight specimens and numerous observations in the field.

Description. Medium-sized *Glenodictyon* with strings 0.9–1.3 mm in diameter and mesh diameters ranging from 2.2–4.7 mm. These smooth, consistently hexagonal networks are preserved in convex hyporelief on the bases of 1.8–3.2 cm thick, medium- to fine-grained sandstones, with evidence of internal grading, as well as internal parallel- and cross-lamination (Tab/Ta,c/Tbc).

Remarks. Ichnospecies of *Paleodictyon* are assigned on the basis of mesh size and string diameter. Accordingly, the current specimens, with their mesh width of 2.2–4.7 mm and string diameters of 0.9–1.3 mm, can be classified as *Paleodictyon* (*Glenodictyon*) *intermedium*. This is based on the dimension values provided by Książkiewicz (1977) in his table 16. In the accompanying descriptions, however, Książkiewicz (1977) notes that *P. intermedium* generally have regular hexagonal-shaped meshes and that the overall size of the ichnofossil rarely exceeds *c.* 5 cm². These latter features aid in distinguishing between *P. intermedium* and *P. latum* (given that there is a small degree of overlap between the two ichnospecies, as noted in his table 16). Uchman (1998), in his review of Książkiewicz's material, included *P. intermedium* under *P. strozzii.* However, Książkiewicz (1977) clearly distinguished between the ichnospecies *P. strozzii* and *P. intermedium* on the basis of their size, noting that the former is distinctly larger (mesh sizes in *P. strozzii* range from 2.5–5.5 mm and riblets between 0.3 and 1.0 mm, whereas in *P. intermedium* they are 2.0–3.5 mm and 0.5–1.0 mm, respectively). However, Książkiewicz (1977) also noted the degree of irregularity in terms of mesh morphology between *P. strozzii* and *P. intermedium*, with the former showing a range of different mesh forms ranging from roughly hexagonal, pentagonal or rhomboidal or even elongated in one direction. Uchman (1998), however, considered that *P. intermedium* was a junior synonym of *P. strozzii*. This, however, is clearly not the case (based on the original descriptions of Książkiewicz, 1970, 1977), and we herein assign the current specimen to *P. intermedium*.

Paleodictyon (*Glenodictyon*) *majus* Savi & Meneghini, 1851

Figure 9e, f

Material. Two specimens and several observations in the field.

Description. Six-sided netlike structures preserved in convex hyporelief at the base of 0.6–2.5 mm thick sandstones. Internally, the sandstones show evidence of grading, parallel-lamination and cross-lamination (Tab, Tbc). Strings are 1.5–2.0 mm in diameter and mesh diameters range from 10–15 mm.

Remarks. *Paleodictyon majus* was originally named in Savi & Meneghini (1851), although neither illustration nor description were provided. However, both De Stefani (1879) and Peruzzi (1880) noted that Savi & Meneghini (1851) were the authors of this form, and as Książkiewicz (1977) writes, it was probably noted in a collection but not described in detail. Indeed, the first written description was by Peruzzi (1880). *Paleodictyon majus* can be distinguished from *P. tauricum* on the basis of its thinner riblets.

Paleodictyon (*Glenodictyon*) *maximum* Eichwald, 1868

Figure 9b

Material. Two specimens and several observations in the field.

Description. Smooth, six-sided netlike structures with meshes ranging in size from 0.54–1.18 cm, while the strings range in diameter from 2.6–4.3 mm. The traces are preserved in convex hyporelief on the bases of 2.0–4.3 cm thick, medium- to coarse-grained, structureless or graded, parallel and cross-laminated (Tac) sandstone beds.

Remarks. The dimensional values of the current specimen accord most closely with those of *Paleodictyon maximum*, which according to Uchman (1998)

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comprises *Glenodictyon* morphologies with riblets of up to 2.8 mm (i.e. smaller than the current specimens) and mesh sizes of up to 1.4 cm (again smaller than the current specimens). The Vera Basin specimens can be distinguished from *Paleodictyon gomezi* on the basis of its larger mesh size (> 4.0 cm).

Paleodictyon (*Glenodictyon*) *miocenicum* Sacco, 1888

Figure 9a

Material. Two specimens and rarely noted in the field.

Description. Six-sided netlike structure preserved in hypichnial relief at the base of 1.2–2.9 cm thick normally graded, medium- to very fine-grained sandstones beds. Internally, parallel- and cross-lamination (Tacd, Tbc) were also noted. Strings are *c.* 1.0 mm in diameter, with some swelling noted in the middle, while the mesh diameter is 5–7 mm.

Remarks. The samples from the Vera Basin coincide well with the descriptions provided by Książkiewicz (1977). However, the present samples do not show any evidence of tubercles in the mesh centres (e.g. the crossing points of the burrows within the network), which are noted as characteristic of *P. miocenicum* by Książkiewicz (1977). This particular feature, however, was not deemed to be of sufficient importance in the assignation of the ichnospecies.

Paleodictyon (*Glenodictyon*) *minimum* Sacco, 1888

Figure 7b–d

Material. Four specimens and several observations in the field.

Description. Smooth, netlike trace fossil preserved in convex hyporelief on the bases of 2.0–2.5 cm thick, medium-grained sandstone beds, with evidence of normal grading and parallel-lamination (Tab). This very small *Glenodictyon* consists of strings which are 0.4–0.5 mm in diameter while the mesh diameters range from 0.5–0.7 mm. Two specimens are preserved in highly convex and prominent hyporelief, resulting in a protruding plate-like appearance.

Remarks. The samples from the Vera Basin coincide well with the descriptions provided by Uchman (1995). According to Seilacher (1977, 2007), *P. minimum* is typically distinguished by the presence of clear burrow systems, which are deeper than those of other *Paleodictyon* species, leading to the formation of a particularly prominent network. Monaco (2008) qualified this characterization suggesting that there are two types of *P. minimum,* namely a shallow and a deep type. Both of these types are recognizable in the samples from the Vera Basin.

Ichnogenus *Phycodes* Richter, 1850

Phycodes bilix Książkiewicz, 1977

Figure 8b

Material. One collected specimen and rarely noted in the field.

Description. Bundled and branching burrows (i.e. flabellate), occasionally falcate on the top of 0.9–1.1 cm thick, medium-grained sandstone beds with internal cross-lamination. The burrows are up to 1 cm in diameter, branching from a central burrow into, up to three, slightly curved burrows separated from the main burrow at angles of *c.* 50°. Occasionally the edges of the burrows are elevated, leading to the formation of a median depression.

Remarks. Although Han & Pickerill (1994) provided a detailed overview of this ichnogenus, Uchman (1998) has noted the need for ichnogeneric reform, suggesting that Książkiewicz's (1977) *Butholrephis bilix* should be included in the *Phycodes* ichnogenus. Comparing the current specimens with the illustrations provided by both Han & Pickerill (1994) and Uchman (1998) would suggest that the current specimen best conforms to the ichnospecies *P. bilix* on the basis of the median depression observed in the samples from the Vera Basin. This depression was also described by Książkiewicz (1977; i.e. *Butholrephis bilix*) and Uchman (1998), with partial collapse of the thick-walled burrows being suggested as the cause of the central depression.

Ichnogenus *Scolicia* de Quatrefages, 1849

Scolicia prisca de Quatrefages, 1849

Figure 10b

Material. Four samples and rarely noted in the field

Description. Tripartite winding trails or burrows, broadly U-shaped in transverse section, preserved in concave epirelief on the surface of 1.5–2.0 cm thick, cross-bedded and medium-grained sandstone beds (Tc). The median ridge, which is 3–5 mm in width, is convex and ribbed (10–11 ribs per centimetre). The ridge is bordered by two concave furrows, which are up to 2 mm deep and have a width of 0.9–1.8 mm. In parts, asymmetrical and looser packed ribs (5–6 ribs per cm) are preserved along the outer slope/margins of the trails/burrows.

Remarks. The samples from the Vera Basin compare well with the *Scolicia prisca* descriptions provided by Książkiewicz (1977) and Uchman (1998). However, the ribs are weakly developed in the current specimens, which may be a result of preservation. Despite this, the samples include the main characteristics of *S. prisca* (i.e. fine, packed transverse ribs along the median lobe and looser asymmetrical ribs along the slopes/margins, cf. Uchman, 1998).

Scolicia plana Książkiewicz, 1970

Figure 10d

Material. Three samples collected and rarely noted in the field.

Description. Three-lobed trace containing deep marginal grooves. The flat median lobe is 6–9 mm in width, while the grooves range from 2.1–2.4 mm in width. The median lobe is ridged, with 8 ribs/cm present. Ribs are slightly concave to straight and oriented at 90° to the axis of the trail. A second form is also trilobate, albeit with shallow marginal grooves. The flat median lobe is 9–10 mm in width, while the grooves are 3–6 mm in width. The ribs are straight (10/cm) and oriented at 90° to the axis of the trail. Both forms are epichnial on the top of 1.9–2.2 cm thick, medium-grained and normally graded sandstones. Internally, the sandstones show evidence of cross-lamination (Tc).

Remarks. Książkiewicz (1977) noted that there was a degree of variability in this ichnospecies, suggesting that there were two forms. His ‘Form A’ comprises an epichnial trilobate furrow with a low flat median lobe, densely striated and bordered by less densely ribbed fringes. The median lobe may be bordered by narrow rims and longitudinally transected by a narrow trench (Książkiewicz, 1977). ‘Form B’ is similar, although lateral strings are present (Książkiewicz, 1977). The lack of these lateral strings suggests that the forms present within the Vera Basin conform to Książkiewicz’s ‘Form A’. In the illustration of the morphologies which occur within ‘Form A’, Książkiewicz (1977) notes morphologies with both deep and shallow marginal grooves, both of which occur in the *Scolicia plana* specimens from the Vera Basin.

Ichnogenus *Thalassinoides* Rieth, 1932

?*Thalassinoides suevicus* Rieth, 1932

Figure 8d

Material. One collected specimen and rarely noted in the field.

Description. Horizontal and smooth trace preserved in a convex hyporelief on the base of a 3 cm thick, parallel- and cross-laminated (Tbc) medium- to fine-grained, normally graded sandstone. The Y-shaped burrow is 1.6 mm in diameter and 16 mm in length. It is enlarged (to 2.2 mm) at the point of bifurcation.

Remarks. The sample from the Vera Basin coincides well with the *Thalassinoides* descriptions of Uchman (1998) and Carvalho, Viegas & Cachão (2007). It is noticeable, however, that the present specimens are distinctly smaller than those described by Uchman (1998; i.e. 5–30 mm in diameter), but, Carvalho, Viegas & Cachão (2007) noted that the size of *T. suevicus* can vary markedly (up to 110 mm in diameter) without providing a minimum size.

Ichnogenus *Urohelminthoida* Sacco, 1888

Urohelminthoida dertonensis Sacco, 1888

Figure 10a

Material. One collected specimen and numerous observations in the field.

Description. Convex hyporelief on a 2.2 cm thick, medium-grained, normal-graded sandstone with internal parallel- and cross-lamination (Tbc). The trace is preserved as a string-sized (2.3 mm in diameter) meandering form. Lateral appendages are up to 10.7 mm in length and pass straight into one arm of the meander, while an angle (*c.* 50°) to the second arm is present.

Remarks. The samples of the Vera Basin are consistent with the description of *Urohelminthoida dertonensis* by Uchman (1995, 1998) and Książkiewicz (1977).

Table 1. Relative frequencies of the ichnogenera from the Abad Member of the Vera Basin

	Location			
Ichnogenus	I	II	III	IV
Circulichnis		x	*x*	
Desmograpton	*xxx*	*x*		
Glockerichnus		*x*		
Helminthoida	*x*	*x*	*xx*	*x*
Helminthopsis	*x*			*x*
Mammillichnis		*x*		
Palaeophycus	*xxxx*	*xxxx*	*x*	*xxx*
Paleodictyon	*xxxx*	*xxxx*	*xx*	*xx*
Phycodes		*x*		
Scolicia		*x*		*xx*
Thalassinoides	*x*			
Urohelminthoida		*x*		

Frequencies range from rare (x) through to relatively abundant (xxxxx).

4.a. Ichnofossil distribution

In total 12 ichnogenera, comprising 21 ichnospecies were recognized from the sedimentary succession in the southern part of the Vera Basin. The ichnoassemblages clearly belong to the Nereites ichnofacies (Seilacher, 1977, 2007), given that they contain many classic ichnogenera (e.g. *Desmograpton, Helminthoida, Helminthopsis*, *Paleodictyon*, *Scolicia* and *Urohelminthoida*) typical of deep-marine settings (e.g. Książkiewicz, 1977; Seilacher, 2007; Uchman, 2007; MacEachern *et al.* 2012). As noted above, the Abad Member extends across the southern and central parts of the basin. The ichnofossil assemblages collected from these two areas differ in terms of both the ichnogenera and ichnospecies present (Tables 1, 2). While the southern area contains mainly *Desmograpton dertonensis, D. ichthyforme, Paleodictyon minimum* and *Urohelminthoida dertonensis*, the central area is generally characterized by *Paleodictyon maximum* and *Scolicia plana*. However, in the northern part of the central region (Fig. 3c, location of profiles 2.1 and 2.2), all traces of biological activity disappear. This apparent absence of bioturbation occurs both in the complex ichnogenera (e.g. *Desmograpton, Paleodictyon*, *Scolicia* or *Urohelminthoida*), as well as in the relatively common and simple ichnogenera (e.g. *Palaeophycus*). The precise reasons for this will be discussed below.

5. Discussion

The Abad Member crops out in the Vera Basin, extending from the southern basin margins where it

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Table 2. Relative frequencies of the ichnospecies from the Abad Member of the Vera Basin

Ichnospecies		Location *I*	*II*	*III*	*IV*
Circulichnis	*montanus*		*x*	*x*	
Desmograpton	*ichthyforme*	*xxx*	*x*		
	dertonensis	*x*			
Glockerichnus	*alata*		*x*		
Helminthoida	*labyrinthica*	*x*	*x*	*xx*	*x*
Helminthopsis	*tenuis*	*x*			*x*
Mammillichnis	*aggeris ?*		*x*		
Palaeophycus	*herberti*		*x*		
	serratus			*x*	
	tabularis	*xxxxxx*	*xxxxxx*		*xxx*
Paleodictyon (*Glenodictyon*)	*maximum*				*x*
	majus	*xx*			
	miocenicum	*x*	*x*		
	gomezi	*x*		*xx*	
	intermedium	*xxx*	*xxx*		*x*
	minimum	*xxx*			
Phycodes	*bilix*		*x*		
Scolicia	*prisca*		*x*		
	plana				*xx*
Thalassinoides	*suevicus*	*x*			
Urohelminthoida	*dertonensis*		*x*		

Frequencies range from rare (x) through to relatively abundant (xxxxx).

interdigitates with the shallow-marine sediments of the Azagador Member through to the central parts of the basin. There is also a corresponding increase in member thickness from the margins through to the basin centre. As noted above, the Abad Member is dominated by marls, with medium- to coarse-grained sandstones concentrated in the southern parts of the basin (i.e. Almocáizar Corridor, which is also the stratigraphically oldest part of the Abad Member, as suggested by field mapping), while fine- to medium-grained sandstones characterize the central parts of the basin.

5.a. Palaeoenvironmental setting

The palaeoenvironmental setting of the Abad Member can be examined from two perspectives: (1) the sediments, and (2) the ichnoassemblages. Both provide important and useful information for the characterization of the depositional setting. As noted above, the sandstone beds of the Abad Member can be uniformly described according to the Bouma (1962) scheme, and can thus be termed classical turbidites (albeit thinner Ta-c, Tbc turbidites, i.e. Facies C2.2, 2.3 of Pickering *et al.* 1986). The presence of sandstone turbidites records the depositional passage of turbidity currents, which can be found in a variety of areas, including deep-marine settings, ramps or slope aprons but also in lacustrine settings (e.g. Stelting, Bouma & Stone, 2000; Mulder & Alexander, 2001; Talling *et al.* 2012; Moernaut *et al.* 2014; Pickering & Hiscott, 2015). Thus, while the presence of turbidites does not automatically imply a deep-marine setting, the presence of interdigitated muddy to silty structureless marls and associated marine fossils (e.g. microfauna, macrofauna, ichnofauna) would suggest a marine setting for the sediments of the Abad Member. Indeed, the relative thicknesses of the turbiditic sandstone beds would imply a broadly distal setting, although whether this can be classified and integrated into an existing submarine fan model (e.g. Pickering *et al.* 1986; Mulder & Alexander, 2001; Talling *et al.* 2012; Pickering & Hiscott, 2015) is questionable.

Based on the ichnofossils present, the sediments of the Abad Member are considered to have been deposited in a setting represented by the classical Nereites ichnofacies (cf. Seilacher, 1964), with a mixture of facies-crossing and facies-controlled ichnogenera present. Seilacher (1964) introduced the concept of ichnofacies, using them to reconstruct specific palaeoenvironmental conditions, with the Nereites ichnofacies representing a deep-marine depositional environment. In detail, this ichnofacies is characterized by the ethologies of the trace-producing organisms and their related trophic styles. These styles are described as complex grazing and patterned feeding or dwelling structures. They occur below the sediment/water interface, and form as a result of organized and efficient feeding strategies (c.f. table 1 of MacEachern *et al.* 2012). These features result in the formation of a suite of characteristic traces that represent the ichnofacies (i.e. graphoglyptids: meanders and networks). The majority of the ichnogenera present within the Abad Member (e.g. *Desmograpton*, *Glockerichnus*, *Helminthoida*, *Helminthopsis*, *Paleodictyon*, *Scolicia* and *Urohelminthoida*) are considered to be characteristic for the Nereites ichnofacies (Seilacher, 1964, 2007; Leszczyński & Seilacher, 1991; Uchman, 2007; MacEachern *et al.* 2012; Uchman & Wetzel, 2012). Additionally, the interpreted palaeoenvironmental conditions as determined by the detailed analysis of the sedimentary facies and facies associations within the Abad Member (i.e. muddy to silty marls with interstratified sandy turbidites) would support, the typical conditions of such environments (i.e. muddy sediments as a result of very slow sedimentation with intercalated sandy turbidites; MacEachern *et al.* 2012). Thus, a possible depositional setting within a lower slope or basin floor environment (and related fan/lobe system) would successfully integrate both the sedimentary and ichnological observations (cf. MacEachern *et al.* 2012).

The Nereites ichnofacies has been revised by a number of workers (e.g. Seilacher, 1977; Uchman, 2001, 2007; Heard & Pickering, 2008; Knaust, 2009; Uchman & Wetzel, 2012) who subdivided it into three sub-ichnofacies (*Nereites, Paleodictyon* and *Ophiomorpha rudis*) based primarily on the lithological characteristics within the individual environmental settings. This subdivision allows more subtle ichnoassemblages to be recognized and classified, and in particular it better reflects the bathymetric differentiation of a typical deep-sea fan system (i.e. inner to outer fan) as well as lateral changes within such a system (i.e. interchannel areas, channel axis, levee and overbank deposits; cf.

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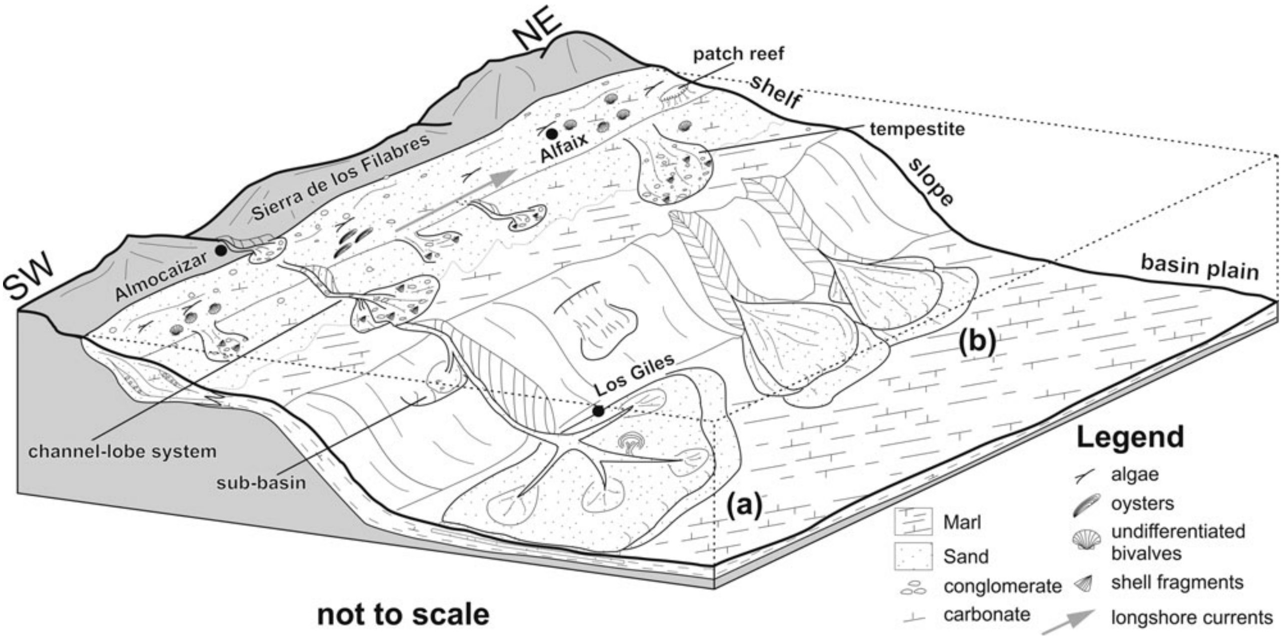

Figure 11. Block diagram reconstructing the depositional setting of the Almocáizar Corridor, Vera Basin (SE Spain) in early Messinian times. This schematic model illustrates the palaeogeography at this time, with the Sierra de los Filabres located in the north, and the shelf/slope/deep-marine areas located further south. Two possible scenarios are envisaged: (a) where a channel-fan system developed downcurrent of a shelf/slope channel system, and (b) a detached lobe system developed basinwards of the narrow shelf with sediment supplied from turbidity currents generated by storms on the shelf. Additionally, a third model would combine aspects of these two scenarios (see text for details). (Shelf morphology and facies modified after Martín *et al.* 2012).

Seilacher, 1977; Uchman, 2001, 2007; Heard & Pickering, 2008; Knaust, 2009; Uchman & Wetzel, 2012).

The ichnoassemblages present within the Abad Member, together with the sedimentary successions, suggest a depositional setting corresponding to the Paleodictyon sub-ichnofacies (i.e. medium- to thin-bedded sandstone turbidites in a mud-rich succession; cf. Uchman & Wetzel, 2012), and suggest an intermediate setting in terms of both bathymetric and lateral differentiation of the Nereites ichnofacies. Such a setting could include overbank, interchannel, interlobe or distal depositional-lobe environments (Wetzel & Uchman, 1997; Uchman, 2007; MacEachern *et al.* 2012; Uchman & Wetzel, 2012).

However, the absence of obvious channel sediments (both, main or distributary channel) in the outcrop area, suggests a possible depositional-lobe-type setting. The palaeogeographic setting of the Almocáizar Corridor, and its extension into the Vera Basin, is that of a mixed siliciclastic–carbonate shelf extending into a deeper-marine environment (Fig. 11). The shelf is oriented E–W and has been classified as relatively narrow, with the shelf-slope break located close to the shoreline (cf. Braga, Martín & Wood, 2001; Martín *et al.* 2012). In this respect, it was probably similar to other published examples of narrow shelf areas (e.g. the Oligocene of New Zealand, Carter & Lindqvist, 1975; present-day Albany Shelf, Australia, James & Bone, 2010). Along the northern margin of the shelf (i.e. Sierra de los Filabres) coastal (including beach systems) and inner-platform sediments were deposited, while small deltas also formed along the coast (e.g. in the area of Almocáizar; Braga, Martín & Wood, 2001; Martín *et al.* 2012). In areas where delta development is marked, the shelf is more clastic (with sediment also being transported parallel to the shoreline by ENE-directed longshore currents), whereas away from the areas of delta formation, the shelf sediments are mixed (i.e. carbonate/siliciclastic).

The coastal systems prograded southwards into shallow shelf deposits, comprising a mixed siliciclastic–carbonate succession, which has been interpreted in terms of a ramp (with distal steepening; Martín *et al.* 2012) or platform (Braga, Martín & Wood, 2001) system. Subaqueous sand-filled channels (Fig. 11) cross-cutting the inner-platform sediments, and located at the mouths of fluvial systems, have also been noted (Braga, Martín & Wood, 2001; Martín *et al.* 2012). Areas adjacent to these channels were presumably subjected to bypass, with sediment being transported across the narrow shelf and deposited along the shelf-slope break, or indeed, being directly transported into deeper-marine areas (i.e. the area forming the subject of this study). Braga, Martín & Wood (2001) suggested that lobe deposits in the deeper-marine area are fed by sediment originating in the Sierra de los Filabres (based on clast analysis) and transported across the shelf.

However, the preserved submarine channel/lobe systems described above (i.e. from Braga, Martín & Wood, 2001) do not appear to be correlatable with the turbidites described as part of this study. Certainly, there are problems both with regard to (a) the precise location (i.e. Braga, Martín & Wood, 2001 describe

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lobes from the area to the south of Turre, see Fig. 3 for location, whereas the present lobes occur in the area of the Almocáizar Corridor), and (b) the stratigraphic position (i.e. the lobes described by Braga, Martín & Wood, 2001 would appear to be younger in age and to have been deposited in a shallower marine setting). In addition, these lobes appear to be smaller in scale and they comprise mainly coarse-grained sediments (sandstones, conglomerates). The lobes in the present study are composed of finer-grained sediments (sandstones). Additionally, there would appear to be a clear correlation between the channels, extending from the fluvial systems north of the Almocáizar Corridor and crossing the narrow shelf, and the deep-marine lobes to the south. This would suggest that the lobes of the Almocáizar Corridor region were directly fed from erosion of the Sierra de los Filabres, with sediment being transported across the shelf and deposited seawards of the shelf-slope break (Fig. 11).

Two hypotheses are proposed for the precise depositional setting of the Almocáizar lobes. In the first situation (Fig. 11a), sediments were transported down the slope via a submarine channel leading to the establishment of a small mud-rich channel-fan system (cf. Richards, Bowman & Reading, 1998). In such a system, a number of features would be anticipated including, for example, clear proximal–distal changes, the presence of a range of turbiditic facies, as well as clear evidence of channelization within the channel-fan system. However, as noted above, the sediments in the Almocáizar Corridor area do not contain evidence of any of these features. The fact that a pronounced channel system was developed on the shelf would certainly suggest that at the shelf-slope break the system would extend basinwards into the deep-marine area. The absence of any evidence of a channel-fan system in the deep-marine parts of the basin does not imply that it never existed, but rather that it was, not preserved or that the current outcrop situation is not extensive enough to allow full recognition of the entire system.

A second option (Fig. 11b) is that the shelf channel system played a minor role, in that the sediments were transported from the coastal areas and deposited in the outer shelf area. In such a scenario, storms on the narrow shelf would have resulted in the generation of slope aprons, and associated turbidity flows, transporting the sediment into the deep-marine area and resulting in the formation of lobe deposits. These lobes, detached from a direct source, would have been formed from individual turbidity currents generated in the shelf/slope region. The fact that the lobes in the present study are generally of similar grain size would suggest pre-sorting in the source area of the transported sediment, an aspect which might correlate with outer shelf deposition. Indeed, the presence of tempestites in the shelf area would support the idea of storm-generated sediment bodies on the shelf.

An alternative option (in addition to the two described above) is that the lobes were produced by a combination of both models, i.e. possible channelization on the slope but with the development of detached lobes, rather than a channel-fan system (i.e. Fig. 11a), coupled with detached lobes developing from slope aprons generated by storm deposits on the shelf (i.e. Fig. 11b). In such a system, the emphasis would be on the lobe morphology and composition (i.e. lobate forms extending basinwards of the slope; finer-grained sediments) rather than the direct presence of feeder systems. The current outcrop situation, however, does not allow any one model to be favoured.

5.b. Bathymetry of the Abad Member

As noted above, the succession is dominated by turbiditic sandstones and marls, although the presence of the former says nothing definitively per se about absolute depths in the depositional area. Seilacher's (1964) ichnofacies, while useful for generalized water depth determinations in the fossil record, are, however, not always directly applicable and, indeed, may lead to a false interpretation (e.g. Fürsich, Taheri & Wilmsen, 2007). MacEachern *et al.* (2012) have suggested that neo-ichnology plays an important role in determining precise depth ranges (or maxima) for organisms in particular settings. For example, *Helminthoida*-like traces have been recorded at depths of 5248 m from the Japan Trench (Fujioka *et al.* 1987), while *Scolicia*-like trails have been noted from 3830 m from the Taira deep-sea fan and from 3835 m from the Tenryu deep-sea fan (Fujioka *et al.* 1987). The possible water depths at which these organisms can exist, therefore, are deep. While similar water depths for the Abad Member are not probable (based on palaeogeographical evidence, see below), it does suggest that similar conditions (e.g. very low energy and related slow rates of deposition) can be presumed. When extrapolating to the fossil record, however, the problematics of depth determination become more obvious. While estimated bathymetries are, at best, imprecise, some ichnofossils (particularly those considered to be facies-controlled, e.g. *Desmograpton*) can be used to provide rough depth estimates of the depositional setting.

As noted above, ichnofacies models have been determined on the basis of trace-fossil morphology, and this is controlled by the feeding behaviour of the trace-producing organisms (Książkiewicz, 1977). Thus, the pattern of the traces and their complexity is dependent on the amount of food available within the sediment. Consequently, with increasing depth a decrease in nutrient availability can be generally assumed (e.g. Thibodeau *et al.* 2010; Moore *et al.* 2013), resulting in the development of more complex trace patterns (e.g. graphoglyptids or networks; Książkiewicz, 1977; Seilacher, 1977, 2007; Uchman & Wetzel, 2012). Furthermore, the type of sediment (e.g. turbidites or deep-sea muds) and the composition of the water (e.g. oxygenation levels) may influence both the form and amount of nutrients present within the sediments of the deep sea. These variations

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may be independent of depth, thus suggesting that palaeobathymetric reconstructions need to take a number of factors into account and not just the morphology of the particular ichnofossils. Additionally, with the Nereites ichnofacies broadly considered to represent 'deep-marine' settings, there is an increasing body of work which suggests otherwise (e.g. Häntzschel, 1975; Ernst & Zander, 1993; Fürsich, Taheri & Wilmsen, 2007). *Paleodictyon*, for example, has been reported from shallow-marine locations in the Lower Palaeozoic (Stanley & Pickerill, 1993), while Gierlowski-Kordesch & Ernst (1987) and Ernst & Zander (1993) have reported it in Upper Cretaceous-age midshelf deposits where it was associated with other ichnofossils considered typical of the Nereites ichnofacies (e.g. *Cosmorhaphe*, *Spirorhaphe*, *Urohelminthoida*). Other evidence for comparatively shallow-marine *Paleodictyon* has been provided by Hantzpergue & Branger (1992), who reported the ichnofossil from an upper Oxfordian limestone unit which they suggested was deposited at a depth of not > 100 m. Depths of 200–300 m have been suggested by Uchman, Janbu & Nemec (2004) from the Cretaceous–Eocene-age central Pontides of Turkey. Considered together, these data question the assumption that the Nereites ichnofacies can always be considered as 'deep marine'. Indeed Fürsich, Taheri & Wilmsen (2007) have gone further, suggesting that the bathymetric range of *Paleodictyon* was wider than generally assumed, and that its dominance in deep-marine turbiditic successions is at least partly a preservational effect. Furthermore, Fürsich, Taheri & Wilmsen (2007) suggested that bathymetric interpretations are best made on the basis of complete ichnoassemblages rather than single ichnogenera/ichnospecies.

This approach, i.e. using complete ichnoassemblages, but also combining them with other factors, was used by Książkiewicz (1977) in order to provide a broad bathymetric range for a series of particular ichnospecies found within Cenozoic-age sediments (and which are comparable with the samples from this study). According to these results, the palaeobathymetry of the Abad Member would fall within the epibathyal zone (200–600 m of Książkiewicz, 1977; cf. his table 11) and extending down to the onset of the mesobathyal zone (600–1000 m of Książkiewicz, 1977; cf. his table 11; p. 40). Interestingly, the water depth estimates suggested by the foraminiferal assemblage present within the Abad Member correlate well with those of the ichnofossils. Baggley (2000) analysed foraminiferal assemblages (predominantly benthic) from several sections within the Sorbas Basin and the Almocáizar Corridor (connecting the Sorbas and Vera basins, and overlapping with the sampling location (I) of this study, Fig. 3a). Nine samples were collected from an 84.5 m thick section (i.e. the '*Barranco de Los Giles (BG)*' section, which is located within the older sediments of this study (i.e. within the Almocáizar Corridor) and *c.* 500–600 m to the south of our sampling area; Baggley, 2000). The foraminiferal assemblage includes *Eponides pusillus*, *Pullenia bulloides* and *Quinqueloculina venusta* suggesting a lower epibathyal to upper mesobathyal depth (500–1300 m; Baggley, 2000), and thus broadly encompassing the 200–1000 m as suggested by the ichnoassemblage.

5.c. Variations between the Vera Basin and the Sorbas/Nijar basins

The Turre Formation (i.e. Azagador and Abad members, Figs 3, 4) crops out in the Vera Basin, as well as in the adjacent Sorbas and Nijar basins (Fig. 4). In all three basins, the Azagador Member is similar in terms of its lithological composition and appearance. However, the overlying Abad Member differs markedly between the Vera Basin, where it contains turbiditic sandstones, and the Sorbas and Nijar basins where it does not. Additionally, foraminiferal studies reflect a clear lateral deepening of the Abad Member towards the Vera Basin (Baggley, 2000). Thus, the depositional history of the Abad Member in the Vera Basin marks a caesura in terms of the regional sedimentary evolution. The question, as to why deepening occurred within the Vera Basin, is problematic. In contrast, the deposits of the basins to the south represent a clear shallowing trend.

The tectonic evolution of the area in Messinian times resulted in basin separation during the period of the deposition of the upper Abad Member leading to the tectonic restriction and isolation of the Sorbas and Nijar basins (Fig. 2; Braga *et al.* 2006). Coevally, extensive carbonate platforms and reefs (e.g. Cantera Member) along the basin margin topographic highs in the Sorbas and Nijar basins developed (Fig. 2b). However, this development did not occur in the Vera Basin, except for some rare and minor occurrences along the central-western margin of the basin (Fig. 3, cropping out to the west of Antas). The reefal growth, especially in the Sorbas Basin (Fig. 2b), would also have resulted in the formation of a topographic barrier to the free movement of water bodies between the Vera Basin to the north (with open contact to the Mediterranean Sea) and the Sorbas and Nijar basins to the south-west (Fortuin & Krijgsman, 2003; Krijgsman *et al.* 2006). These barriers would thus have reinforced the basin separation between the two regions, which from this point in time underwent differing depositional evolutions (cf. see above/regional geology; Fig. 2).

5.d. The lower Abad Member (rapid rise in sea level)

As noted above, there are clear changes in terms of the ichnoassemblage between the older part of the Abad Member (i.e. Almocáizar Corridor) and the younger sediments in the central part of the Vera Basin. This change is characterized by a marked decrease in the amount of recognizable ichnospecies and ichnogenera (Tables 1, 2). In addition, typical ichnofossils of

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the mesobathyal zone (i.e. *Desmograpton ichthyforme*; *Helminthoida labyrintica*) are no longer present. The changes in terms of ichnoassemblage between the two locations can be interpreted in terms of a temporal change in bathymetry from a deeper (upper meso- to lower epibathyal: i.e. older deposits) setting in the basin margin/older deposits through to a shallower setting (mainly epibathyal; i.e. younger deposits) in the basin centre. Such a shallowing trend was also noted by Baggley (2000) in his study of the benthic foraminifera, where a deep-to-shallow trend could also be seen in both the Sorbas and Vera basins. In addition, sequence-stratigraphic models for the Vera Basin (Braga, Martin & Wood 2001), as well as for the Sorbas Basin (Martin *et al.* 1996), support the recognized deep-shallow trend obviously. These models were established on the basis of the Azagador Member deposits immediately underlying (and sometimes interdigitating with) the Abad Member, which comprise shallow-marine sandstones and temperate carbonates. Such sediments are generally deposited in shelf regions at depths of < 200 m (e.g. James & Bone, 2010). The presumed depth of the upper part of the Abad Member, therefore, would involve a sudden and geologically rapid increase in water depth to a maximum depth of *c.* 1100 m. The question is how such a rapid increase in water depth could be explained.

The Azagador Member was deposited along the basin margin, while the Abad Member extended towards the basin centre (Figs 3, 4). However, it cannot be stated with any certainty that a specific stratigraphic level within either member corresponds to a specific stratigraphic time since it is entirely probable that the finer-grained sediments in the basin centre were deposited relatively slowly, in comparison with the coarser basin margin units. Thus, while the stratigraphic interval represented by the joint succession (i.e. basin margin and basin centre) ranges in age from upper Tortonian to uppermost Messinian, the precise ages of the respective successions (i.e. Azagador Member, Abad Member; Fig. 4) and their relationship to one another is unclear.

The rapid change in sea level (i.e. water depth reconstructions between the Azagador and the Abad members) may have been related to tectonic activity in the region. An increase in subsidence of the Vera Basin during the time of deposition of the Abad Member would have coincided with the onset of uplift in the eastern most part of the Sierra de Filabres, which began in late Tortonian times (Fig. 2; Braga, Martín & Quesada, 2003). This would have been coeval with the initial phase of deposition of the Azagador Member in the southwest. By mid-Messinian times, uplift of the crystalline massifs surrounding the basin had progressed to the point that the Sierra Cabrera was uplifting (Braga, Martín & Quesada, 2003; Booth-Rea *et al.* 2004). Additionally, there is a clear correlation between the initial activity of the Palomares Fault Zone (in late Tortonian times) and uplift activity of the Sierra Cabrera in the Vera Basin (c.f. Booth-Rea *et al.* 2004).

5.e. The uppermost Abad Member (end of full marine conditions)

As noted above, there is an obvious change in terms of the ichnofossil assemblages present within the succession between two of the measured profiles (i.e. sections 2.1 and 2.2; Fig. 6) in the central part of the basin. The former area contains an assemblage corresponding to the Nereites ichnofacies, while the latter is characterized by the complete absence of ichnofossils. The latter section (i.e. 2.2) is stratigraphically younger, and comprises finer-grained sediments, including both marls and turbiditic sandstones. A possible explanation for these observed changes may be owing to variations in the palaeoenvironmental conditions, related to temperature, nutrient availability, oxygen level and/or salinity (cf. Wetzel & Uchman, 1998). All of these changes would suggest a transition in terms of the environmental conditions from one favouring the presence of trace-producing organisms to one that could be considered a non-viable zone. In the case of the Vera Basin, which was affected by the Messinian Salinity Crises in latest Messinian times (i.e. uppermost Abad Member), a change in the degree of salinity is the most probable cause. A number of authors have recorded similar facies (i.e. marls and turbidites including *Paleodictyon* and marls with interbedded very thin turbidites) in the eastern Vera Basin (e.g. Cuevas de Almanzora Section; Montenat *et al.* 1976; Gonzalez Donoso & Serrano, 1978; Cita, Schilling & Bossio, 1980; Benson & Bied, 1991; Fortuin, Kelling & Roep, 1995). Within the Cuevas del Almanzora profile, for example, Fortuin, Kelling & Roep (1995) recognized the occurrence of ostracods (e.g. *Cyprideis* sp.) and the algae *Chara*, both indicative of brackish conditions. These fossils are found close to the boundary between the Messinian and the Pliocene, and would appear to correlate with the change in facies as noted in the southern part of the Vera Basin (i.e. from sediments containing a Nereites ichnofacies assemblage to sediments which are barren in terms of ichnofossils). Thus, the observed radical change in the ichnofossil assemblages may be related to a shift from full marine to brackish conditions, and thus reflect the changes wrought on the basin by the onset of the Messinian event.

A variety of foraminiferal studies have been carried out for stratigraphical purposes in the area (e.g. Montenat *et al.* 1976; Gonzalez Donoso & Serrano, 1978; Cita, Schilling & Bossio, 1980; Benson & Bied, 1991; Fortuin, Kelling & Roep, 1995; Sierro *et al.* 2001). These biostratigraphic analyses were mainly based on changes (quantitative and qualitative) in planktonic foraminifera. The aim of these studies was to provide a detailed stratigraphic subdivision of the Tortonian- to Pliocene-aged deposits within the Vera Basin (and the adjacent Sorbas Basin, e.g. Sierro *et al.* 2001), which are dominated by similar, and almost indistinguishable, marl deposits (cf. in the Vera Basin the marls of the Tortonian-aged Chozas Formation, Tortonian- to Messinian-aged Abad Member and the Pliocene-aged Cuevas Formation). Based on these studies, the Tortonian was subdivided into two biostratigraphic units: Tortonian I (of Montenat *et al.* 1976) characterized by *Neogloboquadrina acostaensis* and the stratigraphically younger Tortonian II characterized by *Globorotalia* (*G.*) *miocenica*. The onset of the Messinian was defined by the occurrence of *G. mediterranea* and *G. conomiozea*. The onset of the youngest marine period in the regional basins (i.e. Pliocene) is characterized by the presence of *G. margaritae* and *G. puncticulata* (c.f. Montenat *et al*. 1976; Benson & Bied, 1991; Fortuin, Kelling & Roep, 1995).

The biostratigraphic subdivisions were supplemented and supported by studies on magnetostratigraphy and geochemistry (e.g. Montenat *et al.* 1976; Benson & Bied, 1991; Fortuin, Kelling & Roep, 1995; Sierro *et al.* 2001). The extensive analyses carried out at the Cuevas de Almanzora Section (located in the north-eastern part of the Vera Basin), which is a representative section for the Messinian to Pliocene transition, were integrated into high-resolution stratigraphical studies of the region. The description of Montenat *et al.* (1976), Benson & Bied (1991) and Fortuin, Kelling & Roep (1995) of the Cuevas de Almanzora Section sediments (grain size, internal structures and bed thickness) as well as their general descriptions of ichnofaunal observations (e.g. presence of *Paleodictyon* isp. compared to absence of ichnofossils) matches the observations within the deposits of the younger sediments of this study (e.g. sections 2.1 and 2.2; Fig. 6).

In addition to the stratigraphical work, a number of studies focused on palaeoenvironmental reconstructions. Examination of the foraminiferal and ostracod assemblages showed clear evidence of changes in salinity (e.g. Montenat *et al*. 1976; Benson & Bied, 1991; Fortuin, Kelling & Roep, 1995; Sierro *et al*. 2001; Rouchy & Caruso, 2006; Bourillot *et al*. 2010). Indeed, three different phases of the MSC (5.971–5.33 Ma, cf. Roveri *et al.* 2014) could be identified across the entire Mediterranean area. These three phases were interpreted as representing: (1) the onset of the MSC, (2) the isolation of the Mediterranean area from the Atlantic Ocean, and (3) the reflooding of the Mediterranean Sea (Rouchy & Martin, 1992; Krijgsman *et al.* 1999; Bourillot *et al.* 2010; Manzi *et al.* 2013; Do Couto *et al.* 2014; Roveri *et al.* 2014; Flecker *et al.* 2015). The second of these phases encompasses the Lago Mare Facies (5.55–5.32 Ma, Stoica *et al.* 2016), interpreted as representing predominantly brackish conditions, and which is widely observed in the Mediterranean region (e.g. Deckker, Chivas & Shelley, 1988; Rouchy *et al.* 2001; Warny, Bart & Suc, 2003; Clauzon *et al.* 2005; Orszag-Sperber, 2006; Do Couto *et al.* 2014; Roveri *et al.* 2014; Marzocchi *et al.* 2016; Stoica *et al.* 2016). This particular phase occurred during the time of the continued separation of the Mediterranean Sea from the Atlantic. Thus, waters entering the Vera Basin (and related basins) were derived from freshwater influx from the surrounding region. The marine influence at this time was confined to occasional influxes from the Paratethys, as evidenced from a diverse assemblage of Paratethyan ostracod species (e.g. *Cyprideis and Loxoconcha*; Benson & Bied, 1991; Fortuin, Kelling & Roep, 1995; Do Couto *et al.* 2014; Stoica *et al.* 2016). The combination of the ichnofossil (i.e. absence of bioturbation) and microfossil (ostracods and foraminifera) records from the Abad Member sediments of the central part of the Vera Basin thus suggest that brackish conditions were active at this particular time. This would suggest a possible correlation with the extant Lago Mare Facies elsewhere in the Mediterranean region (e.g. Benson & Bied, 1991; Fortuin, Kelling & Roep, 1995; Do Couto *et al.* 2014; Stoica *et al.* 2016), and that the Abad Member succession in the Vera Basin represents a shift from full marine through to early post-MSC deposition. Thus, the correlation of the sediments of section 2.2 with the Lago Mare Facies would imply that these particular deposits should not be assigned to the Abad Member. A clear stratigraphical assignment to the period of the Messinian Salinity Crises and the corresponding Lago Mare Facies (Fortuin, Kelling & Roep, 1995; Do Couto *et al.* 2014; Stoica *et al.* 2016) is necessary.

6. Conclusions

The succession of the Tortonian- to Messinian-aged Abad Member of the Vera Basin is characterized by distal, low-energy background sedimentation (i.e. marl) with intercalated mixed (i.e. siliciclastic–carbonate) medium- to fine-grained turbidites, which may have been deposited in a deep-marine depositional-lobe-type setting of a channel-fan system and/or detached lobes developing from slope aprons generated by storm deposits on the shelf. The ichnofaunal assemblage of the Abad Member can be assigned to the Nereites ichnofacies of Seilacher (1964) and, in detail, to the Paleodictyon sub-ichnofacies of Seilacher (2007) and Uchman (2007). The range of ichnofossils (12 ichnogenera, 21 ichnospecies) recorded in this study includes facies-crossing and facies-controlled taxa, with the latter commonly considered as typical of deep-marine depositional settings. Bathymetric analysis of the ichnoassemblages suggests that deposition occurred at epi- to mesobathyal depths, with a deep-to-shallow trend from the older parts of the Abad Member (i.e. Almocáizar Corridor) through to the younger parts of the member (i.e. basin centre). The youngest sediments are considered to be Messinian in age and these record the abrupt disappearance of the ichnofossils. This disappearance heralded the onset of the MSC in the region and the onset of sedimentation under restricted

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conditions (i.e. brackish/Lago Mare phase of the Mediterranean region).

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