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The Lower–Middle Cambrian boundary in the Mediterranean subprovince

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ABSTRACT

The position of the Lower–Middle Cambrian boundary, as classically used, is an issue still under discussion by the International Subcommission on Cambrian Stratigraphy (ISCS), and no level has been established yet. At present, there are two oryctocephalid trilobite species–based Global Standard Stratotype-section and Point (GSSP) proposals in the literature, *Oryctocephalus indicus* and *Ovatoryctocara granulata*. These two species have not yet been found in the Mediterranean subprovince. For this reason, other correlation tools that approximate these levels are needed.

A complete chronostratigraphy for the Lower and Middle Cambrian Series of Iberia was proposed by Sdzuy (1971a,b). Recently Geyer and Landing (2004) made a new proposal for the Lower–Middle Cambrian chronostratigraphy of West Gondwana. They proposed the Agdzian Stage. This stage is more or less equivalent to the Bilbilian and Leonian Stages of Spain. The main problem with the Agdzian Stage is that its boundaries are not correlative with a potential global Cambrian Series boundary. Those levels would be in the middle part of the Agdzian Stage. In order to make a more accurate correlation, we prefer to use the previous Spanish scale and try to clarify the correlation between different sequences of this time interval in the Mediterranean subprovince.

Here we present a summary of biostratigraphical data from the Bilbilian and Leonian Stages, the boundary of which is placed at the first appearance datum

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(FAD) of *Acadoparadoxides mureroensis*. This, the classical Lower–Middle Cambrian boundary in the *Paradoxides* realm, is constrained by the data of various areas of the Mediterranean region. A revised correlation chart comparing the Mediterranean and other regions is presented. The position of the Bilbilian–Leonian boundary roughly coincides with the two GSSPs proposed by the ISCS.

Keywords: stratigraphy, biochronology, trilobites, global correlation, Cambrian GSSP

INTRODUCTION

The Cambrian is one of the systems without a complete succession of series and stages recognized globally by the International Subcommission on Cambrian Stratigraphy (ISCS) (Geyer and Shergold, 2000; Peng et al., 2004; Babcock et al., 2005). In part this is due to the provinciality of the trilobites and other faunas. Regional stages have been proposed for several areas (e.g., Siberia, Laurentia, Morocco, Australia, Baltica, China, Iberia).

For Iberia, a complete chronostratigraphy was proposed for the Lower and Middle Cambrian Series (Fig. 1) by Sdzuy (1971a,b). Recently Geyer and Landing (2004) made a new proposal for the Lower–Middle Cambrian chronostratigraphy of West Gondwana; they use different stages and series previously defined in Morocco, Spain, and France. They proposed the new Agdzian Stage, which is more or less equivalent to the Bilbilian and Leonian Stages of Spain (Sdzuy, 1971a; Liñán et al., 1993a; Sdzuy et al., 1996, 1999). The main problem with the Agdzian Stage is that its boundaries do not correlate with the *Oryctocephalus indicus* or *Ovatoryctocara granulata* levels, the levels that are being considered as the base of a global Cambrian Series. Those levels would be in the middle part of the Agdzian Stage. In order to make a more accurate correlation, we prefer to use the previous Spanish scale and try to clarify the correlation between the different sequences of this time interval in the Mediterranean subprovince.

The Bilbilian and Leonian Stages are chronostratigraphic units that were formerly defined in the Cambrian rocks of the Iberian Peninsula (see Liñán et al., 1993a). They represent the last Lower Cambrian regional stage and the first Middle Cambrian regional stage, respectively. The boundary between these stages coincides with the classical Lower–Middle Cambrian boundary defined in the nineteenth century by the appearance of *Paradoxides* species, and it closely corresponds with the previous disappearance of archaeocyathids. Although a new Lower–Middle Cambrian boundary has been proposed by Geyer (1990b) and Geyer and Landing (1995, 2004), identified by the appearance of *Protolenus* (*Hupeolenus*) species (classic upper Lower Cambrian in the Acadobaltic province), we prefer to maintain the first appearance datum (FAD) of *Acadoparadoxides mureroensis* as the Lower–Middle Cambrian boundary marker for the Mediterranean subprovince (according to Sdzuy, 1961, 1971a,b, 1995; Liñán and Gozalo, 1986; Liñán et al., 1993a,b, 1996, 2002; Dean and Özgül, 1994; Loi et al., 1995; Pillola et al., 1995; Sdzuy et al., 1996, 1999; Elicki and Pillola, 2004; and Dean, 2005), at least until the International Commission on Stratigraphy establishes an official subdivision. For a recent discussion, see Sdzuy et al. (1999).

The Bilbilian and Leonian Stages were defined in mixed carbonate-siliciclastic facies and used subsequently for both carbonate and siliciclastic sequences in Spain (Sdzuy and Liñán, 1993; Liñán et al. 1995, 2002). These stages were subsequently applied to Sardinia (Loi et al. 1995; Pillola et al., 1995; Perejón et al., 2000; Elicki and Pillola, 2004), Turkey (Dean and Monod, 1997; Dean, 2005), Germany (Elicki, 1997), France (Álvaro et al., 1998b, 2001a,b; Álvaro and Vizcaïno, 2000), Jordan (Rushton and Powell, 1998; Elicki et al., 2002), and Portugal (Liñán et al. 2004a). Both stages are easily identifiable in the Mediterranean subprovince *sensu* Sdzuy (1971a, 1972) and Sdzuy et al. (1999) because they contain biostratigraphical markers from both inner and outer shelf to basinal environments that can be recognized in Morocco, Spain, France, Italy, Germany, Turkey, Jordan, and Israel.

In this paper we compare the lithostratigraphy and biostratigraphy of the Mediterranean subprovince during Bilbilian and Leonian times in order to propose a hypothesis on the correlation of both stages with the main regional stages and levels proposed by the ISCS.

BILBILIAN AND LEONIAN STRATIGRAPHY OF THE MEDITERRANEAN SUBPROVINCE

The Mediterranean subprovince belongs to the western Gondwana area and corresponds with the so-called European shelf (Fig. 2), in accordance with the paleogeographic proposal of Courjault-Radé et al. (1992). The stratigraphy of the most important areas with Bilbilian and Leonian rocks in the Mediterranean subprovince is shown in Figure 3.

The rocks of this time span are mainly siliciclastic in Morocco, Portugal, southern Spain, and Germany; mainly carbonate in northern Spain, France, Italy, and Turkey; and terrestrial with mixed carbonate-siliciclastic marine intercalations in the Middle East (Jordan and Israel).

Morocco

In the High Atlas and Anti-Atlas, the Bilbilian and Leonian facies are mainly represented by siliciclastic materials (Geyer, 1989; Geyer and Landing, 1995). The top of the Issafen Formation, containing shales and interbedded limestone and belonging to the upper part of the *Sectigena* zone, may be correlated with

IBERIA		MOROCCO		WEST GONWANA COMPOSITE	ISCS correlation levels
CAES. (pars)	*Badulesia tenera*	TOUSHAMIAN (pars)	*Badulesia tenera*	CAESARAUGUSTAN (pars)	
					• *Ptychagnostus gibbus*
LEONIAN	*Eccaparadoxides asturianus*		*Kymataspis arenosa*	AGDZIAN	
	Eccaparadoxides sdzuyi	TISSAFINIAN	*Ornamentasis frequens*		
	Acadoparadoxides mureroensis		*Cephalopyge notabilis*		? *Oryctocephalus indicus* • *Ovatoryctocara granulata*
BILBILIAN	*Protolenus jilocanus*		*Protolenus (Hupeolenus)*		
	Protolenus dimarginatus				
	Realaspis	BANIAN (pars)	*Sectigena* (pars)	BANIAN (pars)	
	FAD				
MARIANIAN (pars)	*Serrodiscus*				
	FAD				• *Hebediscus attleborensis-Calodiscus-Serrodiscus bellimarginatus-Triangulaspis assemblage*

Figure 1. Latest Marianian, Bilbilian, Leonian, and earliest Caesaraugustan chronostratigraphic scheme for Iberia, Morocco, and the unified chronostratigraphy proposed by Geyer and Landing (2004). The scheme for Iberia is according to Sdzuy (1971a), Liñán et al. (1993b, 2002) and Dies et al. (2004). The scheme for Morocco is according to Geyer (1990a) and Geyer and Landing (1995). The west Gondwana composite is according to Geyer and Landing (2004). Abbreviations: ISCS—International Subcommission on Cambrian Stratigraphy; FAD—first appearance datum.

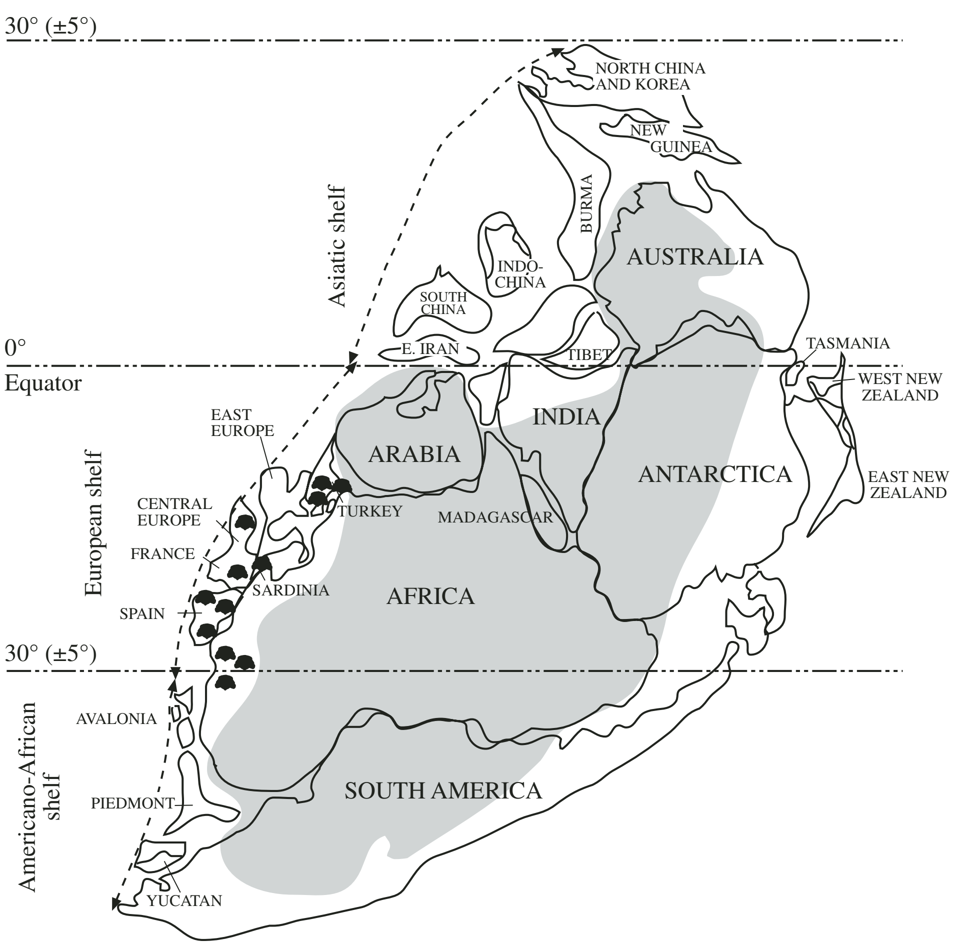

Figure 2. Paleogeographic reconstruction of the European shelf and location of the areas studied in this article (after Courjault-Radé et al., 1992).

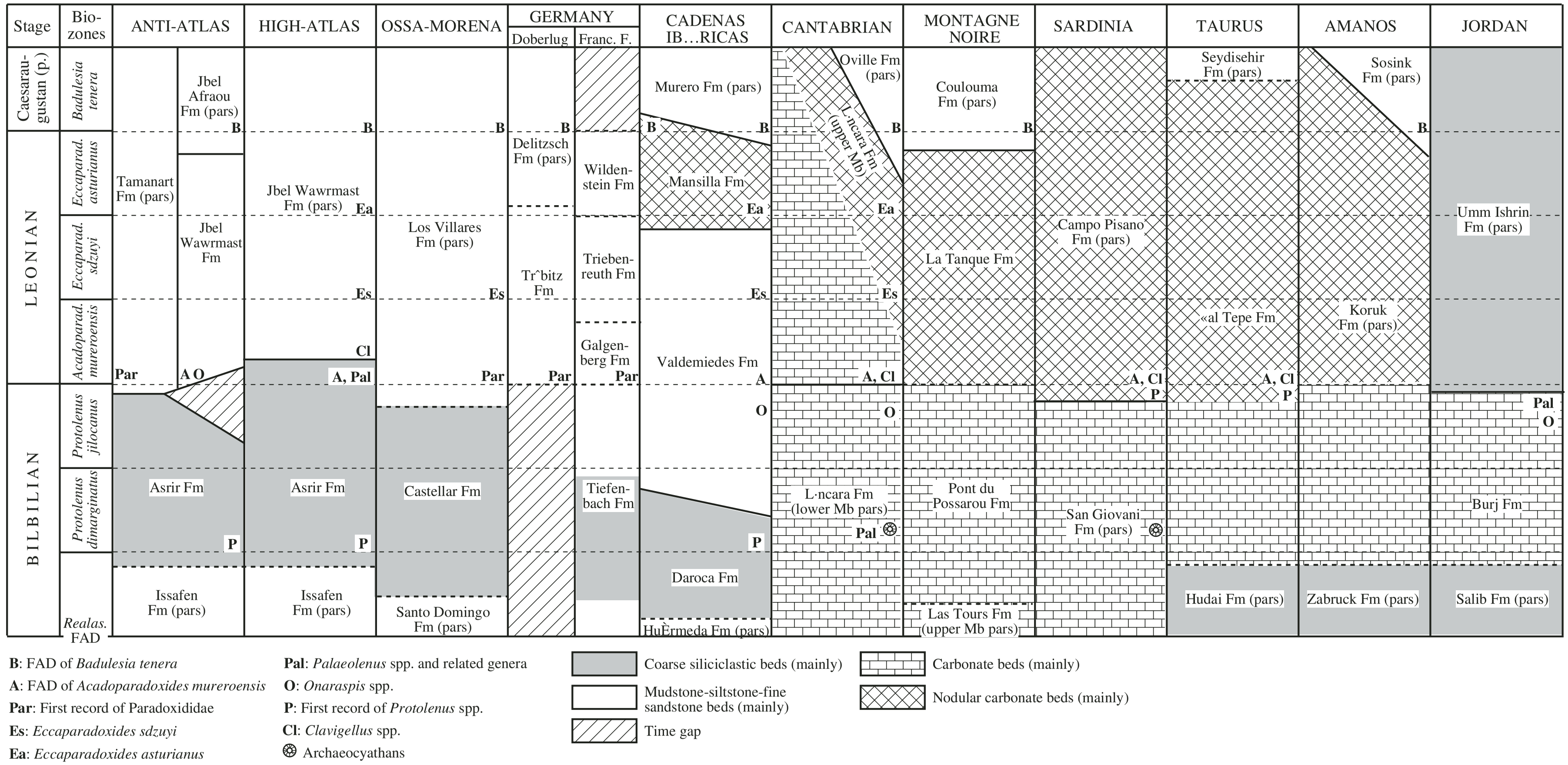

Figure 3. Generalized correlation table of the Bilbilian, Leonian, and earliest Caesaraugustan stages (late Late Cambrian to early Middle Cambrian) in the Mediterranean subprovince *sensu* Sdzuy et al. (1999). Abbreviations: FAD—first appearance datum (FAD); Fm—Formation; Mb—Member; spp.—species.

the lowermost Bilbilian (see Fig. 3 *in* Geyer and Landing, 2004). The Asrir Formation is usually conformable above the Issafen Formation. It is composed of shales and quartzarenites 30–180 m thick that were deposited in shallow marine environments. Fossils are rare. The lower part of this formation belongs to the *Hupeolenus* zone (Bilbilian), and the first appearance datum of *Acadoparadoxides mureroensis* (Leonian) has been reported at the top of it and represents the lower part of the Leonian Stage in both areas (Sdzuy, 1995).

The Tamanart Formation occurs above the Asrir Formation in the Amouslek section and laterally changes, in other localities, into the Brèche à *Micmacca* Member of the Jbel Wawrmast Formation (Geyer and Landing, 1995; Geyer et al., 1995). Abundant trilobites have been recorded in these formations, ranging from the *Ornamentaspis frequens* zone (Leonian) to the *Pardailhania* zone (Caesaraugustan). The FAD of *Badulesia tenera* occurs in the Jbel Wawrmast Formation (High Atlas) and within its lateral equivalent, the Jbel Afraou Formation (Anti-Atlas). This FAD marks the beginning of the Caesaraugustan Stage. The abundant trilobite assemblages found in both regions (Geyer, 1990a, 1994, 1998; Geyer et al., 1995; Sdzuy, 1995; Geyer and Landing, 2004) permit us to recognize the zones of the Bilbilian and Leonian Stages in Morocco.

Germany

Bilbilian–Leonian rocks have been recognized in two areas: Leipzig and the Franconian Forest (Ludwig, 1969; Sdzuy, 1970; Brause et al., 1997; Elicki, 1997; Geyer and Wiefel, 1997). The Franconian Cambrian of this time interval is represented by a siliciclastic succession and is composed of four formations: Tiefenbach, Galgenberg, Triebenreuth, and Wildenstein (Elicki, 1997). The Tiefenbach Formation consists of over 300 meters (m) of quartzites and siltstones and is supposedly Lower Cambrian or/and lowermost Middle Cambrian in age. The Galgenberg Formation is 40–60 m thick, with shales, medium to fine sandstones, and carbonates; the presence of Middle Cambrian trilobites suggests that it belongs in the *Paradoxides insularis* zone. The Triebenreuth Formation is 50 m of volcanoclastics rocks with trilobites of the *P. oelandicus* zone. The Wildenstein Formation is less than 100 m thick and consists of graywackes, sandstones, and shales with carbonate nodules containing trilobites of the *P. pinus* zone. The last three formations are equivalent in age to the Leonian.

A subsurface sequence is known in the Doberlug boreholes (Leipzig area). It is represented by alternating sandstones, quartzites, and shales with rare and very thin carbonate layers. The thickness is more than 500 m (Sdzuy, 1970; Elicki, 1997). The Doberlug IV (pars of the Delitzsch Formation) contains trilobites from the *Badulesia tenera* zone (Sdzuy et al., 1999). The faunas of the LS 1/63 (pars of the Tröbitz Formation) belongs to the Leonian Stage and includes common species known from Spain, such as *Condylopyge cruzensis* and *Paradoxides?* aff. *enormis* (see Sdzuy, 1970; Dies and Gozalo, 2004).

Spain

Ossa-Morena Zone (South Spain)

The Bilbilian and Leonian rocks of the Ossa-Morena zone (southern Spain) crop out as a continuous sequence in the Alconera and Córdoba regions. Relatively good biostratigraphic control is present only in the Córdoba region, where there are several levels with Leonian and Caesaraugustan trilobites in the Los Villares Formation (Liñán Guijarro, 1978; Liñán et al. 1995, 2002; Liñán et al., 2004b).

The Lower Bilbilian in the Córdoba region is probably represented by the top of the Santo Domingo Formation in accordance with Liñán et al. (1993a), and it is composed of red shale, dolostone, and chert-bearing limestone with stromatolites, algae, and bioclastic brachiopods. The facies and sedimentological characteristics suggest deposition in supralittoral to restricted infralittoral environments (García Hernández and Liñán, 1983). The Castellar Formation (*sensu* Liñán et al., 1995) is 75–84 m thick, lies conformably above the Santo Domingo Formation and is composed of sandstone and conglomerate mainly deposited under littoral to shallow sublittoral conditions; it has not yielded fossils of biostratigraphic interest yet. The Los Villares Formation (*sensu* Liñán et al., 1995) consists of more than 450 m of sandstones and interbedded siltstones. The presence of the trilobites *Alueva hastata* at the base suggests an age extending from the Leonian (*Acadoparadoxides mureroensis* zone) through the Caesaraugustan (*Badulesia granieri* zone) (Liñán Guijarro, 1978; Liñán et al., 1995, 2002, 2004a).

Cadenas Ibéricas (Northeast Spain)

The Bilbilian–Leonian rocks are mainly represented by the detrital Daroca Formation and mixed facies of the Mesones Granite The first is a terrigenous sequence 90–250 m thick including heterogeneous lithologies (Sdzuy and Liñán, 1993; Álvaro and Vennin, 1998). In some northern localities, trilobites and acritarchs have been found that confirm a Bilbilian age for the Daroca Formation (Gámez et al., 1991; Álvaro and Liñán, 1997; Palacios and Moczydlowska, 1998; Liñán and Gozalo, 2001).

The Mesones Group is subdivided into the Valdemiedes, Mansilla, and Murero Formations. It is essentially composed of shales with interbedded carbonate nodules, dolostones, and limestones. It was deposited mainly in sublittoral environments (Sdzuy and Liñán, 1993). The Valdemiedes Formation is 20–250 m thick and is mostly composed of green shales and marly shales with carbonate nodules, as well as scarce and fine carbonate sandstone levels; the position of this formation is lower Bilbilian to middle Leonian (Liñán et al., 2002) based on its diverse record of trilobites (see Liñán and Gozalo, 1986; Gozalo et al., 1993a; Dies Álvarez, 2004); in the upper part of this formation is recorded the Valdemiedes event (Liñán et al., 1993b). The Mansilla Formation, 10–90 m thick, is made up of alternating brown dolostones and limestones and purple and violet shales; trilobites occur in the upper part, including late Leonian to earliest Caesaragustan species (e.g., Gozalo and Liñán 1995; Sdzuy et al. 1999; Chirivella Martorell et al., 2003). Only the basal levels of the Murero

Formation correspond to the interval studied herein; they are composed of green lutites with carbonate nodules and interbeds of fine sandstone. The lower boundary is slightly diachronous, yet it coincides approximately with the base of the Caesaraugustan.

Cantabrian Mountains (Northwest Spain)

In the Cantabrian Mountains, the Láncara and Oville Formations represent the time interval studied here. Fossils of such age have been found only in the Esla nappe area and the Porma section (Zamarreño, 1972; Sdzuy and Liñán 1993; Sdzuy, 1995; Perejón and Moreno-Eiris, 2003). The Láncara Formation is made up of 150–225 m of dolostone, limestone, and interbedded shale. The lower member includes a persistent dolostone level followed, only in the Esla nappe, by a level of gray lenticular limestones (ooidal grainstones) with archaeocyathans and trilobites (Álvaro et al., 2000b). Biostratigraphic events are recorded only at the top of the limestone level. Lower Cambrian trilobites of the *Sectigena* zone (Sdzuy, 1995) have been recorded below the Bilbilian archaeocyathans referred from the Valdoré locality (Debrenne and Zamarreño, 1970; Perejón, 1994; Perejón and Moreno-Eiris, 2003), and we have found *Palaeolenus* sp. in the same level (Fig. 4F–H). The paleontological and sedimentological data suggest supralittoral to littoral environments in the western region and shallow sublittoral conditions in the eastern region (Zamarreño, 1972; Aramburu et al., 1992). The lower part of the upper member of the Láncara Formation is composed of pink encrinite packstones; the base of this unit is erosive and, in some places, includes pebbles (Álvaro et al., 2000b). In the Valdoré section, these pebbles contain the Lower Cambrian trilobites *Kingaspis campbelli* (Fig. 4A; Liñán et al., 2003) and *Onaraspis* sp. (Fig. 4E and I). The earliest specimens of *Acadoparadoxides mureroensis* have been recorded from the matrix of this level. Just above this pebble-bearing interval, we have found the trilobite *Clavigellus* sp. (Fig. 4B–D). The upper part of the upper member of the Láncara Formation consists of widespread limestone deposits followed by nodular red limestones (griotte facies). Diachronous boundaries, from Leonian to Caesaraugustan in age (Middle Cambrian), have been inferred for this member based on its trilobite contents (Sdzuy 1968, 1969; Gozalo et al., 1993b; Sdzuy and Liñán, 1993).

Recently Geyer and Landing (2004, p. 193–194) discussed the assignation of the Spanish material to *Kingaspis campbelli.* They noted some small differences, and wrote (p. 194): "One principal character of *K. campbelli* is that anterior facial suture meets the margin exsagittally posterior to the anterolateral corners of the glabella—a character that is not shown in the Spanish material." Curiously, in the topotypic material figured by Rushton and Powell (1998, Figs. 21–26) it is possible to observe that the main character noted by Geyer and Landing (2004) is variable between posterior (Fig. 21 *in* Rushton and Powell, 1998) and anterior (Fig. 24 *in* Rushton and Powell, 1998) to the anterolateral

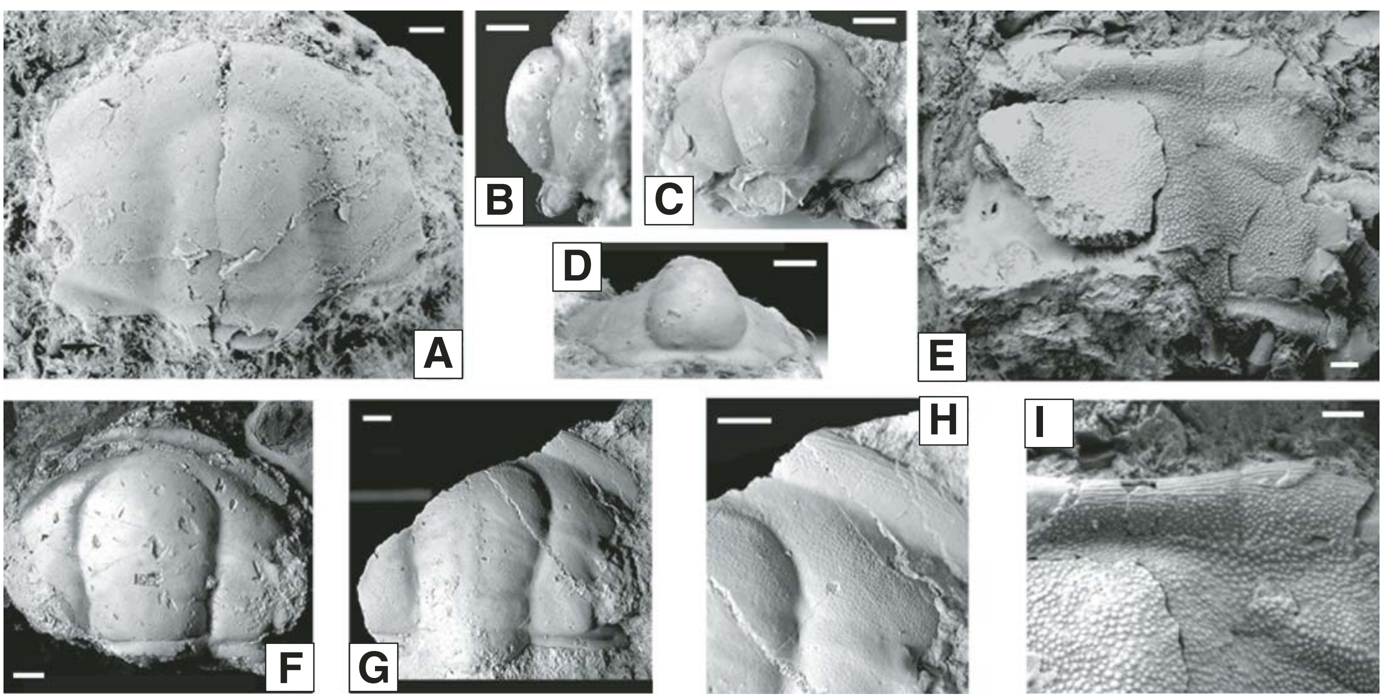

Figure 4. Selected trilobites from the Valdoré section (Cantabrian Mountains); bar = 1 mm. (A) *Kingaspis* (*Kingaspis*) *campbelli* (King, 1923); MPZ 2000/8; cranidium preserved in limestones. (B, C, D) *Clavigellus* sp.; MPZ 2005/296; cranidium preserved in limestones; lateral, frontal, and anterior views. (E) *Onaraspis* sp.; MPZ 2005/297; incomplete cranidium preserved in limestones. (F) *Palaeolenus* sp.; MPZ 2005/298; cranidium preserved in limestones. (G) *Palaeolenus* sp.; MPZ 2005/299; incomplete cranidium preserved in limestones. (H) *Palaeolenus* sp.; enlarged view of MPZ 2005/299. (I) *Onaraspis* sp.; enlarged view of MPZ 2005/297.

corners; thus we considered this character an inner character of the intraspecific variation of *Kingaspis campbelli* in accordance with the identification of Liñán et al. (2003).

The basal levels of the Oville Formation belong to the Leonian or lower Caesaraugustan in some areas; they are mainly glauconitic sandstones and green shales, with some carbonate nodules. The lowest part of the formation contains several fossiliferous levels with trilobites (Sdzuy, 1968, 1969). Diachroneity between this formation and the preceding formation is shown by the presence of different trilobite assemblages ranging from upper Leonian to upper Caesaraugustan in age (Zamarreño, 1972; Sdzuy and Liñán, 1993; Liñán et al., 2002).

France

The successions of uppermost Marianian or Bilbilian to basal Caesaraugustan rocks in the Montagne Noire comprise four formations: the upper member of Las Tours, Pont du Poussarou, La Tanque, and lowest Coulouma (Álvaro et al., 1998b, 2001a,b). The upper member of the Las Tours Formation is 40–150 m thick; thin-bedded limestones are intercalated within green shales. *Ferralsia blayaci* has been recorded in this member and indicates either a late Marianian or an earliest Bilbilian age (Álvaro et al., 1998a). The Pont du Poussarou Formation is a 20–80 m massive limestone with dolomitic intercalations; it is probably Bilbilian in age. The La Tanque Formation reaches 60 m of reddish and purple carbonates and interbedded shales; the age is probably Leonian. The Pont du Poussarou and the La Tanque Formations lack biostratigraphic markers; thus their ages are inferred from their stratigraphic positions in the succession. The base of the Coulouma Formation (green shales with carbonate nodules) contains the trilobite *Asturiaspis inopinatus,* of upper Leonian age, and *Badulesia tenera,* which marks the base of the Caesaraugustan Stage (see Álvaro and Vizcaïno, 2000).

Italy

The Bilbilian and Leonian of Sardinia (Italy) are represented by two carbonate formations, San Giovanni and Campo Pisano (Pillola, 1991; Pillola et al., 1995; Loi et al. 1995; Perejón et al., 2000; Elicki and Pillola, 2004). The first is composed mainly of massive black to gray limestones over 300 m thick, representing mostly a shallow-water carbonate succession. Only rare archaeocyathans have been recorded from the upper part of the San Giovanni Formation, which has been assigned to the Toyonian 2–3 (Debrenne and Gandin, 1985; Zhuravlev, 1995). It is overlain by slightly deeper sediments of the Campo Pisano Formation, mostly 40–60 m thick (well-bedded and nodular limestones, with calcareous shales and marls). This unit represents a condensed succession, spanning the uppermost Lower Cambrian (Bilbilian) through the Middle Cambrian (Caesaraugustan). At the base of the Campo Pisano Formation, the oldest assemblage, CP1, contains *Protolenus* (*Protolenus*) *pisidianus* and *Clavigellus?* n. sp. (Loi et al. 1995; Elicki and Pillola, 2004); this assemblage is considered uppermost Lower Cambrian. A few meters above, in the lower part of assemblage CP2, lies the FAD of *Acadoparadoxides mureroensis* (Leonian). The upper part of level CP2 contains *Pardailhania hispida,* which indicates the Caesaraugustan Stage.

Turkey

In Turkey, Bilbilian, Leonian, and Caesaraugustan levels have been dated. The formations on which Lower and Middle Cambrian strata rest vary considerably. For example, the oldest "red nodular facies" are dated as basal Leonian and occur in the western Taurides (Çal Tepe Formation); the youngest and more southernly occurrences in the Border Folds (Koruk Formation) belong to the middle or upper Caesaraugustan (Dean and Monod, 1997). The two sequences that have been dated by means of Bilbilian, Leonian, and basal Caesaraugustan trilobites are found in the Hüdai and Çal Tepe areas (western Taurides: Dean and Özgül, 1994; Dean, 2005) and in Alan Yayla (Amanos Mountains: Dean et al., 1986).

Cambrian sequences from the Taurus Mountains comprise the Hüdai Quartzite, Çal Tepe and Seydisehir Formations (Dean and Monod, 1970; Dean and Özgül, 1981, 1994; Dean, 2005). The Hüdai Quartzite Formation consists of less than 500 m of thick-bedded, reddish white and gray, laminated quartz-arenite, which exhibits cross-bedding and is considered to represent a beach deposit. The Çal Tepe Formation, which is 130–170 m thick, has been subdivided into four carbonate members in its type area (e.g., Dean, 2005): the dolomite member, 80–150 m, is composed mainly of thickly bedded, coarsely crystalline, brown dolostone; the black limestone member, over 20 m thick, comprises thickly bedded, tough, dark gray to black limestone indicative of a shallow, open marine environment; the light gray limestone member comprises little more than 10 m of pale, thinly bedded limestones, indicating a high-energy, shallow marine environment; finally, the red nodular limestone member comprises 40–16 m of medium-bedded, pink beige and light gray nodular limestone, often with intercalations of bright red mudstone, and marks a transition to lower-energy, deeper marine conditions. The overlying Seydisehir Formation is mainly composed by green to gray shales with thin levels of fine-grained, quartzitic sandstone interbedded. Fossils have only been found in the three last members of the Çal Tepe Formation in the Formation type area and near Hüdai. The trilobite species *Protolenus* (*P.*) *pisidianus*, *Acadoparadoxides mureroensis,* and *Clavigellus venustus* have been found in the light gray limestone member and permitted recognition of the base of the Leonian Stage in this area (Dean and Özgül, 1994; Dean, 2005). In other localities of the Taurus Mountains, the higher red nodular limestones member of the Çal Tepe Formation and the lowest meters of the succeeding siliciclastics of the Seydisehir Formation also contain *Pardailhania* sp. (Dean and Özgül, 1981; Dean and Monod, 1997; Dean, 2005), which marks the Caesaraugustan Stage.

In the Amanos Mountains, the Cambrian sequence comprises the Zabuk, Koruk, and Sosink Formations (Dean et al., 1986; Dean and Monod, 1997). The Zabuck Formation is ~100 m thick and consists of thickly bedded, pink, fluviatile or deltaic arkoses. The Koruk Formation consists mostly of 185 m of dark, thickly bedded dolostones or dolomitic limestones with thin shale interbeds; the succession begins with coarse to fine-grained, gray dolostones that are interpreted as typical supratidal to intertidal deposits initiating a transgressive sequence. In some sections the dolostone member changes conformably upward into black, bioturbated packstones that form the lowest part of the limestone member and are interpreted as a progressive change to shallow, open marine environments; the upper part of the formation is composed of over 10 m of gray and red nodular limestones. The Sosink Formation is 250 m of calcareous shales and shally limestones. *Badulesia tenera* has been found in the lower part of the Sosink Formation near the Alan Yayla (Dean and Krummenacher, 1961; Dean et al., 1986), indicating the beginning of the Caesaraugustan Stage. In other localities, the red nodular limestones on the top of the Koruk Formation have been found to contain middle Caesaraugustan trilobites (Dean and Monod, 1997), showing an evident diachrony in the boundary between the Koruk and the Sosink Formations.

Jordan and Israel

The Cambrian succession in southern Israel was divided by Soudry and Weissbrod (1995) into four formations (Amudei Shelomo, Timna, Shehoret, and Netafim). The lowest and uppermost formations are fluvial deposits, while the Timna Formation accumulated in marine depositional environments; it marks the earliest Paleozoic transgression of the paleo-Tethys on the Arabian-African craton. It contains some carbonate levels in a mainly siliciclastic succession and includes datable fossils, ichnofossils, and stromatolitic structures representing shallow-water and intertidal environments in a marginal basin (Soudry and Weissbrod, 1995, p. 340).

The sequence from the Dead Sea is composed of three formations (Salib, Burj, and Umm Ishrin). As in Israel, the lower and upper ones are fluvial units, while the mixed carbonate-siliciclastic Burj Formation shows, from its base upward, a clear pattern of marine transgression and regression (Rushton and Powell, 1998). This formation has been divided into three members, from the bottom the Tayan Member (up to 20 m of greenish to reddish siltstone and fine-grained sandstone), the Numayri Member (50–60 m of limestone and dolostone), and the Hanneh Member (~30 m of greenish to reddish sandstone and minor siltstone) *sensu* Elicki et al. (2002). The maximum transgressive phase produced shallow subtidal to supratidal environments at the intermediate Numayri Member.

Trilobite faunas are recorded from the Timna and Burj Formations (see Parnes, 1971; Rushton and Powell, 1998). These formations are considered equivalent by Rushton and Powell (1998). Trilobite assemblages of the Burj Formation studied by the latter authors included a level with *Kingaspis campbelli* and *Palaeolenus antiquus* at the top of the Numayri Member and, slightly below, *Realaspis* sp. nov., and *Redlichops blanckenhorni.* Rushton and Powell also found *Onaraspis palmeri* in this member; this species was defined in the Timna Formation from levels correlated with *Kingaspis campbelli* (see Parnes, 1971).

In summary, the Bilbilian and Leonian facies distribution in the Mediterranean subprovince (Fig. 6) is siliciclastic in Morocco, southern Spain, and Doberlug and may represent siliciclastic segments of an old complex marine shelf. Northern Spain, France, Sardinia, and Turkey may represent the carbonate segments of the same marine shelf during Leonian time. The Middle East represents a cratonic sequence. Mixed facies from the Cadenas Ibéricas were deposited in a marine gulf (Sdzuy and Liñán, 1993).

BILBILIAN BIOCHRONOLOGY

The Bilbilian is considered to represent the uppermost Lower Cambrian in Spain; it contains easily recognizable trilobites and acritarchs (Liñán et al., 2002), and it can be correlated with accuracy to other areas of the Mediterranean subprovince. Its upper limit is defined by the top of the *Protolenus jilocanus* interval zone. However, its lower boundary is not well characterized. Liñán et al. (1993a, p. 827) proposed the regional last record of the genera *Andalusiana* and *Serrodiscus* as the upper boundary of the previous Marianian stage; it has also been considered the FAD of the genus *Realaspis* (Liñán et al., 2002).

Sdzuy (1971a) coined the term "Bilbilian" to define a mixed siliciclastic-carbonate sequence without Olenellidae or Paradoxididae but with the presence of Protolenidae, Ellipsocephalidae, Redlichiidae, and genera similar to *Onaraspis.* Sdzuy (1971a) and Liñán et al. (1993a) choose the Huérmeda section, in the Jalón Valley (Zaragoza province) near Huérmeda and Calatayud (which are near the old Roman city of Bilbilis), as the stratotype section for the Bilbilian Stage. In the Cadenas Ibéricas this stage includes strata from shales of the Huérmeda Formation to the last Lower Cambrian rocks within the Valdemiedes Formation. In the Cantabrian region, the Bilbilian is represented by archaeocyath-bearing limestones of the Valdoré Formation (Debrenne and Zamarreño, 1970). Liñán et al. (1993a), in the original definition of the Bilbilian Stage, proposed the Valdoré section as a reference section in the Cantabrian Mountains.

Although the taxa described in the first works about the Bilbilian Stage were mainly endemic forms, subsequent works have recognized several species defined in other regions of the Mediterranean subprovince and vice versa. Furthermore, some genera originally described in distant biogeographical regions have also been described in the Bilbilian of Spain. These finds have allowed the establishment of reliable correlations between the Lower–Middle Cambrian stratigraphic units of different Mediterranean areas: Jordan and Israel (Parnes, 1971; Rushton and Powell, 1998), Turkey (Dean and Özgül, 1994; Dean and Monod, 1997), Morocco (Sdzuy, 1995; Sdzuy et al., 1999), Italy (Pillola et al., 1995; Perejón et al., 2000), Germany (Sdzuy, 1971a; Sdzuy et al., 1999), and Spain (Liñán et al., 2002). Furthermore, the presence of the genus *Onaraspis* in the Cadenas Ibéricas, the Cantabrian Mountains, Morocco, Israel, and Jordan allows good correlation to Australia (see Gozalo and Liñán, 1997; Geyer and Landing, 2004). Finally, the presence of *Palaeolenus* sp. together with archaeocyathans in the Cantabrian Mountains can be a useful tool for correlation with the last Lower Cambrian archaeocyathan levels in Sardinia, China, Australia, and Siberia (see Zhuravlev, 1995).

The recent revision of the taxonomy of Bilbilian trilobites (Dies Álvarez, 2004) allows proposal of the following zonation for the upper part of this stage in the Cadenas Ibéricas. The main problem is that uppermost Marianian and lowermost Bilbilian strata in the Cadenas Ibéricas lack fossils. Thus the lowest levels of the Bilbilian Stage remain without precise faunal zonation. According to Sdzuy (1971a) and Liñán et al. (1993a), the first levels of the Bilbilian Stage, which contain *Realaspis* but not *Protolenus* (*Hupeolenus*), are found near Los Cortijos de Malagón (central Spain). This fauna could be correlated with the top of the *Sectigena* zone in Morocco (Banian Stage). *Realaspis* has also been recorded in Jordan (Rushton and Powell, 1998) and may be the ancestor of the genus *Onaraspis.*

- *Protolenus dimarginatus* zone: This is an interval biozone with the lower boundary determined by the FAD of *P. dimarginatus.* The upper boundary is placed at the FAD of *P. jilocanus.* The FAD of *P. jilocanus* coincides with the FAD of *Hamatolenus* (*Hamatolenus*) *ibericus* (see Liñán et al., 1993b; Dies et al., 2004), so this species can determine the upper boundary of the zone if *P. jilocanus* is not present. In the Cadenas Ibéricas, this zone contains *P. dimarginatus* (Fig. 5A), *Kingaspis* (*K.*) *campbelli* (Fig. 5F), and *P. termierelloides* (Fig. 5G).
- *Protolenus jilocanus* zone (= *Hamatolenus* (*H.*) *ibericus sensu* Liñán et al., 1993b). The original definition of the zone is confirmed with very few changes as follows (Dies Álvarez, 2004): An interval zone with its lower boundary placed at the FAD of *P. jilocanus* and/or of *H.* (*H.*) *ibericus;* the upper boundary is marked by the FAD of *Acadoparadoxides mureroensis.* The trilobite species recorded in the *P. jilocanus* zone of the Cadenas Ibéricas include *H.* (*H.*) *ibericus* (Fig. 5D), *H.* (*Myopsolenus*) sp. A, *Protolenus jilocanus* (Fig. 5E), *P. termierelloides, P. pisidianus* (Fig. 5B), *P. interscriptus, Kingaspis* (*K.*) *campbelli, Sdzuyia sanmamesi, Tonkinella sequei, Onaraspis altus* (Fig. 5C), and *Alueva undulata.*
- *Protolenus dimarginatus, P. interscriptus,* and *P. termierelloides* were defined in Morocco by Geyer (1990a) in the *Hupeolenus* zone. Thus the presence of these species in both zones allows a precise correlation between Morocco and the Cadenas Ibéricas.
- The stratotype of the Bilbilian-Leonian boundary is located in Murero (Cadenas Ibéricas), within the upper Valdemiedes Formation. Liñán et al. (1993b) identified the Valdemiedes event in the uppermost Bilbilian rocks. The event was identified by means of changes in sediment mineralogy and trace fossil contents, as well as the disappearance of numerous trilobite species and dwarfing of the brachiopod fauna. The Valdemiedes event is recorded, at its type locality, Murero, within a conformable, expanded, monofacial succession (in a transgressive context), consisting of mudstones and siltstones that (according to illite crystallinity values) did not surpass the anchizone. Furthermore, some authors used outcrops of the upper Valdemiedes Formation for studies on cyclostratigraphy without finding any important sedimentary break (Álvaro et al., 2000a). The Valdemiedes event has been identified in all Lower or Middle Cambrian localities of Cadenas Ibéricas (northeast Spain). The paleogeographic extent of the Valdemiedes event (and thus its probable significance as a geoevent) is a matter for further research, but its chronological position suggests that it was close to or coincided with the widely accepted Lower or Middle Cambrian mass extinction.
- The Valdemiedes event may be recognized only in areas where uppermost Lower Cambrian sublittoral marine ecosystems were reestablished after the early Bilbilian Daroca regression or its equivalents (such as the Hawke Bay regression). In areas where the Lower–Middle Cambrian transition produced coarse clastic, the Valdemiedes event may be difficult to discriminate from the Daroca regression. In areas where late Early Cambrian regression produced a hiatus extending into the Middle Cambrian (as, for example, in Scandinavia), the Valdemiedes event may be included in this gap (Liñán et al., 2002.)

LEONIAN BIOCHRONOLOGY

The lower boundary of the Leonian Stage was placed at the FAD of *Acadoparadoxides mureroensis* (see Fig. 5H–J). This FAD is one of the most widespread in the Middle Cambrian, for it is recorded in the Cantabrian Mountains and the Cadenas Ibéricas (Spain), Sardinia (Italy), the High Atlas (Morocco), the Taurus Mountains (Turkey), Tuva (Russia), and perhaps also Newfoundland (Canada); see Sdzuy et al. (1999). The Leonian upper boundary has been placed at the FAD of *Badulesia tenera,* which has been recorded from Rhode Island (USA), New Brunswick and Newfoundland (Canada), the High Atlas (Morocco), Sierra Morena, the Cantabrian Mountains and the Cadenas Ibéricas (Spain), Doberlug (Germany), the Amanos Mountains (Turkey), and the Montagne Noire (France).

The sequences from the Cadenas Ibéricas (mixed facies) and the Cantabrian Mountains (carbonate facies) are some of the most continuous and fossiliferous successions known from the Leonian Stage. They permit identification of three trilobite zones named the *Acadoparadoxides mureroensis* zone, the *Eccaparadoxides sdzuyi* zone, and the *Eccaparadoxides asturianus* zone (Gozalo and Liñán, 1995; Sdzuy et al., 1996, 1999). These are interval zones limited by the first appearance of the *Paradoxides* species chosen from a phylogenetic line, and they are also characterized by other trilobite taxa.

The lower boundary of the *Acadoparadoxides mureroensis* zone is marked by the FAD of the trilobite species *A. mureroensis;*

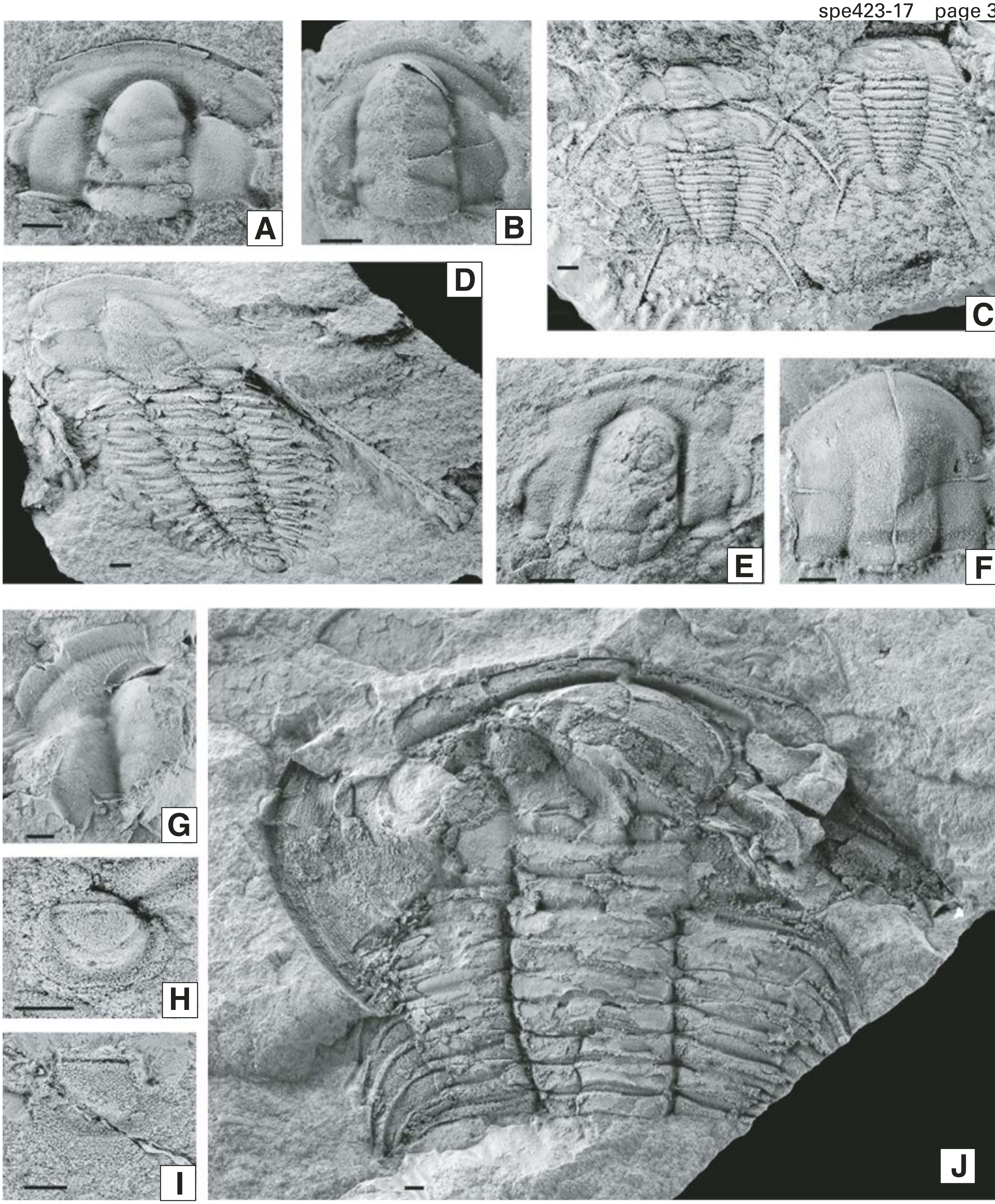

Figure 5. Selected trilobites from sections in Cadenas Ibéricas. (A) *Protolenus dimarginatus* (Geyer, 1990a); MPZ 01/100; internal mold of cranidium preserved in shales; Jarque 1 section; bar = 2 mm. (B) *Protolenus pisidianus* (Dean *in* Dean and Özgül, 1994); MPZ 2004/89; cranidium preserved in limestones; Ateca 16 section; bar = 2 mm. (C) *Onaraspis altus* (Liñán and Gozalo, 1986); MPZ 99/515 and MPZ 99/586; internal molds of complete specimens preserved in shales; Rambla de Valdemiedes 1 section; bar = 2 mm. (D) *Hamatolenus* (*Hamatolenus*) *ibericus* (Sdzuy, 1958); MPZ 99/184; internal mold of a complete specimen preserved in shales; Rambla de Valdemiedes 1 section; bar = 5 mm. (E) *Protolenus jilocanus* (Liñán and Gozalo, 1986); MPZ 01/107; internal mold of cranidium preserved in shales; Jarque 1 section; bar = 2mm. (F) *Kingaspis campbelli* (King, 1923); MPZ 99/34; internal mold of cranidium preserved in shales; Jarque 1 section; bar = 2 mm. (G) *Protolenus termierelloides* (Geyer, 1990a); MPZ 2004/85; incomplete cranidium preserved in limestones; Ateca 16 section; bar = 2 mm. (H) *Acadoparadoxides mureroensis* (Sdzuy, 1958); MPZ 01/84; internal mold of pygidium (morphotype A) preserved in shales; Rambla de Valdemiedes 1 section; bar = 2 mm. (I) *Acadoparadoxides mureroensis* (Sdzuy, 1958); MPZ 01/ 83; internal mold of pygidium (morphotype B) preserved in shales; Rambla de Valdemiedes 1 section; bar = 2 mm. (J) *Acadoparadoxides mureroensis* (Sdzuy, 1958); MPZ 01/82; internal mold of incomplete specimen preserved in shales; Rambla de Valdemiedes 1 section; bar = 2 mm

the position has been considered the Lower–Middle Cambrian boundary in different regions (Sdzuy, 1971b, 1972, 1995; Álvaro et al., 1993; Gozalo et al., 1993b; Liñán et al., 1993a,b; Dean and Özgül, 1994; Loi et al., 1995; Pillola et al., 1995; Elicki and Pillola, 2004). Its upper boundary is the FAD of *Eccaparadoxides sdzuyi. Acadoparadoxides mureroensis* is the guide fossil of this zone and disappears at the base of the following zone. The trilobite species *Hydrocephalus* cf. *harlani, Alueva hastata, Alueva moratrix,* and *Macannaia* are also typical of this interval zone. Other bioevents are the FAD of *Condylopyge cruzensis* and the last records of the genera *Hamatolenus, Protolenus* (*Hupeolenus*), *Latoucheia,* and *Alueva.*

The following *Eccaparadoxides sdzuyi* zone has its upper boundary immediately below the FAD of *Eccaparadoxides asturianus.* The species *Conocoryphe* (*Conocoryphe*) *ovata, Acadolenus decorus,* and *Peronopsella prokovskajae prokovskajae* are typical of this zone. Other important bioevents are the FADs of the genera *Conocoryphe, Cornucoryphe, Bailiella, Asturiaspis, Skreiaspis, Acadolenus, Peronopsella,* and *Dawsonia.*

The upper boundary of the *Eccaparadoxides asturianus* zone is marked by the FAD of *Badulesia tenera.* At present, the trilobite species *Acadolenus inornatus, Jincella? sulcata, Conocoryphe* (*Parabailiella*) *sebarensis, Skreiaspis tosali, Holocephalina? leve,* and *Bailiaspis dalmani* are exclusive to this zone. The FADs of *Peronopsella prokovskajae ovetense, Eccaparadoxides sulcatus, Conocoryphe* (*P.*) *languedocensis,* and *Bailiaspis* cf. *tuberculata* are also included in the zone.

GLOBAL CORRELATION

In recent years, the time interval revisited in this work has been discussed in several papers, and several correlation charts have been produced (i.e., Sdzuy et al., 1999; Geyer and Shergold, 2000; Fletcher, 2003; Geyer and Landing, 2004; Fletcher et al., 2005). There is no general agreement on the main levels. For this reason, we have tried herein to obtain a general view for the Mediterranean subprovince. This allows for a better understanding of regional correlation and for improved global correlation.

The trilobite markers of the Bilbilian and Leonian biozones and their respective associations permit fairly precise global correlation of theBilbilian and Leonian Stages. The main problem is with the lower Bilbilian, because, for the moment, it lacks a biozonation and its lower boundary is not well established.

The base of the Bilbilian Stage is defined by the FAD of the genus *Realaspis,* which has been found in central Spain (Sdzuy, 1961, 1971a) and Jordan (Rushton and Powell, 1998). The next biostratigraphic level is the FAD of *Protolenus.* Perhaps this level is the best way to recognize this stage. *Protolenus* shows a wide distribution in the Acadobaltic province, and allows recognition of the last stage of the Lower Cambrian without Paradoxididae. Other important trilobite taxa for correlation are *Kingaspis campbelli* (see Rushton and Powell, 1998; Liñán et al., 2003), *Onaraspis* (Gozalo and Liñán, 1997; Geyer and Landing, 2004), and *Palaeolenus.* Geyer and Landing (2004) proposed the *Onaraspis* clade as a useful correlation tool, including the genera *Onaraspis* and *Myopsolenites.* We believe that the second is a junior synonym of *Onaraspis;* actually, the name *Myopsolenites* was a misprint of Öpik (1975), as Rushton and Powell (1998) discussed.

On the other hand, the tenth correlative unit for the Early Cambrian proposed by Zhuravlev (1995), which corresponds to the mid-Toyonian *Lermontovia grandis* trilobite zone, is equivalent to the archaeocyathan *Irinaecyathus schabanovi-Archaeocyathus okulitchi* zone of the Siberian Platform. This unit is identifiable by its trilobite and archaeocyathan assemblages. The archaeocyathan assemblage has been recorded in the Siberian Platform, the Altay-Sayan foldbelt, Australia, China, Spain, and Sardinia (see Zhuravlev, 1995). As for Spain, this archaeocyathan assemblage has been found only in the Bilbilian of the Cantabrian Mountains (Debrenne and Zamarreño, 1970; Perejón and Moreno-Eiris, 2003). Now we report the finding of these archaeocyathans together with the trilobite *Palaeolenus* sp. This fact reinforces the correlation to China, where the archaeocyathans belong to the *Megapaleolenus* zone of the Tsanglangpuan Stage (Yuan et al., 2001). Recently Lin and Peng (2004) reviewed the genus *Palaeolenus* and considered the genus *Megapaleolenus* a junior synonym of *Palaeolenus;* furthermore, they agreed with Rushton and Powell (1998), who transferred *Schistocephalus antiquus* to *Palaeolenus.* They also commented that "*Gigoutella* is more likely also a junior synonym of *Palaeolenus.*" We are in agreement with their systematic opinions.

The boundary between the Bilbilian and the Leonian is placed at the FAD of *Acadoparadoxides mureroensis.* This FAD is close to the FADs of *Palaeolenus antiquus, Macannaia* spp., and *Ovatoryctocara granulata,* which may be considered one of the best species for global correlation. The FADs of *Badulesia tenera, Parasolenopleura aculeata, Ctenocephalus* (*Hartella*) spp., and *Ptychagnostus gibbus* may be considered the characteristic bioevents for global correlation of the Leonian upper boundary.

A tentative correlation chart of the Bilbilian and Leonian Stages is presented in Figure 6. Bilbilian correlation is based on the presence of the genera *Realaspis, Protolenus,* and *Onaraspis* and some species such as *Palaeolenus antiquus* and *Kingaspis campbelli,* as well as on the last archaeocyathans. *Palaeolenus antiquus* was defined in Siberia, and its FAD is considered a marker of the Amgan Stage; this species is recorded slightly below the first *Paradoxides* (see Korovnikov, 2001, 2004).

The lower boundary of the Leonian Stage is based on the association of *Acadoparadoxides mureroensis* and *Macannaia* in Spain. *Acadoparadoxides mureroensis* is also recorded in Morocco, Siberia, Sardinia, and Turkey, and probably in Newfoundland, while *Macannaia* is present in Laurentia, Australia, and Siberia. Another important taxon is *Hydrocephalus harlani,* originally defined in Massachusetts (USA), which also occurs in Morocco and probably in Spain (Geyer and Landing, 2001; Dies Álvarez, 2004; Fletcher et al., 2005). Finally, *Tonkinella* aff. *breviceps* is recorded from the upper Leonian and has been correlated with the Hsuchuangian Stage (North China) and the *Ehmaniella* Zone (USA) by Gozalo et al. (2003).

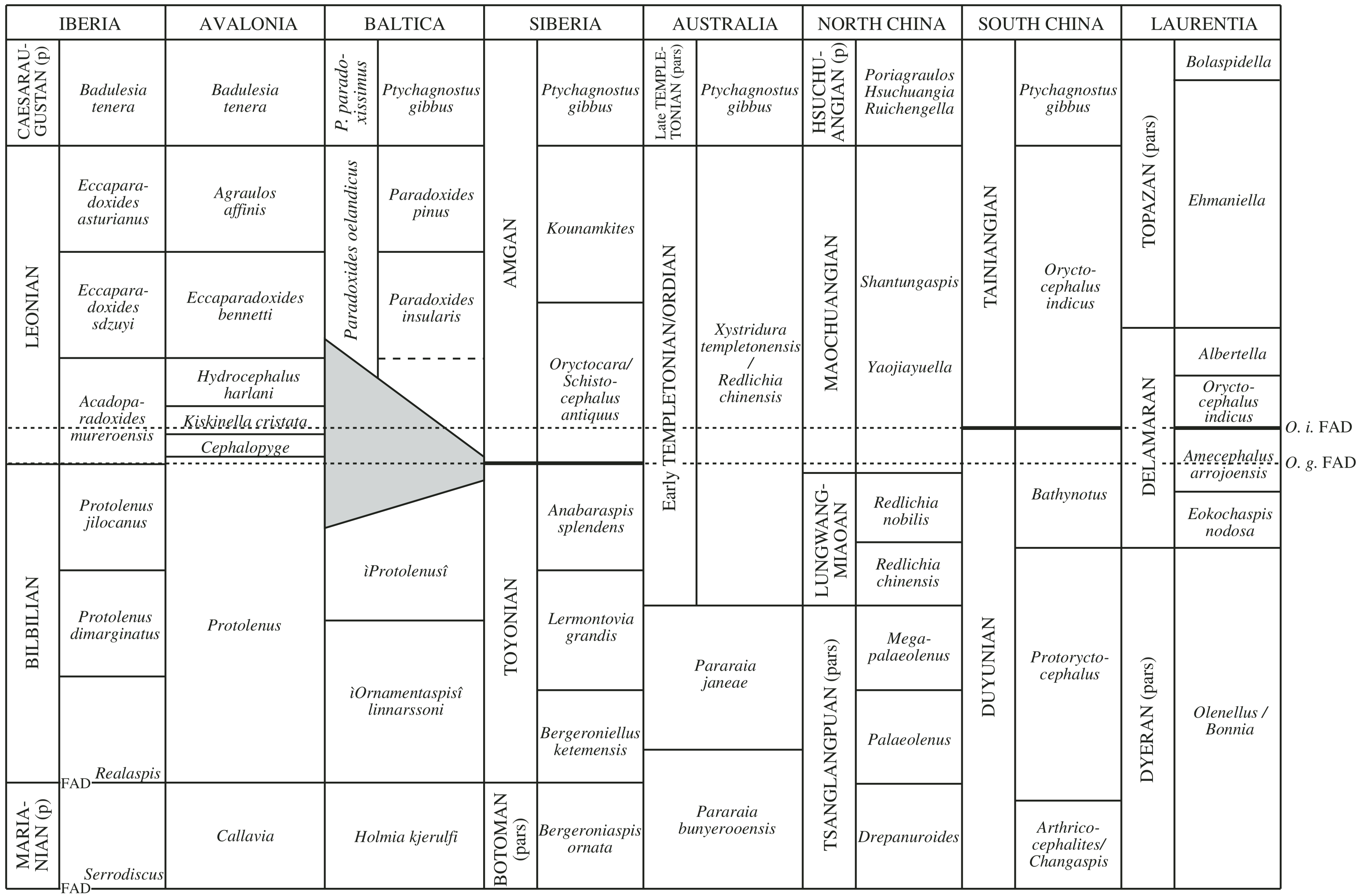

Figure 6. Global correlation of the latest Marianian, Bilbilian, and Leonian and earliest Caesaraugustan stages with other regional stages and zones, based on Sdzuy et al. (1999), Geyer and Shergold (2000), Peng and Babcock (2001), Peng (2003), Geyer and Landing (2004), and Fletcher et al. (2005). The scheme for Laurentia is according to the latest modification by Sundberg and McCollum (2003) and Sundberg (2005). Abbreviations: FAD—first appearance datum; *O. i.* FAD—FAD of *Oryctocephalus indicus; O. g.* FAD—FAD of *Ovatoryctocara granulata.*

The upper boundary of the Leonian is based on the presence of *Badulesia tenera* and *Ptychagnostus gibbus,* but they have not been found to co-occur yet. *Badulesia tenera* is recorded in Spain, Morocco, and Newfoundland, while *Ptychagnostus gibbus* has been identified from Laurentia, North China, Australia, Siberia, and Baltica. This correlation is supported by the association of *Ctenocephalus* (*Hartella*) and *Parasolenopleura aculeata* with *Badulesia tenera* in Spain and Newfoundland (Liñán et al., 1995; Fletcher, 2005) and with *Ptychagnostus gibbus* in Baltica.

In conclusion, the Bilbilian and Leonian Stages are useful Lower–Middle Cambrian stages for the Mediterranean subprovince and also represent a good tool for correlation with other regional stages defined in the upper Lower and lower Middle Cambrian. The Bilbilian–Leonian boundary roughly coincides with the FAD of *Ovatoryctocara granulata,* one of the levels studied by the ISCS. The *Oryctocephalus indicus* level is probably located slightly above the Bilbilian–Leonian boundary, and it correlates to somewhere within the lowermost part of the *Acadoparadoxides mureroensis* zone (see Fig. 6). The close and solomonic occurrence of the Bilbilian–Leonian boundary between the two Global Standard Stratotype-section and Points proposed by the ISCS and the absence of *Oryctocara granulata* and *Oryctocephalus indicus* in the Mediterranean region made this classic Cambrian Series boundary a neccessary and complementary reference for intercontinental correlation. Finally, the Bilbilian–Leonian boundary is placed after the global lowermost Cambrian mass extintion event and before the great Middle Cambrian radiation event in the Earth's History.

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