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A review of the Late Cambrian (Furongian) palaeogeography in the western Mediterranean region, NW Gondwana

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Abstract

The Cambrian–Ordovician transition of the western Mediterranean region (NW Gondwana) is characterized by the record of major erosive unconformities with gaps that range from a chronostratigraphic stage to a series. The *hiatii* are diachronous and involved progressively younger strata along the Gondwanan margin, from SW (Morocco) to NE (Montagne Noire). They can be related to development of a multi-stage rifting (further North), currently connected to the opening of the Rheic Ocean, and concomitant erosion on southern rift shoulders. The platforms of this margin of Gondwana occupied temperate-water, mid latitudes and were dominated by siliciclastic sedimentation, while carbonate factories were only episodically active in the Montagne-Noire platform.

The Upper Cambrian is devoid of significant gaps in the southern Montagne Noire and the Iberian Chains. There, the sedimentation took place in a transgressive-dominated depositional system, with common offshore deposits and clayey substrates, and was bracketed by two major regressive trends. The Late Cambrian is also associated with the record of volcanic activity (*e.g.*, in the Cantabrian and Ossa-Morena zones, and the northern Montagne Noire), and widespread development of a tectonic instability that led to the episodic establishment of palaeotopographies and record of slope-related facies associations.

Several immigration events are recognized throughout the latest Middle Cambrian, Late Cambrian and Tremadocian. The trilobites show a stepwise replacement of Acado-Baltic-type families (*e.g.*, the conocoryphid–paradoxidid–solenopleurid assemblage) characterized by: (i) a late Languedocian (latest Middle Cambrian) co-occurrence of Middle Cambrian trilobite families with the first anomocarid, dorypygid and proasaphiscid invaders; (ii) a Late Cambrian immigration replacing previous faunas, composed of trilobites (aphelaspids, catillicephalids, ceratopygids, damesellids, eulomids, idahooids, linchakephalids, lisariids, onchonotinids, and pagodiids), linguliformean brachiopods (acrotretids, obolids, scaphelasmatis, siphonotretids, and zhanatellids), echinoderms (mitrates, glyptocystitid cystoids, and stromatocystoids), and conodonts belonging to the lower *Peltura* Zone; and (iii) the subsequent input of new trilobites (asaphids, calymenids, catillicephalids, nileids and remopleurids), which

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marks the base of the *Proteuloma geinitzi* Zone, associated with pelmatozoan holdfasts (*Oryctoconus*), and a distinct input of late Tremadocian conodonts (*Paltodus deltifer* Zone).

The biogeographic distribution of latest Middle and Late Cambrian trilobites supports brachiopod data indicating strong affinities between the western Mediterranean region, East Gondwana (North China/Korea, South China, Australia, and Antarctica) and Kazakhstania during the late Languedocian, which became significantly stronger during the Late Cambrian. This major shift may suggest modification in oceanic circulation patterns throughout Gondwana across the Middle–Late Cambrian transition.

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1. Introduction

The geological setting of Late Cambrian sedimentary basins bordering NW Gondwana reflects the presence of extensive shallow-water intra- and epicratonic seas. The identification of Late Cambrian fossils and correlation of their respective strata throughout the western Mediterranean region (herewith applied to Morocco, the Iberian Peninsula, France and Sardinia) have been currently constrained by the abundance of stratigraphic gaps, condensed strata and scarcity of shelly fossils, many of which are exclusively endemic and unavailable for intercontinental correlation, as well as by the paucity of calcareous levels suitable for conodont investigation. There, the Late Cambrian represents a transitional time span between: (i) rifting processes recorded across the Neoproterozoic–Cambrian transition in Ossa-Morena (southern Iberian Peninsula; Sánchez-García et al., 2003) and Morocco (Gasquet et al., 2005); and (ii) a succession of magmatic episodes and tectonic perturbations that precluded the opening of the Rheic Ocean. This was the result of the drift of peri-Gondwanan terranes, such as Avalonia and Carolina from West Gondwana (see, e.g., Prigmore et al., 1997; Stampfli et al., 2002; Murphy et al., 2006; but see Landing, 2005, for another point of view). Upper Cambrian strata of the western Gondwanan margin also recorded a major palaeoclimatic influence related to its southward drift that led to a gradual cooling of waters, grading from Early Cambrian subtropical to Late Ordovician subpolar settings (Álvaro et al., 2000, 2003a), and a distinct immigration of East Gondwanan invaders that reached its peak during the late Languedocian (latest Middle Cambrian) and Late Cambrian (Courtessole et al., 1988; Álvaro et al., 1999; Shergold et al., 2000).

The aim of this paper is to document the sedimentary response recorded in NW Gondwana to the opening of the Rheic Ocean and the southward drift into temperate waters during the Late Cambrian. For this, we offer an integrated stratigraphic framework of the Upper Cam-

brian from the western Mediterranean region, based on litho-, bio-, and ecostratigraphic analyses, sequence- and event-stratigraphic approaches, and reconstruction of benthic community replacements. We are confident that this work might be of some help to overcome the difficulties to apply the recently erected Furongian Series in this margin of Gondwana.

2. The Furongian Series

Numerous regional chronostratigraphic subdivisions of the Upper Cambrian have been traditionally used all over the world (e.g., Shergold, 1982; Rushton, 1983; Ludvigsen and Westrop, 1985; Zhang and Jell, 1987; Chang, 1988; Ergaliev, 1990; Palmer, 1998; Geyer and Shergold, 2000; Peng and Robison, 2000; Peng et al., 2001a; Peng and Babcock, 2001; Ahlberg, 2003). Recently, the *International Subcommission on Cambrian Stratigraphy* selected for the base of a new globally applicable Upper Cambrian Series boundary (named the Furongian Series) the base of the *Glyptagnostus reticulatus* Zone (Shergold and Geyer, 2001).

The agnostoid trilobite *G. reticulatus* has one of the broadest palaeobiogeographic distributions of any Cambrian trilobite. It has been identified in Antarctica, Argentina, Australia, Canada, China, Denmark, Kazakhstan, Norway, Russia, South Korea, Sweden, UK, and USA. *G. reticulatus* is used as a zonal guide fossil in Australia, Kazakhstan, Laurentia, Siberia, and South China (Geyer and Shergold, 2000; Peng and Robison, 2000). Co-occurrences with other agnostoid and polimeroid trilobites allow correlation with Argentina (lower *Aphelaspis* Zone/lower *G. reticulatus* Zone-equivalent; Shergold et al., 1995) and Baltica (*Homagnostus obesus* Zone; Ahlberg, 1998). In addition, the combination of cosmopolitan agnostoids, Gondwanan shelf-dwelling polymeroids, cosmopolitan tropical polymeroids, and other polymeroids from the Jiangnan Slope Belt, where the Furongian was formally defined (Peng et al., 2001b), allows an useful

correlation of the base of the *G. reticulatus* Zone with other Gondwanan sectors, such as the North China Platform (Zhang and Jell, 1987), Kazakhstan (Ergaliev, 1990), Australia (Jago and Brown, 1992), Oman (Fortey, 1994), Antarctica (Cooper et al., 1996), and Iran (Peng et al., 1999).

Unfortunately, the absence of *G. reticulatus* and other coeval trilobites in other areas of Gondwana hampers any possible correlation of the newly erected Furongian Series with other 'Upper Cambrian' strata. This is especially dramatic in some temperate- to cold-water platforms, where carbonate strata are scarce or absent, and other biostratigraphically significant taxa, such as conodonts, are not reported: e.g., the base of the *Westergaardodina proligula* (conodont) Zone occurs slightly below the base of the *G. reticulatus* Zone (Dong and Bergström, 2001), and may be used as a key chronostratigraphic marker. Even the identification of the Cambrian–Ordovician (or Furongian–Tremadocian) boundary reflects the same problem. The *Cambrian–Ordovician Boundary Working Group* selected in 1998 as the base of the Ordovician the base of the *Iapetognathus fluctivagus* (conodont) Zone, which approximates the *Cordylodus lindstromi* Zone, the *Rhabdinopora flabelliforme* Zone and the first appearance (FAD) of the trilobite *Jujuyaspis*. The GSSP for this boundary was chosen at the Green Point section, Newfoundland (Cooper and Nowlan, 1999), but its identification in siliciclastic platforms is problematical.

Another tool for correlation of the base of the Furongian is chemostratigraphy. The base of the *G. reticulatus* Zone closely corresponds with the onset of a large positive shift in $\delta^{13}\text{C}$ values referred to as the Steptoean Positive Carbon Isotope Excursion (or SPICE excursion; Brasier, 1993; Saltzman et al., 1998). The SPICE excursion reaches peak values of about +4‰ $\delta^{13}\text{C}$ between the FAD of *G. reticulatus* and the FAD of *Irvingella* (Saltzman et al., 2000), at a position roughly corresponding to the interval of maximum biotic diversity in the Pterocephaliid Biome of Laurentia (Rowell and Brady, 1976). The excursion has been documented from sections in Paibi and Wa'ergang (South China), the Kyrshabakty river section and Malayi Karatau (Kazakhstan), Queensland (Australia), and the Great Basin (USA). Carbonate environments yielding the SPICE excursion range from slopes where dark, thin-bedded limestones predominate, to shallow platforms where a variety of carbonate lithofacies (boundstones, ooidal grainstones, and fenestral limestones) are present (Saltzman et al., 2000). A rise in seawater $^{87}\text{Sr}/^{86}\text{Sr}$ values, coinciding with the SPICE excursion, has also been documented in Laurentia

(Montañez et al., 1996; Denison et al., 1998), and presumably has global significance.

The Furongian is bracketed between several confident radiometric dates: a latest Middle Cambrian age (U–Pb zircon age of 505.1 ± 1.3 Ma) yielded by ignimbrites from the Taylor Formation (a probable equivalent of the Floran/Undillan, Antarctica; Encarnacion et al., 1999), and a latest Late Cambrian age (U–Pb zircon age of 491 ± 1 Ma) reported from an ash bed located close to the top of the Upper Cambrian in North Wales (Davidek et al., 1998), and two thin volcanoclastic sandstone beds overlain by *Rhabdinopora* debris in North Wales that have yielded an U–Pb zircon age of 489 ± 0.6 Ma (Landing et al., 2000).

3. The Upper Cambrian Series in the western Mediterranean region

Traditionally, the taxa used for the identification of the Late Cambrian in the western Mediterranean region have been ichnofossils and acritarchs. Scattered and probably storm-induced coquinas rich in trilobites, echi- noderms and brachiopods may be only used for regional correlation. Due to the strong endemism of these taxa, intercontinental correlation has only been tentatively advanced based on shared genera.

In this section, an integrated stratigraphic information of the Upper Cambrian from the Demanda Sierra, the Iberian Chains, the Cantabrian Mountains (Spain), Sardinia (Italy), the southern Montagne Noire (France), and Morocco and neighbouring areas (Fig. 1) is updated and completed with new data. Although the respective degree of knowledge of these areas is heterogeneous (e.g., related to sequence and event stratigraphy), the following description will enable a comparative analysis of relative sea-level fluctuations and events that, in some cases, are shared by all the platforms (Fig. 2).

3.1. The Demanda Sierra (NE Spain)

The occurrence of Late Cambrian trilobites in the western Mediterranean region was reported, for the first time, by Colchen (1967, 1974) in the Demanda Sierra. He determined the presence of *Chuangia* and *Prochuangia* in the lower member of the Najerilla Formation (Fig. 3). New collections from the same sections were subsequently described and revised by Shergold et al. (1983), who recognized two fossil associations: (i) the oldest comprises four trilobite taxa (aphelaspidine, leiostegiid?, *Maladioidella colcheni*, and *Langyashania felixi*), associated with the brachiopod *Billingsella* cf. *lingulaeformis* (Colchen and Havlíček, 1968); and

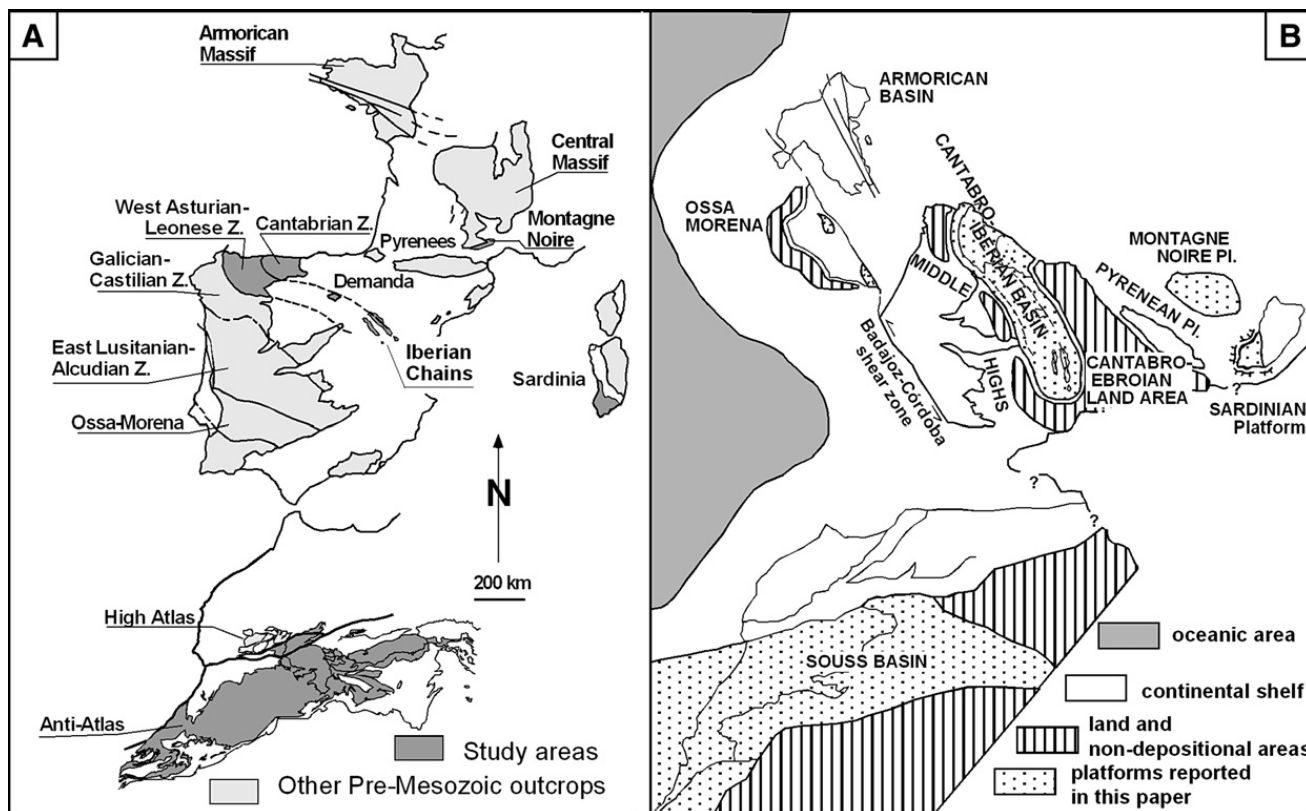


Fig. 1. Location of the Demanda Sierra, the Iberian Chains, the Cantabrian Zone (northern Spain), the Montagne Noire (southern France), Sardinia (Italy) and the Moroccan Anti-Atlas in the pre-Hercynian outcrops of the western Mediterranean region.

(ii) the younger assemblage, from the second member of the Najerilla Formation, contains only two trilobite taxa (pagodiine and a solenopleuroidean? aff. *Lajishanaspis*) that co-occur with the pelmatozoan holdfast *Oryctoconus lobatus* (Colchen and Ubaghs, 1969).

A sedimentological and sequence analysis is here reported from the western bank of the Urbión river (Fig. 4), the paratype of the Najerilla Formation, where the aforementioned fossil associations can be found. The Najerilla Formation was subdivided by Colchen (1974) into three members. The lower member, ca. 100 m thick, is dominated in the study section by brownish shales although some scattered centimetre-thick sandstone interbeds and limestone nodules and layers occur. The calcareous layers are partly to wholly limonitized, and have yielded the aforementioned oldest fossil association. The intermediate member, ca. 500 m thick, consists of alternating sandstones and blue-grey shales, also bearing limonitized limestone nodules, and has produced, at the top, the younger fossil assemblage. The upper member has not yielded shelly fossils, is up to 300 m thick, and consists of amalgamated sandstone channels and beds with subordinate shale interbeds.

The lower member of the Najerilla Formation displays silty layers, local symmetric ripples, parallel and low-angle lamination, and coquinas with erosive bases and grading. No distinct parasequences (or 4th order sequences) are visible, and the sedimentary structures and fossil disarticulation suggest deposition under calm conditions episodically interrupted by waves and storms, in an offshore-dominated setting. A progressive regressive trend is recognized upsection, due to development of coarsening- and thickening-upward parasequences, 1.2 to 4.8 m thick. Parasequences display a vertical succession from: (i) homogeneous shales bearing isolated bioclastic limestone nodules and local slumps; to (ii) thin- to thick-bedded sandstone bodies, with an upward change from tabular to lenticular sets that grade from medium- to large-scale, trough cross-bedding and wave-ripple lamination; some erosive bases are covered by lagged channels, in some cases lined by brachiopod-rich coquinas; and (iii) centimetre-thick sandstone/shale rhythmites with parallel and low-angle lamination, flaser-to-lenticular structures and, locally, centimetre-thick, sandstone channels with polymodal palaeocurrents. Each parasequence represents shoaling processes with progradation from open-sea offshore to shoal complex and back-shoal,

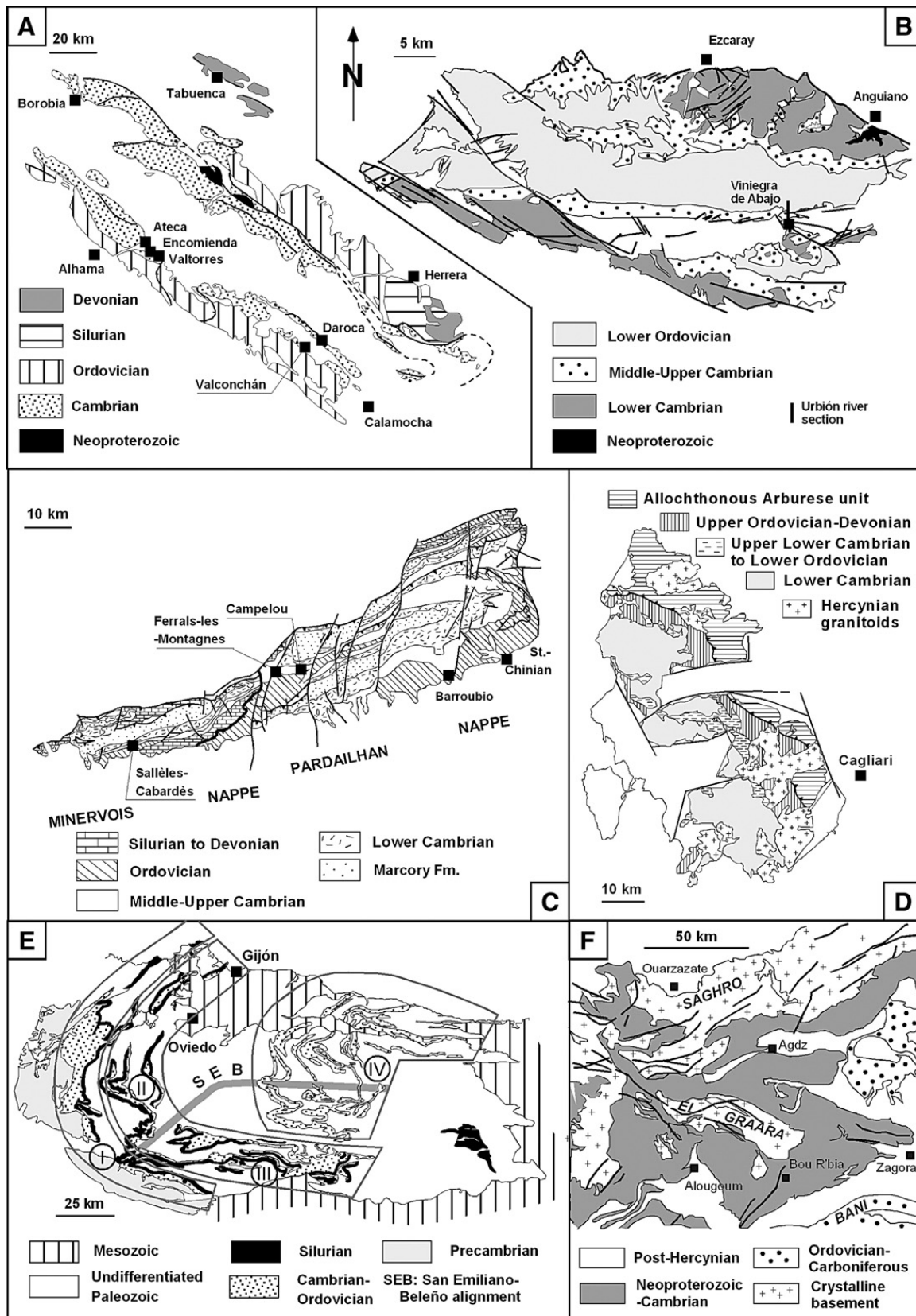


Fig. 2. Geological maps of the pre-Hercynian outcrops of (A) the Iberian Chains, (B) the Demanda Sierra, (C) the Minervois and Pardailhan nappes of the southern Montagne Noire, (D) SW Sardinia, (E) the Cantabrian Zone, and (F) the El Graara massif (Anti-Atlas), with setting of stratigraphic logs reported in the text.

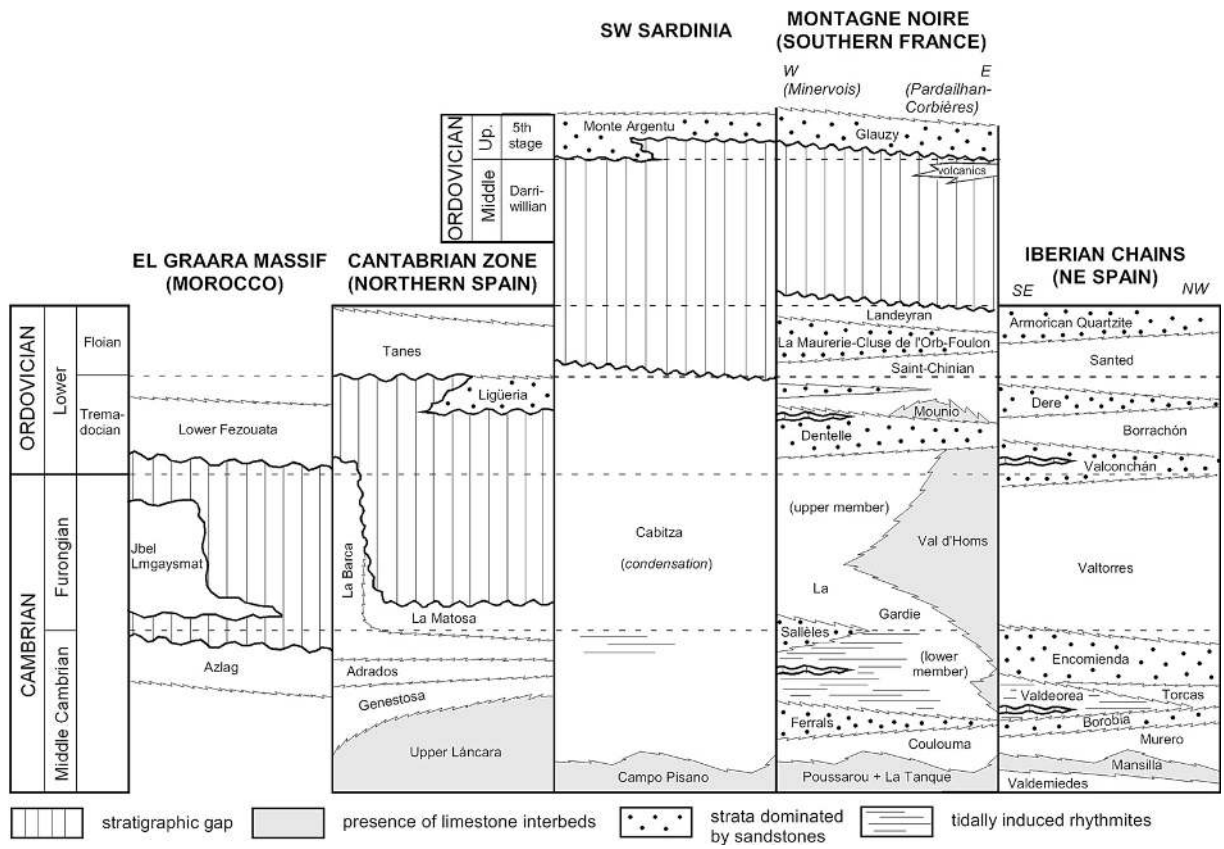


Fig. 3. Sketch illustrating the Upper Cambrian stratigraphic units and their related stratigraphic gaps from the western Mediterranean region, based on papers reported in this paper and new data.

probably tidally influenced, depositional systems. As a result, the Cambrian–Ordovician transition of the Urbión river section has recorded a global regressive trend recorded in a siliciclastic rimmed platform with episodic colonization of trilobites and echinoderms in distal, open-sea, offshore clayey substrates. The regressive trend is capped by an erosive discontinuity that marks the base of the upper member of the Najerilla Formation, and the subsequent amalgamation of nearshore (continental?) coarse-grained sandstones.

3.2. The Iberian Chains (NE Spain)

The upper Middle Cambrian to Tremadocian strata of the Iberian Chains are characterized by a thick and conformable succession of exclusively siliciclastic sediments. These strata were originally grouped into an informal ‘Iberian Series’ (Schmitz, 1971; Josopait, 1972; Shergold and Sdzuy, 1991). This unit was subsequently revised by Álvaro (1995), who subdivided the Acón Group (or ‘Iberian Series’) into the Borobia, Valdeorea, Torcas, Encomienda, and Valtorres formations. Upper Cambrian strata are broadly distributed across the Encomienda, Valtorres (Acón Group) and Valconchán (Ateca Group) formations (Fig. 4), although acritarchs from the underlying Torcas Formation may suggest a Late Cambrian age (Palacios, 1997). The Encomienda Formation, 150–200 m thick, is dominated by sandstones and quartzites interbedded with subordinate shales. The Valtorres Formation is mainly represented by more than 300 m of shales with isolated sandstone intercalations. The Valconchán Formation, 30–400 m thick, consists of sandstones and quartzites with thin intercalations of shales and conglomeratic lenses, the latter becoming significant toward the top of the formation (Wolf, 1980; Álvaro, 1995).

The identification of the Late Cambrian in the Iberian Chains is dramatically constrained by the scarcity of biostratigraphically significant markers within the fossil assemblage, which is dominated by trilobites, brachiopods, acritarchs and ichnofossils (Schmitz, 1971; Josopait, 1972; Havlíček and Josopait, 1972; Kolb and Wolf, 1979; Shergold and Sdzuy, 1991; Álvaro, 1995). The youngest Middle Cambrian trilobites of the Iberian Chains (represented by *Solenopleura* s.l.) are situated in the lower part of the Encomienda Formation. This taxon is associated with some pelmatozoan ossicles, the hyolith *Ortotheca*, and the linguliformean brachiopods *Lingulella* sp., *Obolus* sp., *Obolidae* spp., *Westonia* aff. *iphis*, and *Westonia* sp. The upper part of the Encomienda Formation has yielded an impoverished

brachiopod assemblage composed of *Obolus* sp. and *Westonia* cf. *iphis*.

Trilobites re-appear in the middle part of the overlying Valtorres Formation and in the lowermost part of the Valconchán Formation (Wolf, 1980; Shergold and Sdzuy, 1991; Álvaro, 1995). They form a Late Cambrian association, determined for the first time by Sdzuy (in Josopait, 1972), and subsequently described by Shergold and Sdzuy (1991). This faunal association includes agnostoid, aphelaspidine aff. *Aphelaspis rara* (Orłowski) sensu Żylińska (2001), *Elegantaspis* cf. *beta*, *Parachangshania*? sp., *Pseudagnostus* sp., *Punctaspis*? *schmitzi*, solenopleuroidean, and *Valtorresia volkeri*, associated with the brachiopods *Billingsella jalonensis*, *B.* cf. *jalonensis*, and *B. perarea*. According to Shergold and Sdzuy (1991), this fauna can be considered as probably early Franconian in age (Steptoean, according to the North American chronostratigraphic chart; Palmer, 1998), and approximately related to the *Parabolina spinulosa* Zone (Baltica).

The uppermost part of the Valconchán Formation has yielded a distinct trilobite association, composed of *Pagodia* (*Wittekindtia*) *alarbaensis* and olenid fragments thought to represent a species of *Jujuyaspis* that would indicate an early Tremadocian age (Shergold and Sdzuy, 1991; Álvaro et al., 2003a), and the brachiopod *Protambonites primigenius*. In addition, both here and in the Demanda Sierra, pagodiine trilobites co-occur with the pelmatozoan holdfast *O. lobatus*. The latter is associated in Sardinia with the graptolite *Rhabdinopora flabelliformis*, the trilobite *Proteuloma geinitzi* and age-diagnostic acritarchs (Álvaro and Colchen, 2002), all of them of distinct early Tremadocian age (Barca et al., 1987; Pillola and Leone, 1993; Loi et al., 1995).

About 75% of the aggregate thickness of the Encomienda type section (Encomienda valley, western Iberian Chain) is incorporated into shallowing- and coarsening-upward parasequences, which average 5–25 m in thickness (Álvaro and Vennin, 1996a). From bottom to top, almost all the parasequences display a succession from: (i) massive claystones, poor in benthic fauna, locally interrupted by centimetre-thick, graded silty layers, hummocky structures, and scarce ripple lamination, exhibiting a wide diversity of burrowing traces; (ii) thick-bedded, fine- to medium-grained sandstones exhibiting medium-scale, trough cross-bedding and wave-ripple lamination, interrupted by reactivation surfaces lined by clay laminae, and locally covered by lagged erosive channels, composed of intraformational conglomerates and abraded linguliformean brachiopods; and (iii) thin-bedded laminae of sandstone/claystone rhythmites rich in ichnofossils,

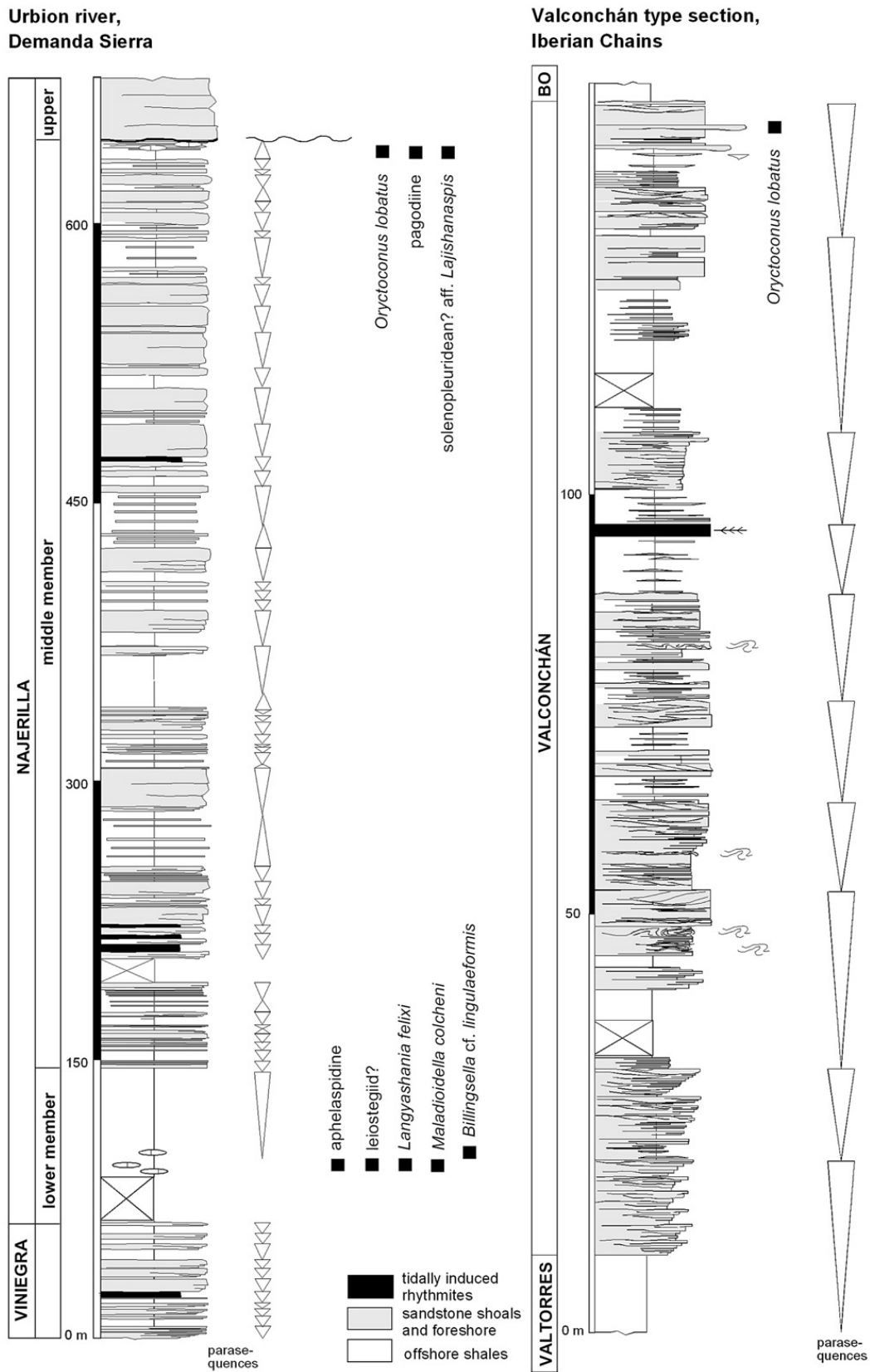


Fig. 4. Facies, fossiliferous levels and sequence-stratigraphic framework of the Cambrian–Ordovician transition from the type sections of the Demanda Sierra (Urbión river) and the Iberian Chains (Valconchán), see legend in Fig. 6.

flaser-to-lenticular siltstone bedding, and horizontal and low-angle laminae, locally truncated by low-angle reactivation and erosive surfaces overlain by fine-grained sandstone beds. The parasequences display vertically repetitive progradational trends from: (i) offshore to (ii) shoal complexes (shoreface) recording minor storm wash-over channels, and (iii) tidally induced back-shoals dissected by channels.

The overlying Valtorres Formation consists dominantly of homogeneous shales commonly interrupted by storm-induced cycles, *ca.* 20 cm in averaged thickness. The formation represents deposition in a low energy outer-platform setting, with only fine-grained terrigenous input and episodic influence of storms (Álvaro and Vennin, 1996a).

The type section of the Valconchán Formation displays shoaling parasequences similar to those described for the middle member of the Najerilla and the Encomienda formations (Fig. 4). Three further features are remarkable: (i) the abundance of slumps and contorted beds at the base of many shoaling parasequences; (ii) the presence of herringbone structures embedded in the tidally induced rhythmites that cap some of the shoaling parasequences; and (iii) the upward increase of channeled conglomerates rich in either *Oryctoconus* holdfasts or linguliformean brachiopods, the latter forming phosphoarenites. These channels truncate both the base and the upper part of amalgamated shoals, reflecting pulses of increased energy probably winnowing benthic communities that colonized the top of shoals during episodes in which the bars ceased to migrate.

It is remarkable the fact that the Encomienda, Valtorres and Valconchán formations display distinct slope-related facies associations. Álvaro and Vennin (1996a) described the local presence of decimetre-scale, slumping and sliding strata (underlain by flute, groove and impact marks), unsorted and ungraded blocks and swarms of siltstone and sandstone pillows ‘floating’ in a shaly matrix. These intraformational blocks and beds were referred to gravity-induced processes related to development of both local slopes and liquefaction and fluidised sediment flow processes, which led the same authors (Álvaro and Vennin, 1996b) to document an interval of episodic tectonic perturbation in the Iberian Chains, broadly restricted to the Late Cambrian.

3.3. The Cantabrian Mountains (northern Spain)

In the northern Iberian Peninsula, the foreland fold belt of the Variscan orogen comprises two major tectonostratigraphic units: the Cantabrian Zone, posi-

tioned within the inner part of the Asturian or Iberoarmoric arc, and the West Asturian-Leonese Zone (Lotze, 1961). Both ‘zones’ (a term used here without any biostratigraphic significance) are separated by the Narcea Antiform, the core of which exposes sedimentary Precambrian rocks. We will follow Aramburu (1989) and Aramburu and García-Ramos’ (1993) subdivision of the Cantabrian Zone into five palaeogeographic domains, named, from West to East: Narcea Antiform (I), central Asturias (II), northern Leon (III), eastern Asturias (IV), and San Isidro-Tona (V) (Fig. 2).

Identification of the Middle–Upper Cambrian and Upper Cambrian–Tremadocian transitions in the Cantabrian Zone is broadly based on ichnofossils (Seilacher, 1970; Crimes and Marcos, 1976; Baldwin, 1978; Marcos et al., 1982; Legg, 1985), and acritarchs (Fombella, 1986, 1987; Vanguetaine and Aramburu, 1988; Albani et al., 2006). Lag deposits of the pelmatozoan holdfast *O. lobatus* occur in Lower Ordovician quartzarenites at El Horno near Cabo Busto, Cantabrian Zone (Seilacher and MacClintock, 2005), although its stratigraphic setting has not yet been documented in detail.

Three members are involved in the Middle–Upper Cambrian and Upper Cambrian–Tremadocian transitions: the La Barca (Oville Formation), La Matosa and Ligüeria (Barrios Formation) members (Aramburu and García-Ramos, 1993; Fig. 2). The La Barca Member consists of alternating sandstones and shales, bearing scattered glauconite-rich levels, and local volcanic sills and volcanoclastic strata. Its thickness strongly increases from East to West, ranging from 8 to 620 m. The uppermost part of the member is diachronous: it is commonly Middle Cambrian but ranges into Late Cambrian toward NW (Marcos et al., 1982; Vanguetaine and Van Looy, 1983; Legg, 1985). The La Matosa Member, 0–395 m thick, is dominated by quartzarenite sandstones that change vertically from medium-sorted, very fine-to-fine sandstones with shale interbeds to unsorted, medium-to-coarse-grained sandstones bearing scattered quartzite granules. The member occurs across the whole Cantabrian Zone, except in the northern part of domain I. In domain III, some volcanoclastic levels and a distinct kaolinite-rich bentonite (the so-called Valverdín Bed; García-Ramos et al., 1984) are also documented. The presence of ichnofossils (several ichnospecies of *Cruziana*; Crimes and Marcos, 1976; Baldwin, 1978) and acritarchs (Vanguetaine and Aramburu, 1988) allows a broad identification of the Upper Cambrian–Tremadocian transition. Finally, the Ligüeria Member, 0–130 m thick, is underlain by an erosive unconformity, and characterized by a broad

upward decrease in grain size. The member changes vertically from shale/very fine-grained sandstone alternations, to medium-to-very coarse sandstones bearing upward quartzite-rich conglomerate layers. The erosive unconformity located at the La Matosa/Ligüeria contact, locally scoured and channelled, was firstly related to the Sardinian Phase by Aramburu and García-Ramos (1988), although recently Aramburu et al. (2004) have referred it to the Central-Iberian Toledanian unconformity. The overlying conglomerate bed, up to 19 m thick to the East, contains quartzite granules that can reach 34 cm in diameter, and shows a northwesternward decrease in grain size and thickness.

The sedimentology of these deposits was studied and successively updated by, among others, Van den Bosch (1969), Gietelink (1973), Baldwin (1977), Legg (1985), Aramburu (1989), Aramburu et al. (1992), and Aramburu and García-Ramos (1993). Although a complete sequence framework is not yet available, the global trend from the La Barca to the Ligüeria members has been studied in detail. The La Barca-La Matosa strata display a global shallowing-upward depositional system capped by the lower Tremadocian erosive unconformity located at the La Matosa/Ligüeria contact. The La Barca strata overlie an essentially offshore-dominated sedimentary succession (lower part of the Oville Formation), and represent transitional marine-to-continental deposits with common alluvial sheet-flood sediments episodically reworked by wave activity. The La Matosa Member shows a global increase in grain size and bed thickness, from: (i) very fine-to-medium grained sandstones with shale interbeds arranged into coarsening-upward, unimodal sets and rich in parallel, low-angle, and cross laminae reflecting input of alluvial sand bars (Aramburu, 1989), although they were also interpreted as foreshore and sand ridges of a delta complex (Baldwin, 1977; Legg, 1985); to (ii) unsorted, coarse-grained sandstones displaying channels that represent migration of sheet (fluvial) braid-plain deposits. After the incision of a regional erosive unconformity, sedimentation led to deposition of a channelled braided fluvial system (the Ligüeria Member; Aramburu and García-Ramos, 1993). The latter occurs in disconnected outcrops reflecting sedimentation in isolated depocentres related to a synsedimentary tectonic activity, overlain by overlapping geometries.

As in other basins and platforms described in this paper, the Cantabrian platform was also episodically affected by tectonic instability. Aramburu and García-Ramos (1993) described the central (or central Asturias-N León) palaeohigh and the San Emiliano-Beleño alignment, which may represent a major synsedimentary

fracture. The central palaeohigh, situated in domains II and III, began its activity during the early Middle Cambrian and was re-activated across the Cambrian–Ordovician transition. Its geometry is suggested by sharp changes in thickness of the Oville and Barrios formations. The abundance of volcanoclastic beds at the top of the Matosa Member in domain III may suggest the instability of the platform related to volcanic activity. Transversally to the palaeohigh, the San Emiliano-Beleño alignment is characterized by a distinct decrease in thickness from N to S, and the disappearance of the Ligüeria Member to the South (domain V).

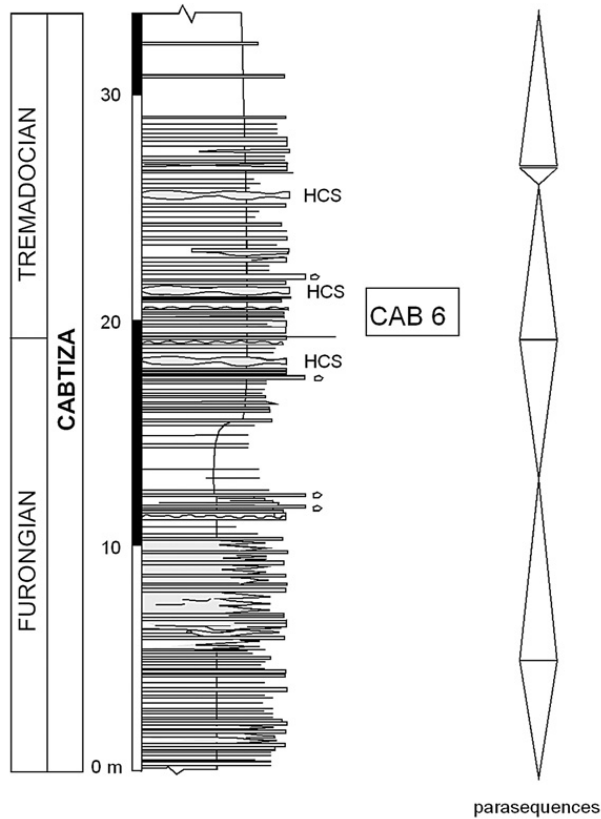
The Upper Cambrian of the West Asturian-Leonese Zone is also incompletely constrained. There, the so-called Cabos Series has been subdivided into three members: the lower member bearing Middle Cambrian trilobites and the upper one Early Ordovician ichnofossils (such as *Cruziana furcifera*, *C. rugosa* and *C. cf. goldfussi*; Baldwin, 1977). The middle member has yielded the polytoechioid brachiopod *P. primigenius* (Fig. 5) whose genus is restricted to the Tremadocian in Bohemia (Villas et al., 1995), Morocco, the Uralian margin of Baltica and Iran (Popov et al., 2001; Fortey and Cocks, 2003), and is associated in the Iberian Chains with earliest Tremadocian trilobites and pelmatozoan holdfasts (see above). The species occurs in storm-induced, brachiopod-dominated coquinas, 1–30 cm thick, and ca. 400 m below the supposed Cambrian–Ordovician boundary based on ichnofossils.

3.4. Sardinia (Italy)

Late Cambrian trilobites have been documented in the upper part of the Cabitza Formation in the Cabitza area and North of Domusnovas (Loi et al., 1995, 1996). They occur in fine-grained sandstones and siltstones probably representing a tide-dominated deltaic environment. Illustrated trilobites belong to the so-called faunal assemblage CAB 5b (Loi et al., 1995, 1996), which contains *Macropyge* sp., *Maladioidella* cf. *colcheni*, *Micragnostus* cf. *haudei*, *Niobella* cf. *primaeva*, *Onchonotellus?* *amsassensis*, *Proceratopyge* sp., a leiostegiid aff. *Pagodia*, a eulomid, and a calymenid. At Monte Cani this assemblage is succeeded by green siltstones containing (CAB 6) *R. flabelliformis* (Pillola and Gutiérrez-Marco, 1988; Pillola and Leone, 1993), *P. geinitzi* (Pillola, 1991), *Oryctoconus* cf. *lobatus* and related acritarchs. The younger assemblage is clearly of earliest Tremadocian age (Barca et al., 1987).

Late Cambrian conodonts (24 form-species of para-, proto- and euconodonts), correlatable with the lower

'TUBI' SECTION AT RAILWAY LINE
CLOSE TO CABITZA STRATOTYPE,
SW SARDINIA



LA CARIDAD SECTION, NAVIA AND
HIGH SIL DOMAIN, WEST-ASTURIAN
LEONESE ZONE, SPAIN

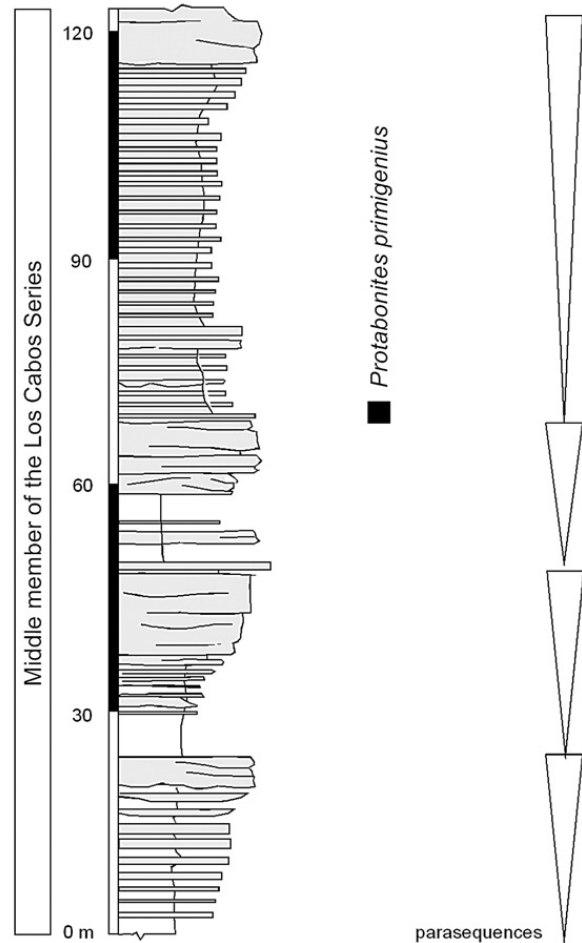


Fig. 5. Facies, fossiliferous levels and sequence-stratigraphic framework of the Cambrian–Ordovician transition from the La Caridad section of the West Asturian-Leonese Zone (modified from Villas, 1995), and the Cabitza ‘Tubi’ section from SW Sardinia (modified from Loi et al., 1995), see legend in Fig. 6.

Peltura Zone, have also been reported and figured from centimetre-thick calcareous lenses of the Cabitza Formation near Villamassargia, SW Sardinia (Serpagli et al., 1998).

A younger biostratigraphically significant level has been recently discovered in the Fluminese subregion (Monte Argentu–Piscina Morta area). This is characterized by a new graptolitic assemblage that includes the anisograptid *Araneograptus murrayi* (Hall, 1865), the dichograptids *Clonograptus* (*Clonograptus*) cf. *rigidus* (Hall, 1858), *Clonograptus* (*Clonograptus*) cf. *multiplex* (Nicholson, 1868), and two unassigned species of *Didymograptus* (Pillola et al., in press). The horizon of the upper part of the Cabitza Formation that has yielded *A. murrayi* documents a late Tremadocian–early Floian age. As a result, marine sedimentation persisted in SW Sardinia at least until the end of the Tremadocian.

The Cabitza Formation (Middle Cambrian to early Floian) consists of at least 600 m of siliciclastic strata displaying a monotonous succession in the Iglesias and Sulcis areas (SW Sardinia). The formation is dominated by shales, bearing subordinate carbonate coquinas, and fine- to coarse-grained sandstones that increase in thickness upward. Loi et al. (1995) documented across the Cambrian–Ordovician transition a broad transgressive trend, although it is punctuated by a shallowing related to the occurrence of fossil assemblage CAB 6, and named by the authors ‘the *Acerocare* Regressive Event’ (*sensu* Erdtmann, 1986). The transition consists of shallowing-upward parasequences, 2–14 m thick, grading upsection from: (i) lower-offshore siltstones and claystones with local ripple cross-lamination; (ii) upper-offshore laminated shales and fine-grained sandstones; (iii) hummocky

cross-bedded sandstones; and (iv) graded rhythmites interpreted as tidally influenced after an analysis of tidal bundles thickness (Fig. 5). The lower Floian part of the Cabitza Formation is unconformably overlain by the so-called Sardinic Phase (Stille, 1939), where the involved stratigraphic gap affected a part of the Lower and Middle Ordovician, as the overlying Monte Argentu Formation is 'Caradoc' in age (Fig. 3).

Late Cambrian acritarchs have been recently described from the Arburese area (Ribecai et al., 2005), where the Mt. Fonnesu Sandstone has yielded acritarchs correlatable with the *Peltura* trilobite Zone of Newfoundland (*sensu* Parsons and Anderson, 2000). Other Late Cambrian acritarchs from low-grade metasediments of central Sardinia (the Solanas Sandstone) occupy a biostratigraphic range from the *Agnostus pisiformis* (?) to the *Parabolina spinulus* trilobite zones (Albani et al., 1985; Di Milia, 1991; Di Milia et al., 1993).

3.5. The southern Montagne Noire (southern France)

Late Cambrian trilobites, brachiopods and echinoderms occur in the Val d'Homs and La Gardie formations of the southern Montagne Noire. Both units are differentiable by the presence/absence of limestone intercalations, respectively. The La Gardie Formation is a siliciclastic succession, 5 to 500 m thick, and middle Languedocian (Middle Cambrian) to Tremadocian in age (Álvaro et al., 2001). It is composed of green shales with thin sandy intercalations at the top, and has been subdivided into three members: (i) the lower member, 60–100 m thick and middle Languedocian in age, consists of sandstone/shale rhythmites that pass basinward into homogeneous shales, and contains trilobites and cinctan echinoderms; (ii) the late Languedocian middle member (also named Sallèles Member; Fig. 6), up to 15 m thick, is composed of sandstones with subsidiary shales, can exhibit centimetre-thick limestone nodules at the top, and contains endemic trilobites, undetermined brachiopods and hyoliths; and (iii) the upper member, 0.5 to 5 m thick and Late Cambrian to Tremadocian in age, which consists of a shale-dominated succession, with green and purple colours, locally interbedded by sandstone beds. The fossiliferous Val d'Homs Formation, up to 300 m thick and also late Middle Cambrian to Tremadocian in age, consists of green and purple shales containing centimetre- to decimetre-thick, white, reddish and purple, lenticular to bedded limestones and yellow dolostones.

Late Cambrian trilobites were described for the first time by Feist and Courtesole (1984) from a limestone lens

close to the base of the Val d'Homs Formation in Ferrals-Montagnes (Pardailhan nappe). The authors recognized two species referred to *Bergeronites latifalcatus* and *Prochuangia gallica*. Subsequent collecting from the same lens has revealed the presence of further taxa: *Abharella* sp., *Ammagnostus* (A.) aff. *sinensis*, *Kormagnostus*? sp., *Olentella* cf. *africana*, *Palaeadotes latefalcata*, *Paraacidaspis ultima*, *Proceratopyge* (P.) spp., *P. gallica*, *Shengia* cf. *spinosa*, and *Stigmatoa courtesolei* (Shergold et al., 2000). The age of this fauna is judged to be similar to, but slightly older than that characterized by *Maladioidella* in the Demanda Sierra. The same limestone lens has yielded some linguliformean brachiopods that apparently do not cross the Middle–Upper Cambrian boundary elsewhere, such as *Neotreta* and *Stilpnotreta* (González-Gómez, 2005a), as well as *Canthylotreta* (L. Popov, pers. comm., 2007); as a result, its age was considered by the former author as related to the Middle–Late Cambrian transition interval. Elsewhere in the Montagne Noire, an assemblage containing trilobite species of *Maladioidella*, *Onchonotellus*, *Probilacunaspis*, *Proceratopyge*, *Prochuangia*, and a pseudagnostinid occurs in limestones of the Val d'Homs Formation (Álvaro et al., 2001, 2003a). This assemblage is the youngest Cambrian fauna found so far in the Montagne Noire, and has not yet been described nor illustrated.

The limestone strata and nodules of the Val d'Homs Formation display a widespread diversity of phosphate-walled brachiopods (Fig. 7A–L), which include acrotretids (*Angulotreta brevis*, *Canthylotreta*? n. sp., *Dactylotreta* n. sp., *Dicondylotreta* n. sp., *Ferralstreta globosa*, *Neotreta* sp., and *Stilpnotreta magna*), obolids (*Lingullela* sp.), scaphelasmatis (*Eoscapheasma* n. sp.), siphonotretids (*Schizambon convexus*), and zhanatellids (*Wahwahlingula*? sp., *Zhanatella rotunda*) (González-Gómez, 2005a,b). Late Cambrian echinoderms are also abundant in the Val d'Homs Formation: they are represented by the mitrate *Lobocarpus vizcainoi*, several glyptocystitid cystoids such as *Barroubiocystis radiata*, *Velieuxicystis ornata*, and *Scoteinocystis cambriensis*, and a stromatocystoid (*Stromatocystites* sp.) (Ubaghs, 1998).

The earliest Ordovician has been traditionally marked by the appearance of *P. geinitzi* described by Sdzuy (1958) from reddish limestones and shales (Val d'Homs and La Gardie formations) just below the base of the overlying La Dentelle Formation. The occurrence of this species marks the base of its homonymous interval zone, traditionally reported as the oldest Tremadocian trilobite zone in the Montagne Noire (Vizcaino and Álvaro, 2003). However, the recent finding of abundant conodont assemblages, belonging

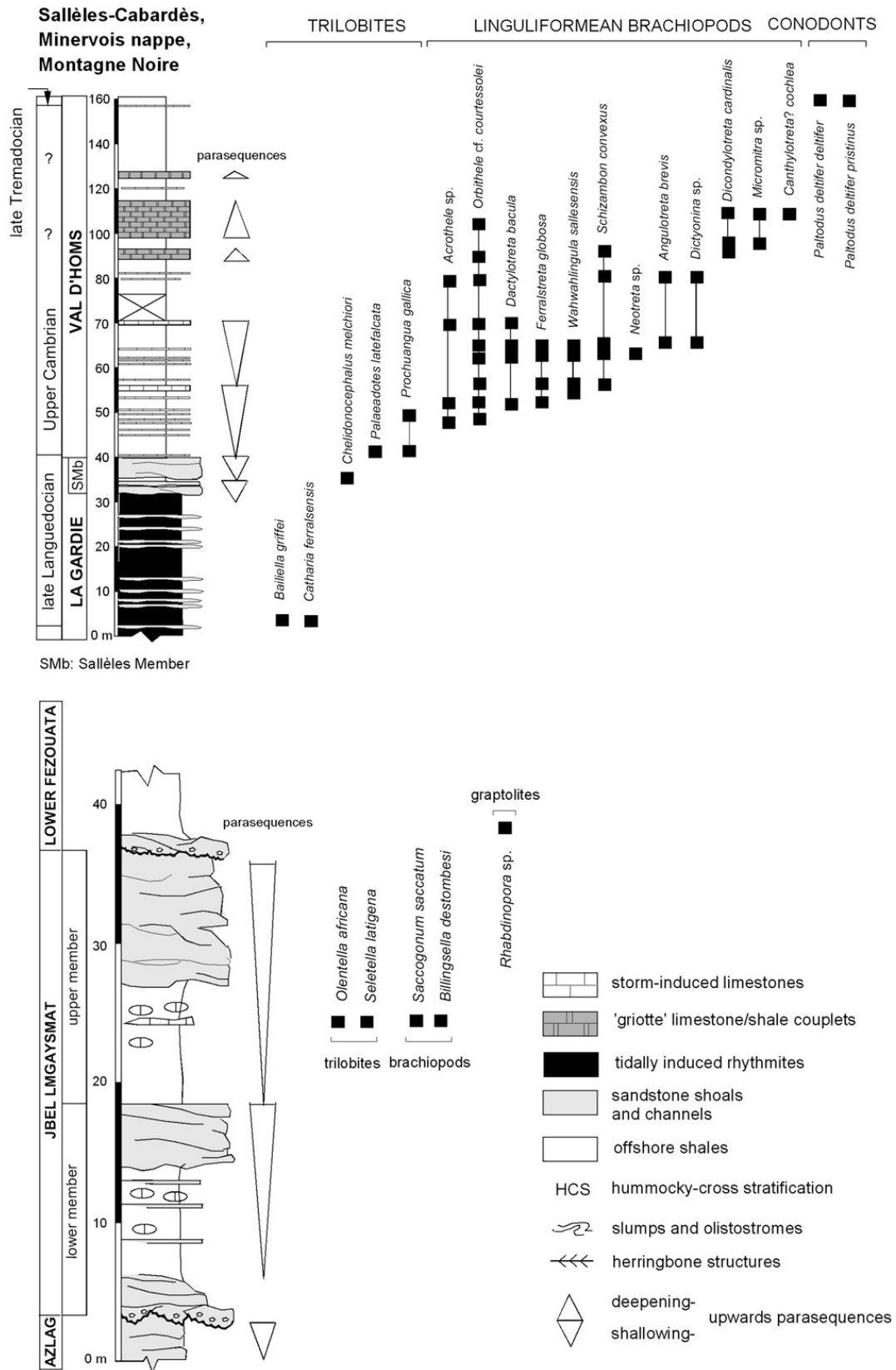
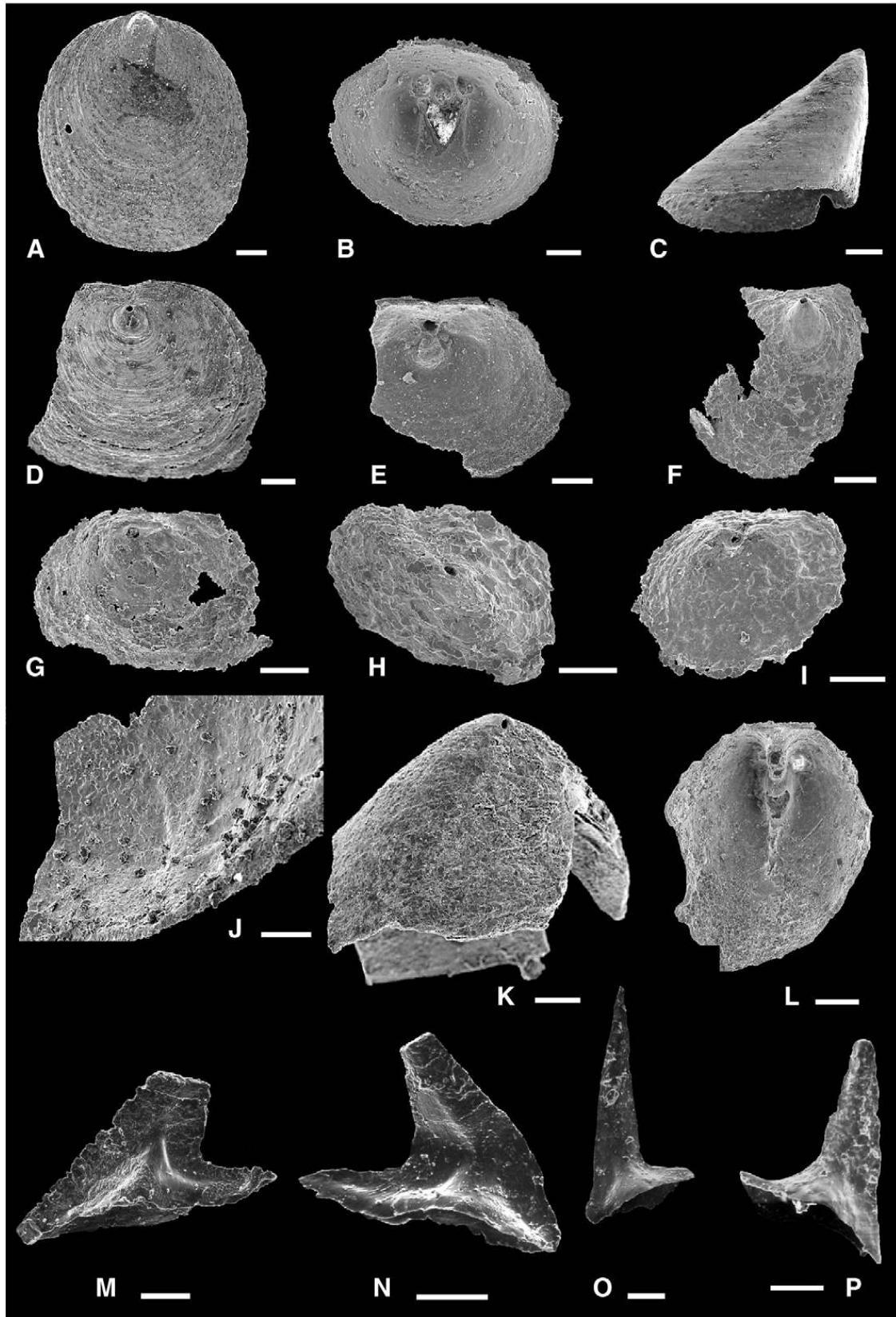


Fig. 6. Facies, fossiliferous levels and sequence-stratigraphic framework of the Cambrian–Ordovician transition from the southern Montagne Noire (Sallèles-Cabardès, Minervois nappe; modified from Álvaro et al., 2003b, 2005; González-Gómez, 2005b), and the Bou-R'bia section of the El Graara Massif (modified from Destombes, 1989).

to the middle part of the Val d'Homs Formation in Sallèles-Cabardès (Minervois nappe; [Álvaro et al., 2005](#)) and to a limestone lens embedded in shales of

the lowermost part of the Saint-Chinian Formation ([Serpagli et al., 2007](#)), allows a better constraint of the Upper Cambrian-Tremadocian boundary interval in the



southern Montagne Noire. The fossiliferous level of Sallèles-Cabardès (Figs. 6 and 7M–P) has yielded in fact the conodont subspecies *Paltodus deltifer pristinus* (Viira, 1970) and *Paltodus deltifer deltifer* (Lindström, 1955), which allow attribution of the horizon to the *P. deltifer* Zone and, in particular, to the upper part of the zone (*P. deltifer deltifer* Subzone) on the basis of the following considerations. According to Szaniawski (1980), *P. deltifer pristinus* characterizes the older subzone of the *P. deltifer* Zone whereas *P. d. deltifer* is the index fossil of the younger subzone. In some areas of South-Central Sweden, *P. d. pristinus* co-occurs with *P. d. deltifer* but this appears to be in most cases the result of redeposition (Löfgren, 1997). In the same localities, *P. d. deltifer* spans also into the lowermost part of the overlying *Paroistodus proteus* Zone. Similarly, in our material, both *P. d. pristinus* and *P. d. deltifer* co-occur. Nevertheless, the former subspecies is represented by extremely delicate forms characterized by the same good preservation than *P. d. deltifer* elements. Based on this argument, we see no reasons to invoke redeposition to justify the concurrent presence of both subspecies in our material. *Paltodus d. pristinus* may therefore co-occur with *P. d. deltifer* at least in the lowest part of the *P. d. deltifer* Subzone. However, as we do not exactly know if this co-occurrence might extend higher up in the *P. d. deltifer* Subzone, it appears more reasonable for the moment to attribute the studied level to the whole *P. d. deltifer* Subzone.

It is well known that no agreement exists in the subdivision of the Tremadocian into two or three parts. In Great Britain, location of the historical type area, the Tremadocian is subdivided into two parts, named Cressagian and Migneintian (Fortey et al., 1995). Graptolite workers usually subdivide the Tremadocian into two parts, placing the boundary, according to the areas, at the first appearance of *Psigraptus* or *Adelograptus tenellus* (Zhang et al., 2004: Fig. 9). A three-fold subdivision was also proposed by Erdtmann (1988). In the Montagne Noire, trilobite workers have been traditionally adopting a three-fold subdivision with *P. geinitzi*, *Shumardia (C.) pusilla* and *Euloma filacovi*

zones characterizing the lower, middle and upper part of the Tremadocian, respectively (Vizcaino and Álvaro, 2003; Tortello et al., 2006). However, this subdivision based on regional trilobites is at present under revision based on the recent discovery of conodonts. Conodont workers are currently using both a two- and three-fold subdivision of the Tremadocian. Some authors place the two-fold boundary in the uppermost part of the *Cordylodus angulatus* Zone (e.g., Zeballo et al., 2005: Fig. 3; Ortega and Albanesi, 2005: Fig. 2). In this case, the whole *P. deltifer* Zone would completely correspond to the Late Tremadocian. However, other conodont stratigraphers (such as Löfgren, 1997: pp. 264–265) subdivide the Tremadocian into three parts, with the *P. d. pristinus* Subzone marking the middle Tremadocian and the *P. d. deltifer* Subzone the late Tremadocian. Even in this case, the middle part of the Val d'Homs Formation in the Minervois nappe, corresponding to the *P. d. deltifer* Subzone, would be late Tremadocian in age.

In the southern Montagne Noire, studies focused on early Palaeozoic acritarchs are exclusively reduced to Martin's (1972) contribution from the Lower Ordovician Saint-Chinian Formation. We have tested the presence of acritarchs in Upper Cambrian, *Langyashania*-bearing shale beds from the uppermost part of the La Gardie Formation in the Campelou section (Pardailhan nappe). Unfortunately, preservation of organic-walled microfossils is not optimal and, associated with undiagnostic *Leiosphaeridia* Eisenack, 1958, and additional unrecognizable acanthomorphs and diacromorphs, only two distinct species were identified: *Timofeevia phosphoritica* Vanguetaine, 1978, and *Cristallinium cambriense* (Slavíková) Vanguetaine, 1978 (Fig. 8A–D). *Timofeevia phosphoritica* is a species found in the Mediterranean region (e.g., Algeria, Sardinia, and Turkey), Central and northern Europe, the Eastern European Platform, and eastern Newfoundland (Albani et al., 1991). Its known stratigraphic occurrence ranges from the *Paradoxides paradoxissimus* trilobite Superzone (Middle Cambrian; Martin and Dean, 1981) to the *Peltura* trilobite Zone (Late Cambrian; Martin and Dean, 1981). *Cristallinium cambriense* also shows

Fig. 7. Representative Late Cambrian brachiopods and Tremadocian conodonts from the Val d'Homs Formation of the southern Montagne Noire, reported from the first time in this work. A–C. *Dactylotreta bacula* González-Gómez, 2005: inner view of ventral valve; external view of dorsal valve; and oblique view of ventral valve; Ferrals-les-Montagnes. D–E. *Ferralstreta globosa* González-Gómez, 2005: external view of ventral valve; interior view of ventral valve; Ferrals-les-Montagnes. F–G. *Canthylotreta?* n. sp.; external view of ventral valve; interior view of ventral valve; Refescals ravine. H. *Zhanatella rotunda* Koneva, 1986; detail of the interior side of the dorsal valve; Refescals ravine. I–J. *Eoscaphelesma* n. sp.; external view of ventral valve; interior view of ventral valve; Refescals ravine. K–L. *Dicondylotreta* n. sp.; external view of ventral valve; interior view of ventral valve; Sallèles-Cabardès section. M–N. *Paltodus d. deltifer* (Lindström, 1955), M elements; Sallèles-Cabardès section. O–P. *Paltodus d. pristinus* (Viira, 1970), M elements; Sallèles-Cabardès section. Brachiopod scales = 200 µm and conodont scales = 100 µm. Brachiopod illustrated specimens are housed at the Muséum National d'Histoire Naturelle (Paléontologie), Paris, and conodont illustrated specimens at the Dipartimento del Museo di Paleobiologia e dell'Orto Botanico, Università di Modena e Reggio Emilia, Modena, under repository numbers IPUM 27992–27995, respectively.

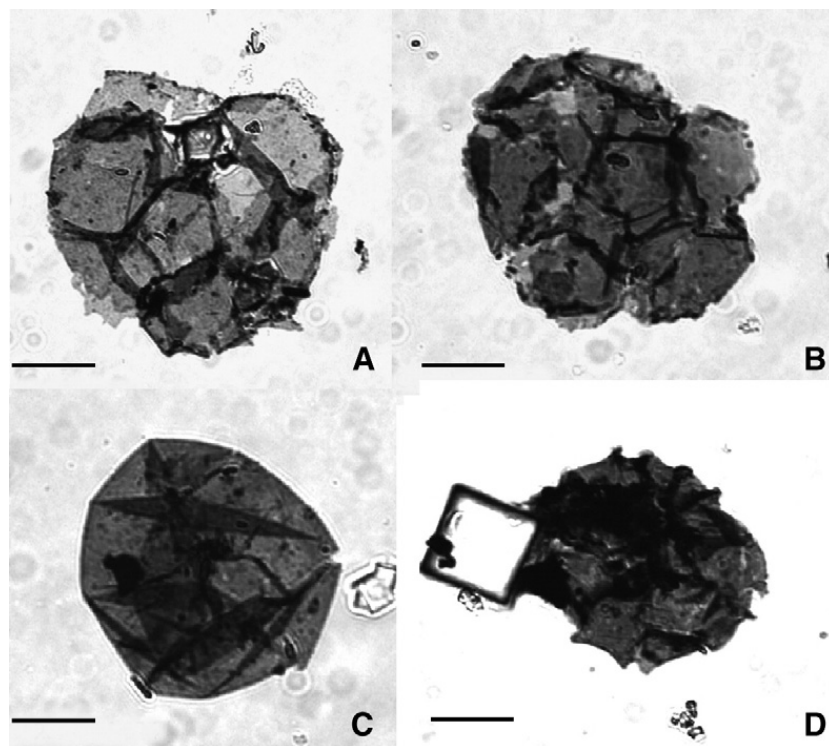


Fig. 8. Representative acritarchs from the Late Cambrian of the southern Montagne Noire (Campelou section; Pardailhan nappe), reported for the first time in this work. A–B. *Crystallinium cambiense* (Slavíková) Vanguetaine, 1978. C. *Leiosphaeridia* sp. D. *Timofeevia phosphoritica* Vanguetaine, 1978.

a worldwide palaeobiogeographic distribution, and its stratigraphic distribution ranges between the *Ptychagnatus atavus*–*Tomagnostus fissus* trilobite Zone (Middle Cambrian) in eastern Newfoundland (Martin and Dean, 1981) to the Cambrian–Ordovician transition (*Cordylodus lindstromi* conodont Zone in Dayangcha, Jilin Province, China; Yin Lei-ming in Chen et al., 1988). Therefore, diagnostic acritarchs from the Upper Cambrian are, by the moment, absent in the southern Montagne Noire.

In the proximal part of the southern-Montagne-Noire platform (Minervois nappe), the lower member of the La Gardie Formation consists of rhythmic, millimetre-thick, lenticular-bedded shale to wavy and flaser-bedded sandstone intervals associated with channels displaying complex lateral accretion patterns (Fig. 6). The preservation of millimetre-thick, claystone/sandstone rhythmites cut by meandering channels developed in tidal environments in the inner reaches of macrotidal estuaries affected by meander channels with reversely oriented foresets (Álvaro et al., 2003b).

Both the Sallèles Member and the La Dentelle Formation have erosive and abrupt lower and interbedded contacts, scouring into the underlying sediments. They comprise large-scale, trough and planar cross-beddings with sets ranging in thickness from 0.4 to 1.8 m, topped by

symmetric ripples and ripple lamination. They were deposited as short-crested megaripples and sandwaves. The association of sedimentary structures suggests a shallow platform dominated by wave activity, and minor storm reactivation related to interbedded erosive contacts. Episodes in which the bedforms ceased to migrate allowed colonization by an open-sea benthic community. Strata are generally incorporated into coarsening-upward parasequences (0.8–1.2 m thick): from bottom to top, almost all the parasequences display a systematic succession in which the finer-grained storm deposits are gradationally or sharply covered by the coarser-grained sandstones. At the top of some parasequences occur erosive and truncating surfaces, partly stained by iron oxides, and locally highly bioturbated by *Skolithos* and *Arenicolites*. Shoaling (prograding trends related to shallowing-upward fluctuations of the relative sea level) during times of rapid sediment influx offers a simple and repeatable mechanism for creating these coarsening-upward parasequences, topped by bioturbated hardgrounds (Álvaro et al., 2003b).

The stratigraphic interval bounded between the Sallèles Member and the La Dentelle Formation is represented by the offshore shale-dominated upper member of the La Gardie Formation and the heterolithic strata of the Val d'Homs Formation. In the latter, two

kinds of limestone/shale alternations occur: the so-called 'griotte' and carbonate tempestites. The 'griotte' consists of centimetre-thick alternations of bedded to nodular limestone and shale exhibiting reddish to purple colours. The thicker carbonate beds (up to 20 cm thick) are dominated by packstone textures, including disarticulated to broken trilobites, echinoderm ossicles, hyolith-like shells, chancelloriid sclerites, carbonate- and phosphate-shelled brachiopods, and rarer conodonts and sponge spicules. The thinner limestone beds and nodules (less than 5 cm thick) are mainly wackestones rich in the same fossil assemblage, in some cases displaying erosive local contacts and grading, up to 1 cm thick. Cycles or alternations exhibit a repeated increasing-upward shale/limestone ratio, starting with limestone beds with stylonodular textures and millimetre-thick clay seams, grading upward into shales with isolated thin limestones. The rhythmic alternation in lithology indicates periodic fluctuations in carbonate productivity and/or supply of fine siliciclastic sediments, the latter inhibiting the former. The thicker limestone intercalations have recorded the influence of bottom currents and waves (shoreface), while the thinner ones illustrate quieter conditions interrupted by high-energy pulses (offshore). The repeated (decimetre- to metre-thick) changes reflect deepening-upward trends where bioclastic pavements correspond to distal expressions of storm-induced processes. The most distinct feature of this facies association is its important lateral variation of thickness. Similar variegated limestone/shale alternations are known from the Lower–Middle Cambrian transition of southwestern Europe (named 'griotte' by their colour), and currently represent carbonate deposition on tectonically induced palaeohighs, whereas shale deposition took place in relative, laterally equivalent depressions.

The alternating shale and bioclastic (tempestitic) limestones, 0.1 to 1.4 m thick, display sharp and erosive contacts. Bioclastic limestones consist of packstones to wackestones, whose main constituents are poorly-sorted trilobites, echinoderms, sponge spicules, chancelloriid sclerites, calcite- and phosphate-shelled brachiopods, and conodonts. The preservation of a non-fragmentary fossil record and high mud content alternating with fragmented skeletons and graded units, with erosive lower contacts, indicates that the substrate was episodically affected by storm events.

Slope-related deposits are abundant in the Upper Cambrian La Gardie and Val d'Homs formations of the southern Montagne Noire. These consist of shales and sandstone alternations episodically characterized by a chaotic arrangement of contorted beds, interrupted by

truncation surfaces, intraformational slumps and syn-sedimentary bedding distortion. These structures are interpreted as having undergone different types of down-slope movements by basal sliding of plastic to semi-rigid sediment masses. The reworked material was developed on slopes close to the sedimentary environments from which they were derived. The lack of breccia deposits and rhythmic turbidites suggests low-angle slopes, in contrast with the conventional steeped submarine fan models, which imply base-of-slope to basin deposition dominated by turbidites.

The La Dentelle sedimentation occurred when shoreline and nearshore facies prograded across a tectonically induced palaeotopography, as a result of an increase in terrigenous supply and establishment of regressive conditions. During deposition of the La Dentelle Formation, the inherited palaeorelief disappeared or was highly attenuated, since the coarse-grained siliciclastics extended to the whole platform, and no tectonic interruptions are recorded. At the end of the La Dentelle progradation, a subsequent abrupt relative sea-level rise caused a marked change in depositional patterns, marked by a correlatable glaucaenite. This documents a major transgressive surface reflecting a sharp change in the style of sedimentation and the flooding of the platform. Continued transgression during Tremadocian times (Saint-Chinian Formation) flooded most of the platform, where tectonically induced 'griotte' facies are still residual in some areas (Mounio Formation; Álvaro et al., 2003b).

From a sequence-stratigraphic point of view, the La Gardie-Val d'Homs-La Dentelle sedimentary succession represents a composite retrogradational–progradational (or transgressive–regressive) depositional system. The lower retrogradational (transgressive) depositional system is characterized by a vertical succession from mixed tidal (estuarine?) flats and channels (back-shoal heterolithic beds of the lower member of the La Gardie Formation), covered by shoreface to foreshore shoal complexes (Sallèles Member), and capped by the upper member of the La Gardie Member and the Val d'Homs offshore sediments. The Val d'Homs, outer-platform sedimentation was dominated by suspension setting of mud under fair-weather conditions punctuated by sharp storm events. The difference in sedimentation rates of both carbonate and siliciclastic substrates suggests establishment of topographic highs on the platform where isolated windows of carbonate productivity were rhythmically intense in the 'griotte' facies, surrounded by deposition of terrigenous sediments on adjacent lows or depressions. This was laterally accompanied by relatively common high-energy currents transporting

sediment down-slope as a result of high-slope instabilities resulting in slumping, sliding and debris flow. In contrast, coeval deposition on intra-platform ramp settings was marked by much quieter conditions where substrate stability was higher.

Although the Cambrian–Ordovician transition of the southern Montagne Noire did not record volcanic events but a rather extensive regime inducing palaeotopographies, a major extensional regime was recorded across the transition in other areas of the French Massif Central involving an episodic input of tholeiitic intra-plate lavas and tuffites (Guérangé-Lozes and Burg, 1990; Ledru et al., 1994).

3.6. The Anti-Atlas (Morocco) and neighbouring areas

The Upper Cambrian of Morocco has been exclusively reported in the Jbel Lmgaysmat Formation (Tabanite Group; Destombes et al., 1985). Its outcrops seem to be limited to a part of the El Graara Massif (Central Anti-Atlas), a geographic extension that is probably related to the erosive unconformity that overlies the unit. The formation consists of shales and fine-grained sandstones, with thin calcareous layers and nodules rich in fossil fragments (Fig. 6). The base of the Jbel Lmgaysmat Formation, up to 35 m thick, is an erosive discontinuity covered by a conglomeratic to coarse-grained sandstone that displays cross-bedded sets, is strongly limonitized, and rich in rhyolitic gravels (Destombes et al., 1985; Destombes, 1989). Two shallowing-upward parasequences are recognized, 10–15 m thick, dominated by shales with isolated, centimetre-thick limestones rich in trilobites and brachiopods, and topped by respective iron-stained sandstone shoals. The upper parasequence is capped by up to 10 m of amalgamated, trough cross-bedded sandstone sets. They are overlain by an erosive unconformity that, laterally, cuts into the underlying strata leading to a sharp decrease in thickness (from SW to NE) and final disappearance of the Jbel Lmgaysmat Formation. The overlying Lower Fezouata Formation begins with a conglomeratic bed, less than 1 m thick, which passes laterally into a glauconite-rich, coarse-grained sandstone, on the top of which occurs the first debris of *R. flabelliformis* in a shale-dominated succession.

Scattered coquinas interbedded with shales of the Jbel Lmgaysmat Formation have yielded the trilobites *Olentella africana* and *Seletella latigena* (Destombes and Feist, 1987), and the brachiopods *Saccogonum saccatum* and *Billingsella destombesi* (Havlíček, 1971). The presence of additional aphelaspid and elviniid trilobite species associated with debris of *Saccogonum*

has also been reported in the Central Anti-Atlas (Geyer et al., 2002), but this fauna has not yet been described nor illustrated.

The erosive unconformity that overlies the Jbel Lmgaysmat Formation has been correlated with the Sardinian unconformity (Michard, 1976) or with epeirogenic uplifts (Destombes et al., 1985). The hiatus is common to all North-African basins from Morocco through Algeria, Libya, and Tunisia (Crossley and McDougall, 1998). Crossley and McDougall (1998) reported evidence for block faulting and marked angular unconformities in Algeria, although similar evidence is absent in the Anti-Atlas of Morocco, where some lateral thickness changes are subtle at best, and strongly overprinted by later folding (Burkhard et al., 2006).

4. Toward an integrated sequence—stratigraphic framework

Although a biostratigraphic subdivision of the Upper Cambrian is still unavailable in the western Mediterranean region, some tie points can be made based on trilobite, brachiopod and echinoderm faunas. This leads to the recognition of a succession of transgressive–regressive packages, commonly bounded by regionally correlatable, erosive unconformities. As regressive strata represent nearshore platform and continental facies, age-diagnostic fossils are not always common in the regressive packages.

4.1. Relative sea-level fluctuations

As illustrated in Fig. 3, Upper Cambrian sedimentation was relatively continuous and devoid of significant stratigraphic gaps in the southern Montagne Noire and the Iberian Chains. There, Upper Cambrian strata are bracketed by two major regressive trends. Both regressions are topped by: (i) an uppermost Middle Cambrian discontinuity related to the progradation of back-shoal environments, some of them tidally influenced (lower part of the La Gardie and Valdeorea-Torcas formations; Álvaro, 1995; Álvaro et al., 2003b); and (ii) an uppermost Cambrian–lower Tremadocian unconformity related to the progradation of foreshore to shoreface, shoal complexes (La Dentelle and Valconchán formations; Álvaro et al., 2003b). In this context, the Upper Cambrian sedimentation developed a broad transgressive-dominated depositional system, with common offshore deposits and both clayey and carbonate substrates (upper part of the La Gardie/Val d'Homs and Valtorres formations; Álvaro and Vennin, 1996a; Álvaro et al., 2003b).

The base of the *G. reticulatus* Zone coincides in the Jiangnan Slope Belt (Hunan, China), the type area where the GSSP for the base of the Furongian has been defined, with the initial stages of a transgression (Yang and Xu, 1997). Transgression coinciding with the lower part of the *G. reticulatus* Zone is followed by a highstand phase and then a regression documented in South and North China (Yang and Xu, 1997). This regression is represented in Laurentia by the Sauk II–Sauk III hiatus (Palmer, 1981; Osleger and Read, 1993; Saltzman et al., 2000). In addition, the ‘*Acerocare* Regressive Event’ of Erdtmann (1986) is the base of the Tremadocian traditionally applied in Scandinavia. Nicoll et al. (1992) redefined it to refer only to the regressive peak at the top of its homonymous zone, and correlated it with the base of the Warendian in shelf sediments of Australia. Subsequently, Artyushkov et al. (2000) reinterpreted the ‘*Acerocare* Regressive Event’ as a result of a misinterpretation influenced by a synsedimentary tectonic uplift, and not by eustatic fluctuations, recorded in Oeland and southern Sweden during the Tremadocian. Accordingly, this regressive event cannot be used as an argument for intercontinental correlation.

As a result, the Cambrian–Ordovician transition seems to be globally represented by a regression, probably of eustatic character, which was slightly diachronous in southwestern Europe. The regression represented by the progradation of the La Dentelle (Montagne Noire) and Valconchán (Iberian Chains) formations culminated with the record of distinct erosive unconformities (Fig. 9). This was also reflected in SW Sardinia by the record of tidally induced rhythmites in the condensed Cabitza Formation (Loi et al., 1995). The erosive unconformity that tops this regression is distinctly diachronous: it took place in the Iberian Chains at a virtual Cambrian–Ordovician boundary interval (the lower part of the Valconchán Formation contains Late Cambrian trilobites, whereas its upper part has yielded early Tremadocian echinoderms), and in the southern Montagne Noire within the *P. geinitzi* (Tremadocian) Zone. The delayed progradation of foreshore and shoreface depositional systems in the southern Montagne Noire was probably due to the record of subsidence perturbations. These are indicated by the abundance of slope-depositional facies in the La Gardie, Val d’Homs, Mounio and Saint-Chinian formations, and sharp lateral variations in thickness that favoured an episodic development of palaeotopographies, only buried by the progradation of the La Dentelle sandstone shoals (Álvarez et al., 2003b).

4.2. Erosive unconformities and related gaps

In the Anti-Atlas, the Cantabrian Zone, SW Sardinia, and the southern Montagne Noire a Late Cambrian–Early Ordovician regression truncated large areas of their platforms. The related gaps are diachronous, becoming younger from SW to NE: (i) the gap can include the entire Upper Cambrian in the Anti-Atlas; (ii) it ranges from lower Upper Cambrian to the Tremadocian–Floian transition in the Cantabrian Zone; (iii) from lower Tremadocian to the ‘5th-Ordovician’ stage in SW Sardinia; and (iv) from the Floian–‘3rd Ordovician’ stage transition to the ‘5th Ordovician’ (Sandbian) stage in the southern Montagne Noire (Fig. 3). In addition, the Armorican Massif does not have a record of Upper Cambrian strata, due to the existence of a gap that ranges from uppermost Lower–lowermost Middle Cambrian to the transition across the Floian and ‘3rd Ordovician’ stages (see a synthesis in Paris et al., 1999). By contrast, sedimentation in the Iberian Chains was relatively continuous across Late Cambrian and Tremadocian times (Fig. 3). There, some authors (e.g., Wolf, 1980; Babin and Hammann, 2001; Gutiérrez-Marco et al., 2004) placed a stratigraphic hiatus at the top of the Armorican Quartzite; however, its sedimentological implications and biostratigraphic gap have not yet been described in detail.

The aforementioned gaps can be related to non-deposition and erosion, but their diachronous migration across the Late Cambrian and Early–Middle Ordovician, in a palaeogeographic SW–NE transect, suggests a possible common geodynamic origin. Gaps were also preceded and succeeded by tectonic instability and intra-continental extension in the western Mediterranean region, favouring episodic development of palaeotopographies.

The Late Cambrian hiatus recorded in Morocco and adjacent areas has been interpreted as related to a phase of neighbouring rifting (further North) and concomitant erosion on southern rift shoulders (Burkhard et al., 2006). A possible explanation for the SW–NE diachronous shift of the aforementioned erosive unconformity may be related to an associated northeastward migration of a northern rift that led to numerous magmatic and plutonic episodes of tholeiitic and alkaline affinities. In the Cantabrian Zone, Heinz et al. (1985) and Loeschke and Zeider (1982) described: (i) sills intruded into not yet lithified shales and sandstones of the Oville Formation; and (ii) pyroclastic rocks forming the infill of several hydrothermal craters and pipes caused by phreatomagmatic eruptions; most of the necks are cut off by erosion shortly below the unconformity of the La Matosa/Ligüeria

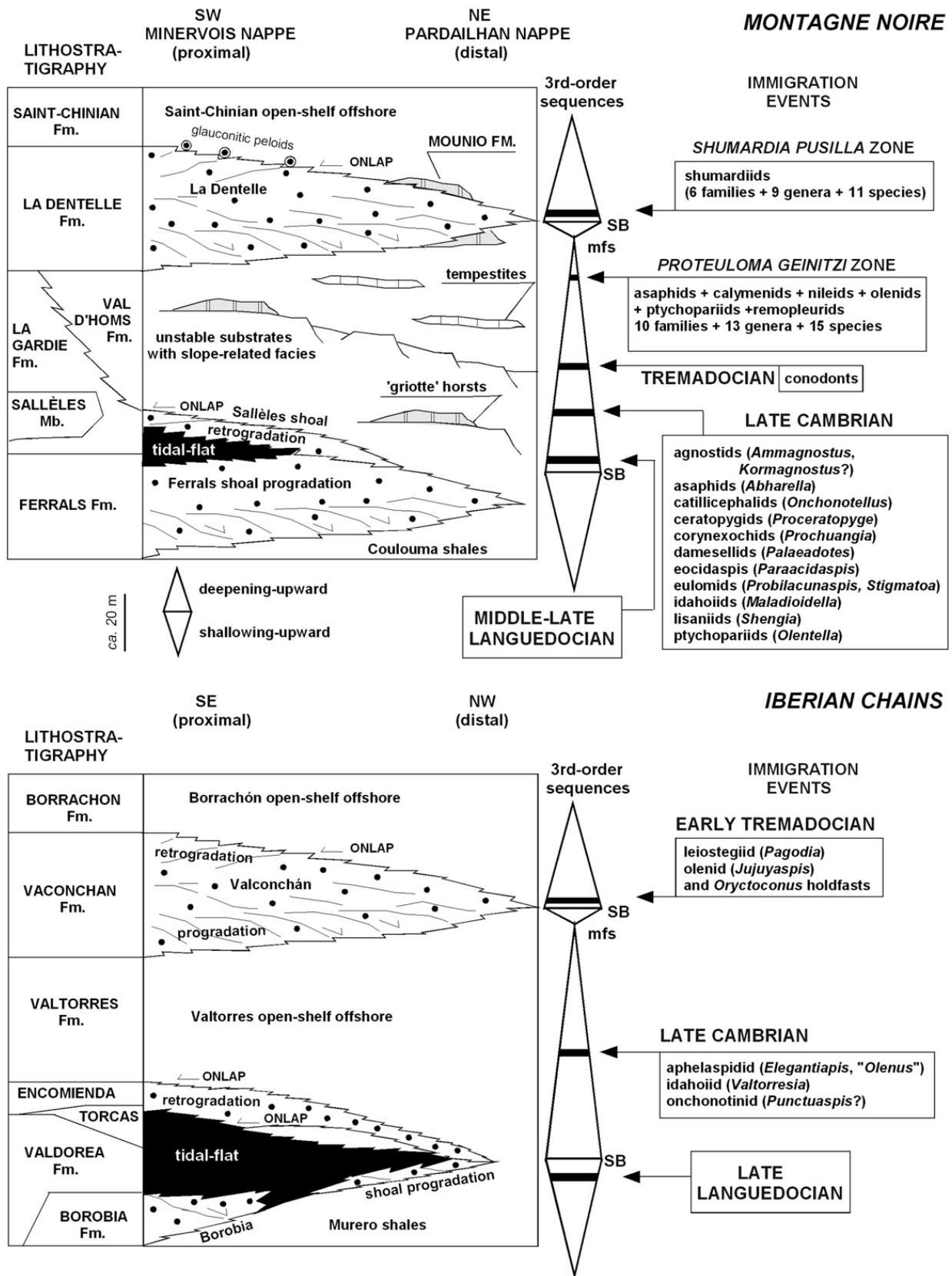


Fig. 9. Integrated stratigraphic comparison of the Late Cambrian from the southern Montagne Noire and the Iberian Chains, showing the relationship between immigration events, biostratigraphy and third-order sequences.

contact. The authors described all these volcanic products as belonging to a same magmatic phase, where the volcanic bombs, subvolcanic xenoliths and pyroclastic rocks are geochemically assigned to alkaline olivine basalts and trachy-basalts. As a result, the late Middle Cambrian to Tremadocian volcanic activity recorded in the Cantabrian Zone was interpreted as connected with rifting and mantle-plume processes that also affected the continental crust of the northwestern Hesperian Massif (Van Carlssteren and Den Tex, 1978; Van der Meer Mohr et al., 1981). Lower Ordovician lavas and plutonic rocks of the Armorican Massif are also tholeiitic and alkaline, and characterize intra-plate extensions (Cabanis, 1986). The Lower Ordovician tholeiites of the Albigeois (northern Montagne Noire) suggest crustal thinning (Marini, 1988) and intra-plate magmatism (Guérangé-Lozes and Burg, 1990; Ledru et al., 1994). The base of the Ordovician Series in the Central and western Pyrenees has rhyolitic interbeds (sills and rare lava flows) and conglomeratic layers rich in rhyolitic debris (Majeste-Menjoules and Debat, 1994), where Lower Ordovician granitoids and metavolcanic rocks are common (Calvet et al., 1988; Deloule et al., 2002). In the Ollo de Sapo domain of the Central Iberian Zone, widespread Lower Ordovician granitoid intrusions of Floian age are followed by the Toledanian unconformity (Valverde-Vaquero and Dunning, 2000). The eventual end of the Avalonian detachment seemingly caused the final deformational overprint at the Middle Ordovician Sardic Phase in Sardinia. Pre-Sardic strata folded generally under very low-grade metamorphic conditions but at its type locality in SW Sardinia the Sardic Phase is not considered as an orogenic event, but related to rifting and evolution of the Rheic Ocean (Helbing and Tiepolo, 2005).

Another volcanosedimentary complex related to the opening of the Rheic Ocean is recorded in the Ossa-Morena Zone (SW Iberian Peninsula). There, progressive crustal thinning, inducing rifting and the building of a volcanically active passive margin facing southward to the future Rheic Ocean, represents the first volcanic stages associated with the drift between NW Gondwana and Avalonia (Etxebarria et al., 2006). Rifting propagated diachronously across the zone from the Early Cambrian to the Late Ordovician, but by Early Ordovician time, the existence of a significant tract of new ocean is evidenced by a breakup unconformity (Sánchez-García et al., 2003). Finally, the Tremadocian–early Floian is also marked by a period of break-up of the Uralian margin of Baltica. This faced southward the NW Gondwanan margin at the beginning of the Ordovician (Torsvik and Rehnström, 2001), and recorded the birth of a new rifting zone located in SE Baltica (Stuesson et al., 2005).

5. Ecostratigraphic patterns

The scarcity of biostratigraphically significant fossils has not favoured the proposal of any fine chronostratigraphic subdivision in the Upper Cambrian of the western Mediterranean region. Correlation of their strata is approximated with spot horizons, and the actual base of chronostratigraphic links is only approximate and can suffer further modifications in the future depending on new fossil findings.

5.1. Major benthic community replacements

During the Cambrian, the western Gondwanan margin is commonly portrayed as oriented approximately SW–NE in the southern hemisphere (McKerrow et al., 1992). As a consequence of this orientation, the shape of the tropical zones was affected by the course of major ocean currents transporting cool waters toward the tropics. This would have caused the tropics to occupy a narrower latitudinal area on this western margin respect to the eastern margins (Briggs, 1995). As stated by Álvaro et al. (2003a), this inferred palaeogeographic situation may be compared with that of the western Australian margin during the Eocene, when Australia and Antarctica were close enough to prevent the development of a circum-Antarctica circulation (McGowran et al., 1997). As a result, two main surface circulation patterns took place: a South-Equatorial Current flowing (up to the Recent) as a low-salinity surface component of the global thermocline system, and a western Australian current (parallel to the western face of Australia) that disappeared with the Eocene opening of a gap between both continents. Apparently, a similar western Gondwanan SW–NE current rising in latitude from polar areas operated during Cambrian times, contrasting with an opposite (NE–SW) current bringing subtropical waters into this temperate Gondwanan margin. The variable dominance of both currents directly affected faunal migrations and palaeoclimates.

A shift from subtropical carbonate-dominated platforms to temperate-water siliciclastic platforms is attributed to changing oceanographic and palaeoclimatic conditions across the Middle–Late Cambrian transition, when the southward-moving subtropical margin of NW Gondwana progressively invaded temperate and cold seas. The episodic development of Late Cambrian–Tremadocian carbonate factories within temperate-water settings of the southern Montagne Noire (Val d'Homs and Mounio formations) signals short-lived warming episodes in meridional parts of NW Gondwana. These carbonate substrates represent sporadic development of

Languedocian–Late Cambrian cancelloriid-echinoderm-sponge (*CES*) relics, also rich in linguliformean brachiopods and trilobites, which were widely distributed during the Early and Middle Cambrian. This association changed during the Tremadocian, as indicated by the disappearance of cancelloriids and the input of conodonts.

By contrast, the same cooling trend, from subtropical to temperate waters, was marked differently in siliciclastic substrates. Álvaro and Vennin (2001) described in the Iberian Chains the successive decline and disappearance of: (i) late Early Cambrian ooids, evaporite relics and microbial carbonates; (ii) cancelloriid-echinoderm-sponge meadows crossing the Early–Middle Cambrian transition; (iii) Middle Cambrian hydrodynamic bioclastic carbonates related to the contraction of carbonate factories into increasingly narrow belts ('griotte' facies); (iv) a late Middle Cambrian increase of trilobite-dominated communities on clayey substrates; and (v) late Middle–Late Cambrian impoverished benthic communities dominated by linguliformean brachiopods in sandy shoals and trilobites on open-sea, clayey substrates. The Languedocian–Late Cambrian interval seems to mark in these substrates the culmination of a cooling trend as shown by the pervasive decrease in trilobite biodiversity (Álvarez et al., 2003a), associated with the drastic disappearance of bioclastic carbonates.

Late Cambrian trilobites are scattered in the western Mediterranean region compared with the abundance recorded in Lower and Middle Cambrian strata of the same area. This suggests that the Late Cambrian, temperate-water faunas of the margin were less diverse and more impoverished than the Early–Middle Cambrian subtropical ones. However, the palaeoclimatic modification related to the southward drift of NW Gondwana was not the single control on biodiversity. For instance, Late Cambrian faunas from the British Islands (eastern Avalonia) and Baltica are extremely rich and diverse. This wealth is directly controlled by the distribution of the prolific (although sampling biased) olenid biofacies, which was environmentally, not climatically controlled, and is absent in the western Mediterranean region.

5.2. Immigration events and their control on biostratigraphy

As indicated above, a common Languedocian regression has been recorded in the southern Montagne Noire and the Iberian Chains. In both platforms, the regression is characterized by progradation of a siliciclastic rimmed platform with three major deposi-

tional systems, in ascending order (or from distal to proximal environments): (i) offshore clayey substrates (Coulouma and Murero formations); (ii) shoal complexes sequentially arranged in shoaling parasequences (Borobia and Ferrals formations); and (iii) tidally induced rhythmites (mixed tidal flats; Valdeorea and proximal outcrops of the lower member of the La Gardie formations) and back-shoal bioturbated siltstones (Torcas Formation). Late Languedocian trilobites are recognized in the Borobia and La Gardie/Val d'Homs formations, and are dominated: (i) in the Montagne Noire, by agnostids (*Megagnostus* and *Pseudoperonopsis*), paradoxidids (*Eccaparadoxides*), conocoryphids (*Bailiaspis*, *Bailiella*, *Conocoryphe*, and *Holocephalina*), solenopleurids (*Jincella*), agraulids (*Skreiaspis*), proasaphiscids (*Chelidonocephalus*, *Derikaspis*), dorypygids (*Dorypyge*), and the last record of cinctans (*Sucocystis*); and (ii) in the Iberian Chains, by an impoverished assemblage of conocoryphids and paradoxidids. The conocoryphid–paradoxidid–solenopleurid assemblage was one of the typical Leonian–Caesaraugustian–early Languedocian (Middle Cambrian) trilobite associations of the Acado-Baltic province *sensu* Sdzuy (1972). During the late Languedocian, this palaeobiogeographic pattern changed with the input of more cosmopolitan invaders (*e.g.*, *Chelidonocephalus*, *Derikaspis*, and *Dorypyge*) that firstly co-occurred with species of the conocoryphid–paradoxidid–solenopleurid assemblage, and subsequently replaced them.

In the southern Montagne Noire, the succeeding late Languedocian–early Tremadocian transgression is characterized by a stepwise immigration of new trilobite families. Several events can be distinguished:

- (i) A re-colonization of offshore substrates, coinciding with the retrogradation of the Sallèles shoal complex, was made by paradoxidids (*Eccaparadoxides*), dorypygids (*Dorypyge*) and, for the first time, anomocarids (*Abharella*). This event marks a distinct episode during which the shoal complexes of the Sallèles Member ceased their migration and allowed colonization of sandstone substrates by this faunal assemblage.
- (ii) The retrogradation of coarse-grained siliciclastic packages allowed establishment of open-shelf (offshore) conditions and, in the Montagne Noire, of carbonate factories. In the Iberian Chains, the Late Cambrian immigration (Valtorres and lower part of Valconchán formations) is represented by aphelaspidids (*Elegantiaspis*, "*Olenus*"), idahoiids (*Valtorresia*), olenids

(*Jujuyaspis*), and onchonotiniids (?*Punctaspis*). This event is much more diversified in the shale/limestone alternations of the southern Montagne Noire (Val d'Homs Formation), where it is characterized by the input of agnostids (*Ammagnostus*, ?*Kormagnostus*), anomocarids (*Abharella*), aphelaspids (*Olentella*), catillicephalids (*Onchonotellus*), ceratopygids (*Proceratopyge*), damesellids (*Palaeadotes*), eulomids (*Probilacunaspis*, *Stigmatoa*), idahoiids (*Maladioidella*), lichakephalids (*Paraacidaspis*), lisariids (*Shengia*), pagodiids (*Prochuangia*), as well as new echinoderm faunas.

- (iii) After the first record of isolated Tremadocian conodont-rich lenticular limestones at the middle and upper parts of the Val d'Homs Formation (Montagne Noire; Küppers and Pohler, 1992; Álvaro et al., 2005), an abrupt trilobite turnover is recorded in the reddish and purple shales and limestones that underlie the La Dentelle Formation. This immigration marks the base of the *P. geinitzi* Zone, and contains a rich trilobite assemblage composed of agnostids (?*Anglagnostus*, *Geragnostus* and *Leiagnostus*), asaphids (*Niobella* and *Symphysurina*), calymenids [*Platycalymene* (*Pharostomina*)], catillicephalids (*Onchonotellus*), possible hystericurids (*Holubaspis*), nileids (*Hemibarrandia*), and remopleurids (*Macropyge*). The oldest Tremadocian trilobite record represents a sharp immigration of highly diverse trilobites, which comprise 10 families, 13 genera and 15 species. In Sardinia, *P. geinitzi* (reported in the C6 assemblage of Loi et al., 1995) is associated with the graptolite *R. flabelliformis*, earliest Ordovician acritarchs (Barca et al., 1987) and the pelmatozoan holdfast *O. lobatus*. The latter co-occurs in the Iberian Chains with leiostegiids (*Pagodia*), representing a re-colonization of near-shore substrates (Valconchán Formation).

After the delayed installation of a progradational, coarse-grained siliciclastic platform in the southern Montagne Noire (La Dentelle Formation), a new immigration phase is recorded both in carbonate and siliciclastic substrates (Mounio and Saint-Chinian formations, respectively). By comparison with the *P. geinitzi* Zone, a relatively impoverished trilobite assemblage is recognized with only 6 families, 9 genera and 11 species, in which the exceptional occurrence of the family Shumardiidae is remarkable. This immigration event allows the identification of the base of the *Shumardia* (*C.*) *pusilla* Zone, located in the lowermost

part of the Mounio and Saint-Chinian formations. The drastic trilobite turnover recorded across the *P. geinitzi-Shumardia* (*C.*) *pusilla* zone transition, related to the onset of regressive conditions, involved the disappearance of all the previously known species. The *Shumardia* (*C.*) *pusilla* Zone comprises a new trilobite assemblage mainly composed of agnostids (*Anglagnostus* and *Geragnostus*), ptychopariids (*Euloma*) and shumardiids [*Shumardia* (*Conophrys*)], and the last record of conodonts belonging to the *P. deltifer* Zone (Serpagli et al., 2007). The immigration of shumardiids is also documented in the Borrachón Formation of the Iberian Chains (Schmitz, 1971; Josopait, 1972).

In summary, the immigration events described above do not seem to have a direct relationship with major relative sea-level fluctuations, although they were more numerous and implying more diversified faunas when they took place in transgressive trends. In fact, two of the major faunal turnovers (marking the bases of the Upper Cambrian and the Tremadocian *P. geinitzi* Zone) are included within the same transgression. The only exception is related to the progradation of the La Dentelle Formation (Tremadocian), which was succeeded by a distinct faunal turnover, biostratigraphically marked by the base of the Tremadocian *Shumardia* (*C.*) *pusilla* Zone.

6. Palaeobiogeographic affinities

The biogeographic distribution of latest Middle Cambrian and Late Cambrian trilobites supports brachiopod data indicating strong affinities between NW Gondwana (Mediterranean region), East Gondwana (North China/Korea, South China, Australia, and Antarctica) and Kazakhstan during the late Languedocian, which became significantly stronger during the Late Cambrian (Fig. 10). This major shift in palaeobiogeographic connections, which contrasts with the Leonian–Caesaraugustian–early Languedocian (Middle Cambrian) dominant distribution throughout the Acado-Baltic province (Álvaro et al., 1999), may suggest a significant change in oceanic circulation patterns throughout Gondwana, a process already suggested by Brock et al. (2000) and Álvaro et al. (2003a).

6.1. Trilobites

According to Álvaro et al. (2003a), Late Cambrian trilobite biofacies possibly occur in the Mediterranean region at only three stratigraphic levels: (i) the Idamean or Steptoean (Iberian Chains, Montagne Noire, and Morocco), characterized by aphelaspoid morphologies; (ii) the

Iberian or Sunwaptan (Demanda Mountains, Montagne Noire, Sardinia, and western Turkey), characterized by the occurrence of *Maladioidella*; and (iii) the Datsonian, of *Cordylodus proavus* Zone age. If the age of strata with *Niobella*, *Macropyge*, *Pagodia* (*Wittekindtia*), and *Parakoldinioidia* can be firmly established as of *Cordylodus proavus* Zone, then that biofacies becomes the third of latest Cambrian age. Some support for this assumption comes from conodonts recovered by Özgül and Gedik (1973) from the Sedişehir Formation in the Central Taurus Mountains, which by Australian standards are terminal Cambrian. Strata with *Oryctoconus* also support this assignment, since they occur in association with the Mediterranean 'Acerocare Regressive Event' associated with Tremadocian acritarchs and trilobites (Erdtmann, 1986; Nicoll et al., 1992; Loi et al., 1995, 1996).

As explained above, one of the typical Leonian–early Languedocian (Middle Cambrian) trilobite assemblage of the Acado-Baltic province *sensu* Sdzuy (1972), composed of conocoryphids, paradoxidids and solenopleurids, recorded, during the late Languedocian, the immigration of new (relatively) cosmopolitan invaders. Firstly, new genera, such as *Abharella*, *Chelidonocephalus*, *Derikaspis* and *Dorypyge* (King, 1937; Kushan, 1973; Wolfart, 1974; Fortey and Rushton, 1976; Dean, 1982; Courtessole et al., 1988; Álvaro et al., 1999), co-occurred with the aforementioned Middle Cambrian-type families, but subsequently replaced them, and even co-existed with new Late Cambrian invaders.

Although the Asian affinity of some Late Cambrian trilobite invaders has been widely discussed in previous works (Courtessole et al., 1988; Álvaro et al., 1999, 2003a), an affinity subsequently expanded into an

Australo-Asian (East Gondwanan) influence by Shergold et al. (2000), the successive trilobite immigration events recorded in the western Mediterranean region show more widespread palaeobiogeographic affinities, not only reduced to peri-Gondwanan margins. Late Cambrian trilobites from the Iberian Chains and the Demanda Sierra exhibit both: (i) highly constrained palaeobiogeographic distributions [e.g., *Elegantiaspis* has been exclusively found in Kazakhstan, *Pagodia* (*Wittenkindtia*) in Afghanistan, and *Langyashania* in N-China/Korea]; and (ii) cosmopolitan distributions (e.g., *Maladioidella* and *Prochuangia* occur in Turkey, Iran, Avalonia, Antarctica/Australia, N-China/Korea, S-China, Afghanistan, Kazakhstan, and Siberia). The Late Cambrian trilobites found in the Montagne Noire share the same pattern, with trilobite genera showing: (i) restricted distributions [e.g., *Shengia* or *Lisania sensu* Peng et al. (2004) occurs in South China]; (ii) intermediate distributions (*Paraacidaspis* and *Probilacunaspis* occur in South China, Kazakhstan and Siberia); and (iii) cosmopolitan distributions (e.g., *Onchonotellus*, *Proceratopyge*, *Palaeadotes*, *Stigmatotoa*, and *Olentella*; see Fig. 10). It is also remarkable the co-occurrence of *Selentella* in Morocco and Kazakhstan (Ivshin, 1962).

A cluster analysis of the aforementioned palaeobiogeographic affinities, based exclusively on the trilobite genera found in the western Mediterranean region, documents closer relationships of the western Mediterranean region with, in decreasing importance, (i) Turkey, Avalonia, Australia/Antarctica, and South China; (ii) Laurentia, Precordillera, Baltica, Siberia, Kazakhstan, and North China/Korea; and finally (iii) Iran, Afghanistan, eastern Cordillera, and Famatina (Fig. 11).

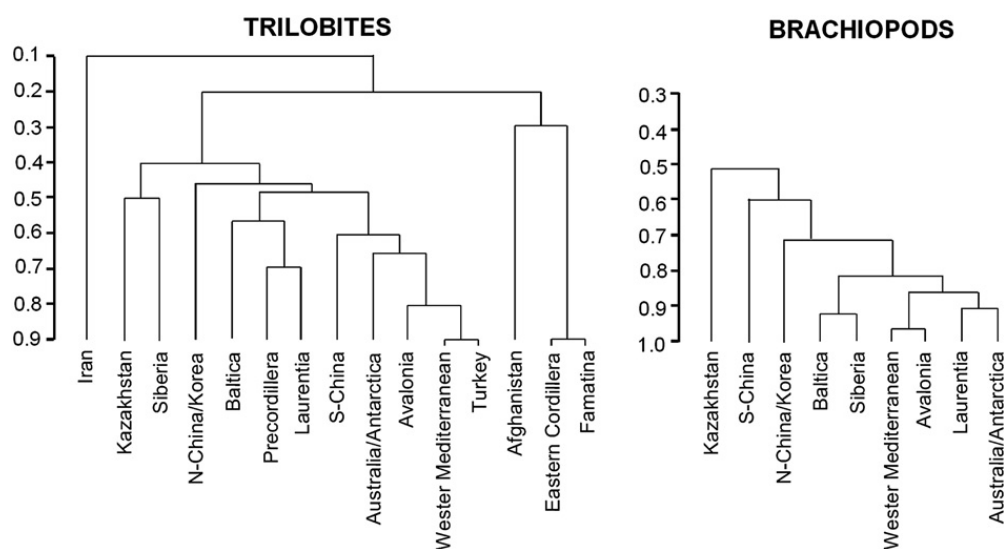


Fig. 11. Analysis of hierarchical Phi-Pearson similarity showing palaeobiogeographic affinities of the late Languedocian, Late Cambrian, and early Tremadocian trilobite and brachiopod genera found in the western Mediterranean region.

Finally, trilobite endemism of Late Cambrian trilobite species is close to 85%, which contrasts with the estimate close to 33–36% made by Vizcaíno and Álvaro (2003) for Tremadocian endemic species of the southern Montagne Noire [*P. geinitzi* and *S. (C.) pusilla* zones].

6.2. Brachiopods

The low-diversity patterns shown by the brachiopod-bearing sandstones and shales of siliciclastic-dominated platforms contrasts with the abundance and diversity of late Languedocian and Late Cambrian linguliformean brachiopods preserved in limestones, which offer the possibility of testing palaeobiogeographic affinities. Some of the brachiopods reported from the southern Montagne Noire in Section 3.5 show cosmopolitan distributions, e.g., *Acrothele*, *Dictyonina*, *Neotreta*, *Micromitra* and *Stilpnotreta*. The pandemic affinity is also shared, in a single case, at the specific level: *S. magna*, originally described from the Middle Cambrian of Australia (Henderson and MacKinnon, 1981; Engelbretsen, 1996), was later found in Kazakhstan (Holmer et al., 2001) and Canada (Robson et al., 2003) (Fig. 10).

Dactylotreta occurs in the Middle and Upper Cambrian of many continents, such as Laurentia (USA, Greenland and western Newfoundland; Rowell and Henderson, 1978; Zell and Rowell, 1988; Robson and Pratt, 2001), Kazakhstan (Holmer et al., 2001), and eastern Gondwana (Antarctica and Australia; Rowell and Henderson, 1978; Popov in Solovjev et al., 1984; Henderson et al., 1992), and the Argentinian Precordillera (Holmer et al., 1999). The genus also occurs in the Tremadocian of Baltica (Sweden, Norway and southern Urals; Popov and Holmer, 1994; Holmer et al., 2001). *Angulotreta* shows a widespread distribution from Laurentia (USA and Canada; Zell and Rowell, 1988; Robson and Pratt, 2001) to low latitudes of eastern Gondwana (Australia; Henderson, 1974) and Kazakhstan (Holmer et al., 2001).

Other genera show more restricted palaeobiogeographic distributions: *Eocaphelasma* only occurs in the Upper Cambrian of Kazakhstan (Koneva et al., 1990; Popov and Holmer, 1994), and *Zhanatella* in the Upper Cambrian of Kazakhstan (Koneva, 1986; Popov and Ushatinskaya, 1992; Popov and Holmer, 1994), East Gondwana (Antarctica; Henderson et al., 1992), and Laurentia (USA; Popov and Ushatinskaya, 1992; Popov and Holmer, 1994).

All the aforementioned genera share subtropical to temperate palaeolatitudes. The late Middle Cambrian to Ordovician micromorphic linguliformean brachiopod associations are widely spread palaeogeographically.

However, in low latitudes they occur mainly in outer-shelf environments, whereas in Baltoscandia they may occur in relatively shallow-marine environments. Taking into account their nearshore–offshore distribution, their palaeobiogeographic distribution does not necessarily represent an argument for low thermal gradient between tropical and temperate latitudes (L. Popov, pers. comm., 2007).

A cluster analysis is also available in Fig. 11, although its result must take into account some biases that are more important in the study of phosphate-walled brachiopods than in that of trilobites. Published works on Late Cambrian brachiopods directly reflect the abundance (or presence/absence) of limestones because valves are currently studied after etching. As a result, the method of study of tridimensionally preserved brachiopod valves directly controls the quantity and quality of works on brachiopod systematics. As in the case of trilobites, three palaeobiogeographic influences can be identified, in order of decreasing importance: (i) Avalonia, Laurentia, and Australia/Antarctica; (ii) Baltica, Siberia, and North China/Korea; and (iii) South China and Kazakhstan. The differences of palaeobiogeographic affinities between trilobites and brachiopods may also be associated with the different capacity of pelagic transport of their respective larvae.

The linguliformean brachiopods found in the limestones of the Val d'Homs Formation share with the aforementioned trilobites a distinct character: a high degree of endemism. Although González-Gómez (2005a,b) described 17 species in the latest Middle–Upper Cambrian of the southern Montagne Noire, only two of them are known outside the Montagne Noire; the rest is either described in open nomenclature or erected as new species.

6.3. Echinoderms

Echinoderms are extremely rare in the Upper Cambrian of the western Mediterranean region. Their disarticulated ossicles are commonly associated with trilobite and brachiopod coquinas, but their determination is difficult. There are two exceptions: the endemic fauna of the Val d'Homs Formation in the southern Montagne Noire and the *Oryctoconus* holdfasts. In the Barroubio valley (Pardailhan nappe), numerous limestone nodules embedded in siltstones of the Val d'Homs Formation have yielded an echinoderm assemblage, composed of four endemic genera: the phyllocystid? (cornute) *Lobocarpus*, the glyptocystitids (cystoid) *Barroubiocystis* and *Velieucicystis*, and the stromatocystid? *Scoteinocystis* (Ubaghs, 1998) (Fig. 10).

The pelmatozoan holdfast *O. lobatus* is herewith used as a biostratigraphically useful taxon, due to its co-occurrence with early Tremadocian trilobites and acritarchs in Sardinia, the Cantabrian Zone, the Demanda Sierra, and the Iberian Chains (Álvaro and Colchen, 2002), although its first appearance could be latest Late Cambrian in age. Another species, *Oryctoconus dorecki*, is known from the Tremadocian of the Leimitz Shales (Germany; Sdzuy, 1955), and some uncertain Early Ordovician echinoderm debris from Finmark (Norway), described originally by Erdtmann et al. (1984), were assigned to *Oryctoconus* by Berg-Madsen (1986).

7. Was the drift of West Gondwana unequal?

Both the Cambrian and Early Ordovician global palaeogeographic models of NW Gondwana have been greatly improved in the last decade due to analyses on palaeomagnetism, palaeobiogeography and climatically controlled facies. The western Gondwanan margin, which spread across South America, NW Africa, Avalonia, and the Mediterranean region, virtually suffered the same South-poleward drifting during the Cambrian and Early Ordovician. One methodological problem to document graphically this drift is the kind of global palaeogeographic reconstructions, as Cambrian workers commonly use equatorial perspectives and Ordovician ones polar perspectives. The latter are useful for discussing palaeoclimatic implications and are used in this work (Fig. 12).

One unresolved problem is the setting of the South Pole in Late Cambrian–Tremadocian palaeogeographic reconstructions. In some of them (e.g., Cocks and Torsvik, 2002; Fortey and Cocks, 2003), the South Pole is situated close to southwestern Europe, so that the Iberian Peninsula and the Montagne Noire are inside the 60°S polar circle. However, three key data seem to evidence a temperate setting for the western Mediterranean region across the Late Cambrian–Tremadocian. The first is the setting of this region across the Lower–Middle Cambrian transition. Although the distribution of climatically restricted facies and lithologies is related to Recent latitudinal belts controlled by the modern ‘icehouse’ situation, and not to the Cambrian ‘greenhouse’ time (Bernier, 1990), it offers key information to estimate relative rates of drifting. This area seemingly crossed the 30°S arid subtropical circle at this time, as reported by a peak in evaporitic and carbonate deposition (Álvaro et al., 2000, 2003a). Obviously, the southward drifting rate could not accelerate during a short time span of ca. 12 m.y. (Middle Cambrian) crossing 30–40° of latitude, and subsequently returning to previous rates.

Another argument is the presence of Late Cambrian–Tremadocian active carbonate factories in the southern Montagne Noire (Val d’Homs and Mounio formations; Álvaro et al., 2003b; Vizcaíno and Álvaro, 2003). And the third argument is yielded by palaeomagnetic data: Nysæther et al. (2002) located the Cabrières Wildflysch of the Montagne Noire (southern France) at higher southerly latitudes ($68^{\circ} +17/-15$) during Middle Ordovician times (Llanvirn to early Caradoc, ca. 470–458 Ma). As a result, the western Mediterranean region probably occupied med (temperate-water) latitudes, and not subpolar settings, during the Late Cambrian and Tremadocian.

8. Concluding remarks

The identification of Upper Cambrian strata in the western Mediterranean region is dramatically constrained by the record of erosive unconformities and condensed units. In the Moroccan Anti-Atlas, Cantabrian Zone, Montagne Noire and SW Sardinia, a diachronous Late Cambrian-to-Middle Ordovician unconformity truncated large areas of their platforms. These hiatus can be related to a phase of neighbouring rifting (further North) and concomitant erosion on southern rift shoulders. The rifting is currently related to the opening of the Rheic Ocean, widely believed to have formed in the Late Cambrian–Early Ordovician as a result of the drift of peri-Gondwanan terranes from the northwestern Gondwanan margin.

The Upper Cambrian of the southern Montagne Noire and the Iberian Chains lacks significative gaps. There, Upper Cambrian strata are bracketed by two major regressive trends, which are topped by: (i) an uppermost Middle Cambrian discontinuity related to the progradation of back-shoal tidal-flat environments (lower part of the La Gardie and Valdeorea-Torcas formations, respectively); and (ii) an Upper Cambrian–lower Tremadocian discontinuity related to the progradation of foreshore to shoreface, shoal complexes (La Dentelle and Valconchán formations). In this context, the Upper Cambrian sedimentation took place in a transgressive-dominated depositional system, with common offshore deposits and clayey substrates (upper part of the La Gardie/Val d’Homs and Valtorres formations).

The Late Cambrian is also associated with: (i) the record of volcanic activity in the Cantabrian Zone and the northern Montagne Noire; and (ii) widespread development of tectonic instability. The latter is documented in the western Mediterranean region by episodic development of palaeotopographies and record of slope-related facies associations. The reported basins and platforms occupied temperate-water latitudes,

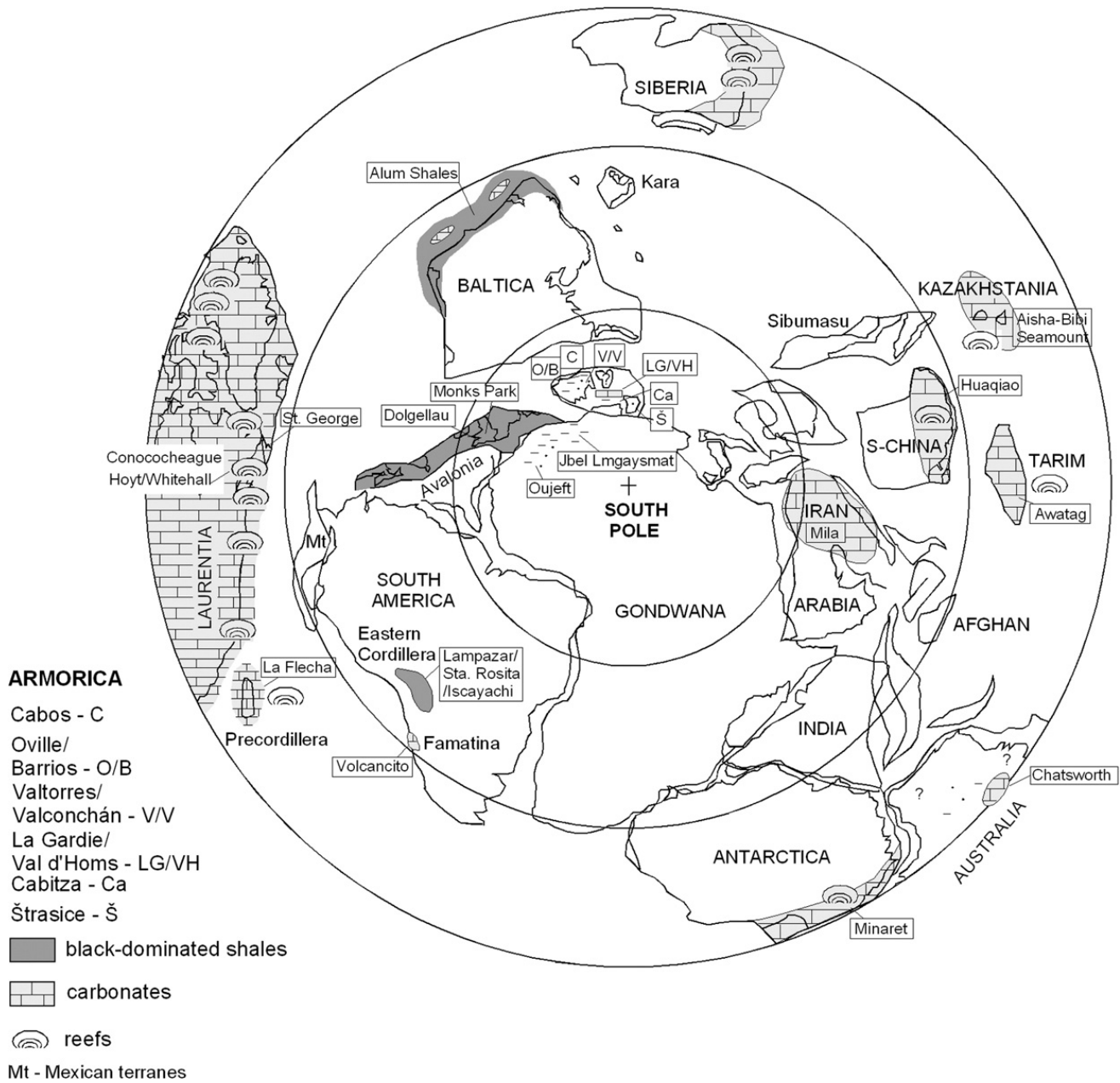


Fig. 12. Global palaeogeographic reconstruction (after Cocks and Torsvik, 2002; Rowland and Shapiro, 2002; Fortey and Cocks, 2003; and papers reported in this work) with setting of subtropical- and temperate-water carbonate factories, terrigenous belts and black shales. Note the anomalous position of the carbonate factories related to the Montagne Noire.

where carbonate factories were episodically active in the southern-Montagne-Noire platform, which represents the northernmost part of the study region.

Several immigration events are recognized throughout the latest Middle Cambrian, Late Cambrian and Tremadocian. The trilobites show a stepwise replacement of Acado-Baltic-type families (*e.g.*, the conocoryphid–paradoxidid–solenopleurid assemblage) characterized by: (i) a late Languedocian (latest Middle Cambrian) co-occurrence of Middle Cambrian trilobite families with the first anomocarid, dorypygid and proasaphiscid invaders; (ii) a Late Cambrian (lower Peltura Zone) immigration

replacing previous faunas, composed of trilobites (aphe-laspidids, catillicephalids, ceratopygids, damesellids, eulomids, idahoïids, linchakephalids, lisariids, oncho-notinids, and pagodiids), linguliformean brachiopods (acrotretids, obolids, scaphelasmatids, siphonotretids, and zhanatellids), echinoderms (mitrates, glyptocystitid cystoids, and stromatocystoids) and conodonts; (iii) and the subsequent input of new trilobites (asaphids, calymenids, catillicephalids, nileids and remopleurid), which marks the base of the *P. geinitzi* Zone, associated with pelmatozoan holdfasts (*Oryctoconus*), and late Tremadocian conodonts (*P. deltifer* Zone). These immigration

events took place associated with a broad transgression, so that they were not affected by relative sea-level fluctuations, and are useful for bounding biostratigraphic units.

The biogeographic distribution of Late Cambrian trilobites supports brachiopod data indicating strong affinities between NW Gondwana (Mediterranean region), East Gondwana (North China/Korea, South China, Australia, and Antarctica) and Kazakhstania during the late Languedocian, which became significantly stronger during the Late Cambrian. This major shift may suggest modification in oceanic circulation patterns throughout Gondwana across the Middle–Late Cambrian transition.

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