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ORIGINAL PAPER

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The Middle Jurassic radiolarites and pelagic limestones of the Nieves unit (Rondaide Complex, Betic Cordillera): basin starvation in a rifted marginal slope of the western Tethys

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Abstract Middle Jurassic radiolarites and associated pelagic limestones occur in the Rondaide Nieves unit of the Betic Cordillera, southern Spain. The Rondaide Mesozoic includes: (a) a thick succession of Triassic platform carbonates, comparable to the Alpine *Hauptdolomit* and *Kössen* facies; (b) Lower Jurassic pelagic limestones comparable to the Alpine Hierlatz and Adnet facies; (c) the Middle Jurassic Parauta Radiolarite Formation, described herein; and (d) a thin Upper Jurassic–Cretaceous condensed limestone succession. The Parauta Radiolarite Formation and associated limestones were studied with respect to stratigraphy, petrography, micropalaeontology (radiolarians, calcareous nanno- and microfossils) and facies. Radiolarite sedimentation occurred in the Middle Bathonian in a restricted and dysoxic deep Nieves basin, perched in the distal zone of a continental margin fringing the Tethyan ocean. This margin was adjacent to a young narrow oceanic basin between the South-Iberian margin and a continental block called Mesomediterranean Terrane. The Nieves basin was part of a marine corridor between the Proto-Atlantic and Piedmont-Ligurian basins of the Alpine Tethys. The regional tectonic position, the stratigraphical evolution since the Triassic, the age and the nature of the Mesozoic facies and the palaeogeographic relations to adjacent domains show striking analogies between the Betic Rondaide margin and coeval units of the Alps.

Keywords Bathonian · Radiolaria · Calcareous nannofossils · Microfacies · Chert · Paleoceanography · Paleogeography · Western Tethys

Introduction

Radiolarian cherts generally are deep-marine pelagic deposits. They are usually thought to characterise the deepest zones in distal areas of continental margins developed on thinned continental crust (Garrison and Fisher 1969; McBride and Folk 1979), or in deep basins with oceanic crust (Folk and McBride 1978; Marcoux and Ricou 1979; Gursky 1994) or exhumed mantle rocks (Weissert and Bernoulli 1987). Palaeozoic and Mesozoic radiolarian sediments include, however, a wide group of facies which may show striking differences in composition and textures, fossil content, bedding style, sedimentary structures and colour (Diersche 1980; Hein and Karl 1983; Jones and Murchey 1986; Gursky 1996). Radiolarites are commonly associated with other siliceous and non-siliceous, usually fine-grained deposits (terrigenous mudstones, biogenic pelagic carbonates, clastic and authigenic sediments). This variety of facies associations indicates that a wide spectrum of sedimentary processes and environments may be involved in radiolarite deposition. Radiolarites are commonly formed when the input of non-siliceous components is scarce, so that the radiolarians are concentrated in the bottom sediment. They form either tens to a few hundreds of metres thick successions deposited with relatively high

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sedimentary rates (Diersche 1980; De Wever et al. 1994; Gorican 1994), or very thin and condensed deposits that were accumulated during long periods of geological time under conditions of basin starvation (Baumgartner 1990; O'Dogherty et al. 1989a; Maate et al. 1993; Baumgartner et al. 1995b). The Middle-Upper Jurassic of the Rondaide Nieves unit (Betic Cordillera) is characterised by condensed sediments in which a thin radiolarite intercalation is present. The aim of this paper is to provide new lithostratigraphical, biostratigraphical and petrographical data on these radiolarites, to establish the main features of their depositional environment and to evaluate their palaeogeographical significance within the framework of the western Tethys.

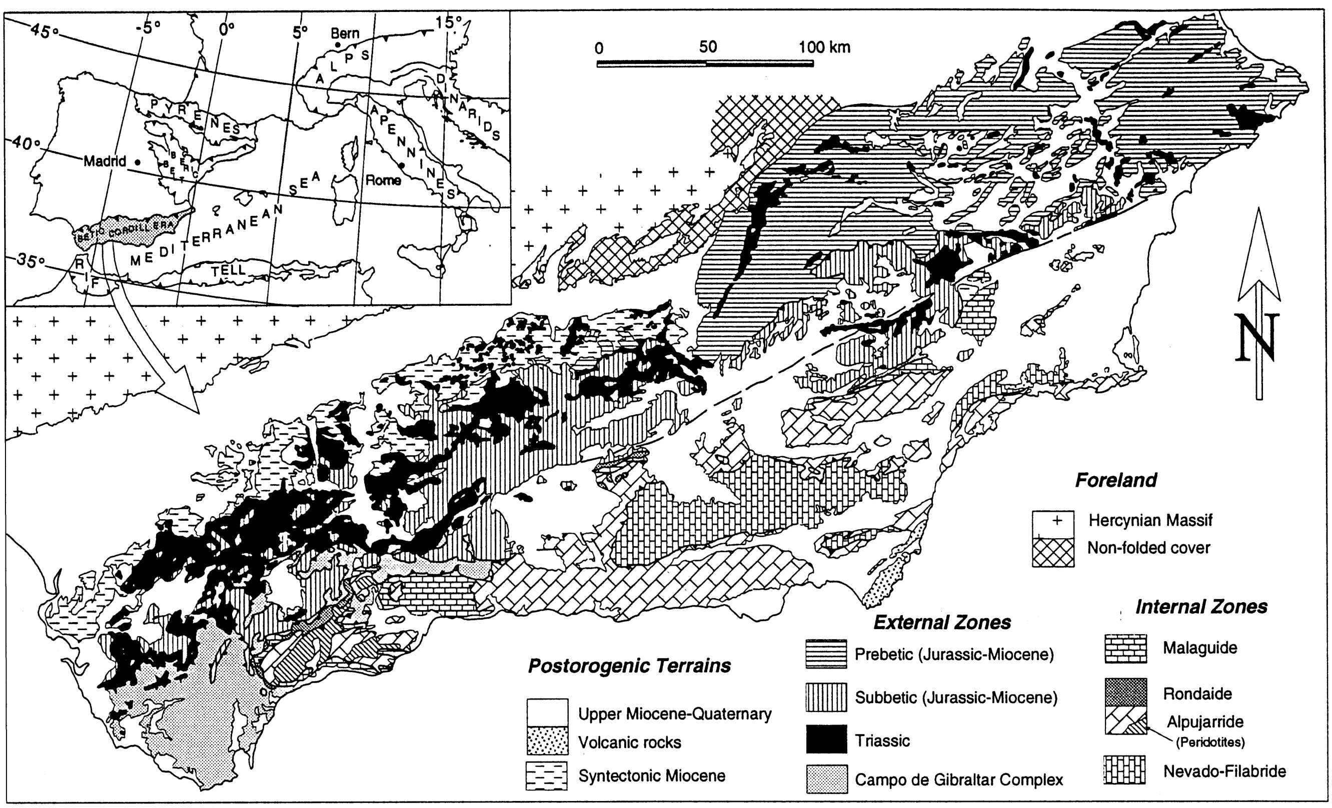
Geological setting

The Betic Cordillera is subdivided into external zones, Campo de Gibraltar Complex and internal zones (Fig. 1). The internal zones are a nappe pile which is subdivided into three thrust complexes named, from bottom to top, Nevado-Filabride, Alpujarride and Malaguide. In addition, the front of the internal zones, especially in its western part (Fig. 2), is characterised by several nappes and thrust slices, called Rondaide complex by Blumenthal (1927, 1949), Hoeppener et al. (1963, 1964), Felder (1980) and Martín-Algarra (1987). These units tectonically underlie the higher Alpujarride and the Malaguide nappes.

Palaeogeographically, the external zones constituted the proximal (Prebetic) and the distal (Subbetic) areas of the Meso-Cenozoic Southern Iberian continental margin. They are traditionally considered to be the Spanish equivalents of the Alps and Jura nappes derived from the Eurasian continental margin (Blumenthal 1927; Fallot 1948). The Campo de Gibraltar Complex is made up of Cretaceous to Lower Miocene flysch, mainly mudstones and turbidites. It is tectonically and palaeogeographically equivalent to the flysch zone of the Eastern Alps. In the internal zones, it is difficult to establish the exact palaeogeographical location of most units and nappes because, as in the Alps, both pre-Mesozoic basement and Meso-Cenozoic cover were strongly deformed and metamorphosed during the Alpine orogeny.

The Nevado-Filabride Complex was classically considered to be equivalent to the Alpine Penninic (Brouwer 1926). Most of its rocks probably represent the pre-Alpine basement of the former Southern Iberian margin, but it also includes strongly dismembered ophiolitic units which some authors have interpreted as remnants of a western arm of the Piedmont-Ligurian ocean (Puga et al. 1995; Tendero et al. 1993). The Alpujarride Complex, composed mainly of thick Triassic carbonate successions with a typical Tethyan platform facies, was considered to be a Betic equivalent of the Austroalpine nappes (Staub 1926; Fallot 1954).

Fig. 1 Tectonic sketch map of the Betic Cordillera



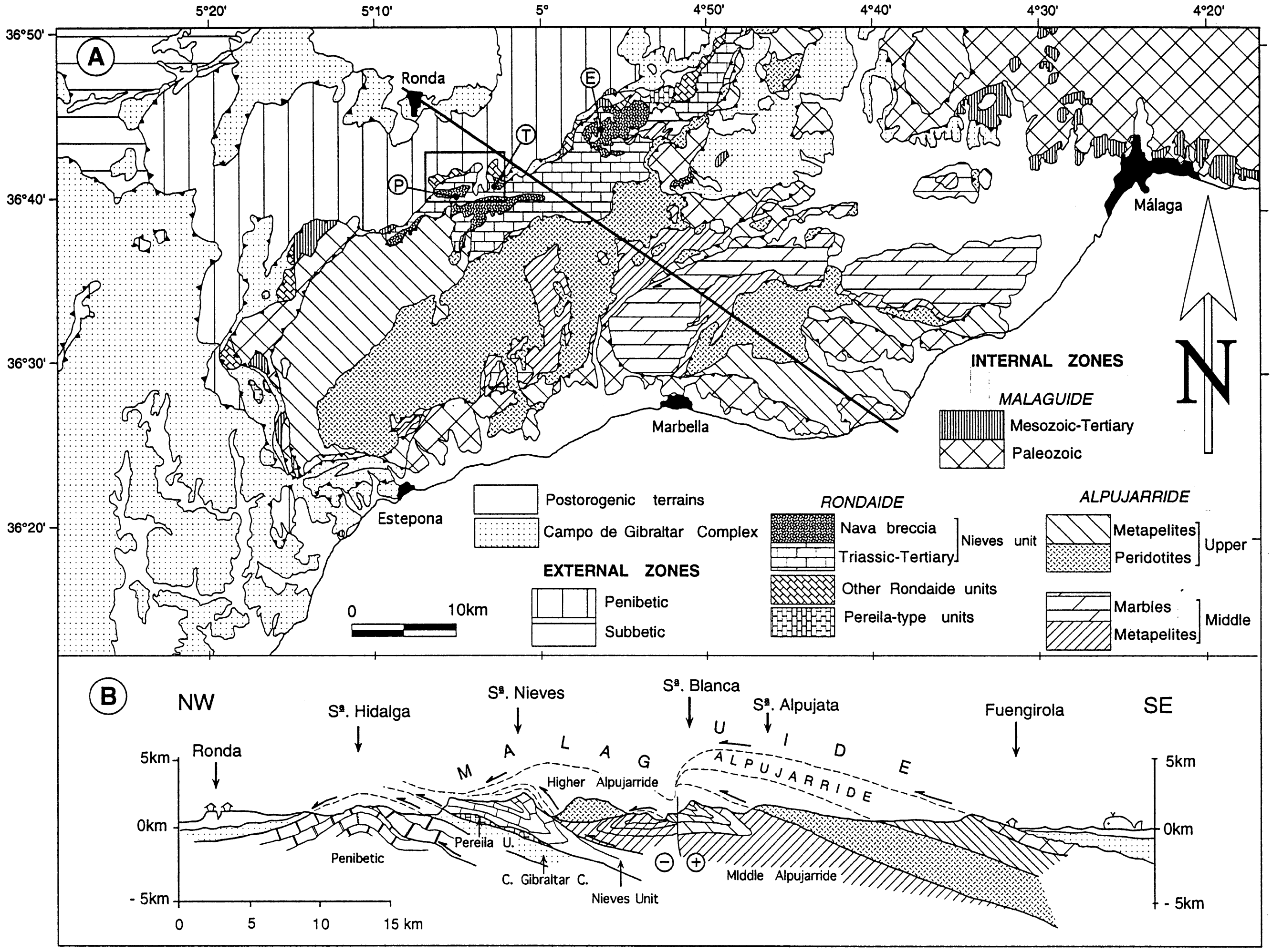


Fig. 2 **A** Tectonic sketch of the Western Betic Cordillera and **B** tectonic cross section illustrate the nappe structure in the area. *Inset* shows location of Fig. 3; *P*, *T* and *E* correspond to the location of the Parauta, Taramar and Encina sections

The Rondaide Triassic is identical to that of some of the intermediate Alpujarride nappes but, in addition, Rondaide units also include Jurassic to Tertiary sediments which are absent in most Alpujarride units. The Malaguide is the highest nappe complex and is formed by a metasedimentary Palaeozoic basement covered by Triassic Verrucano-type sediments followed by a mainly shallow-marine, thin, incomplete and condensed Jurassic to Lower Miocene succession.

The Rondaide Nieves unit

The Nieves unit is the most typical and the most widely extended Rondaide unit (Dürr 1967; Martín-Algarra 1987). It forms a NE/SW-striking, northward vergent recumbent syncline with an increasingly metamorphosed overturned southeastern limb, which is overlain by the highly metamorphic western Alpujarride nappes, which include at their tectonic base the famous Ronda peridotites, and by the Malaguide nappes (Fig. 2B). The Nieves unit is essentially made up of a highly deformed Mesozoic and Tertiary succession that tectonically overlies the Campo de Gibraltar Complex and the most internal Subbetic (=Penibetic) in the Ronda region (Fig. 3).

The stratigraphic succession of the Nieves unit can be subdivided into two major, unconformity-bounded stratigraphic units: a shallow-marine to pelagic, Upper Triassic to Aquitanian succession, and the Lower Miocene continental Nava Breccia Formation (Figs. 3, 4) The Mesozoic succession of the Nieves unit shows striking similarities to other areas of the Alpine Belt, e.g. the Northern Rif (Wildi 1983), the Austroalpine nappes of the Northern Calcareous Alps (Diersche 1980; Gawlick 1996), the Lower and Upper Austroalpine series of the Central Alps (Manatschal and Nievergelt 1997) and some domains of the Southern Alps (Lombardian Basin: Kälin et al. 1979; Baumgartner et al. 1995b). The following main stratigraphical units are distinguished from bottom to top (Fig. 4):

1. A 1100-m-thick Carnian to Norian dolomite formation (Main Dolomite Formation) with peritidal

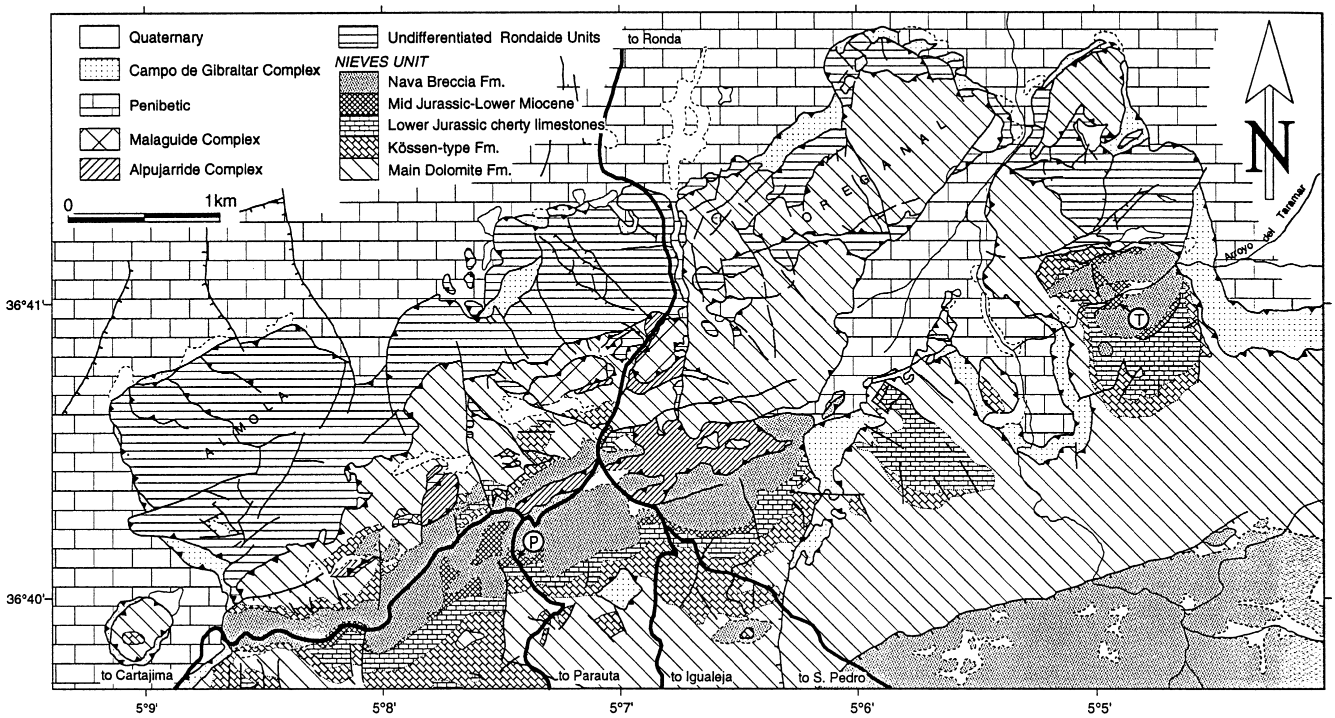


Fig. 3 Geological map of the study area, with location of measured and sampled sections. *T* Taramar; *P* Parauta

to lagoonal facies. This formation is part of the classical Triassic carbonate platforms fringing the Alpine Tethys, e.g. the Alpine “Hauptdolomit”.

2. A 150- to 200-m-thick Rhaetian succession of marlstone–limestone alternations deposited in moderately deep, open platform environments, grading upwards into massive, partially reefal limestones (comparable to, for example, the Austroalpine “Kössener Schichten”).
3. A 100- to 200-m-thick Lower Jurassic pelagic, ammonite-bearing series, essentially composed of cherty limestones and marlstones with some intercalations of red nodular limestones (Sinemurian) and crinoidal limestones (Pliensbachian). This succession is similar to, for example, the Austroalpine and Southalpine “Hornsteinplattenkalk” and “Kieselkalk” (Hierlatz facies; Böhm 1992) and to the Adnet Formation, respectively.
4. A few tens of metres thick, extremely condensed pelagic succession, Middle Jurassic to Early Cretaceous in age. This heterolithic unit includes the radiolarites of the Parauta Formation addressed in this paper, which correspond stratigraphically to the radiolarites in the Austroalpine nappes and in the Lombardian basin of the Southern Alps.
5. A few metres of marlstones with intercalated siliciclastic sandstones and calcarenites, Paleogene to earliest Miocene in age (Taramar Formation). This series predates the deposition of the Nava Breccia Formation and the main tectonogenesis in the area.

Lithostratigraphy, microfacies and petrography

The condensed Middle Jurassic to Lower Cretaceous succession of the Nieves unit is observed in the area south of Ronda (Figs. 2, 3). A well-defined radiolarite interval occurs in the Parauta, Taramar and Encina sections (Figs. 2, 3, 4). The first two outcrops were examined in detail (Fig. 5) and 176 samples were studied in order to identify the petrographical features, microfacies and microfossils of the siliceous rocks and associated limestones and marlstones in thin sections. Three stratigraphical units are distinguished: (a) a pre-radiolarite succession dominated by cherty limestones topped by red nodular limestones; (b) a radiolarite interval (the Parauta Radiolarite Formation); and (c) a post-radiolarite succession of pelagic marlstones and limestones.

Pre-radiolarite succession

The condensed succession starts with red, subordinately greenish, nodular and strongly stylolitised limestones with red or green marly intercalations and local red chert nodules. In Parauta these limestones are nearly 10 m thick and overlie a well-bedded succession of greyish cherty limestones and marls that include some thick beds of light-grey crinoidal calcarenites near the top. In places, the nodular limestones are thinner and they may alternate (Encina section) and/or laterally grade into platy marly limestones and marls with chert nodules (Taramar section) which resemble the rocks of the underlying Lower Jurassic formation.

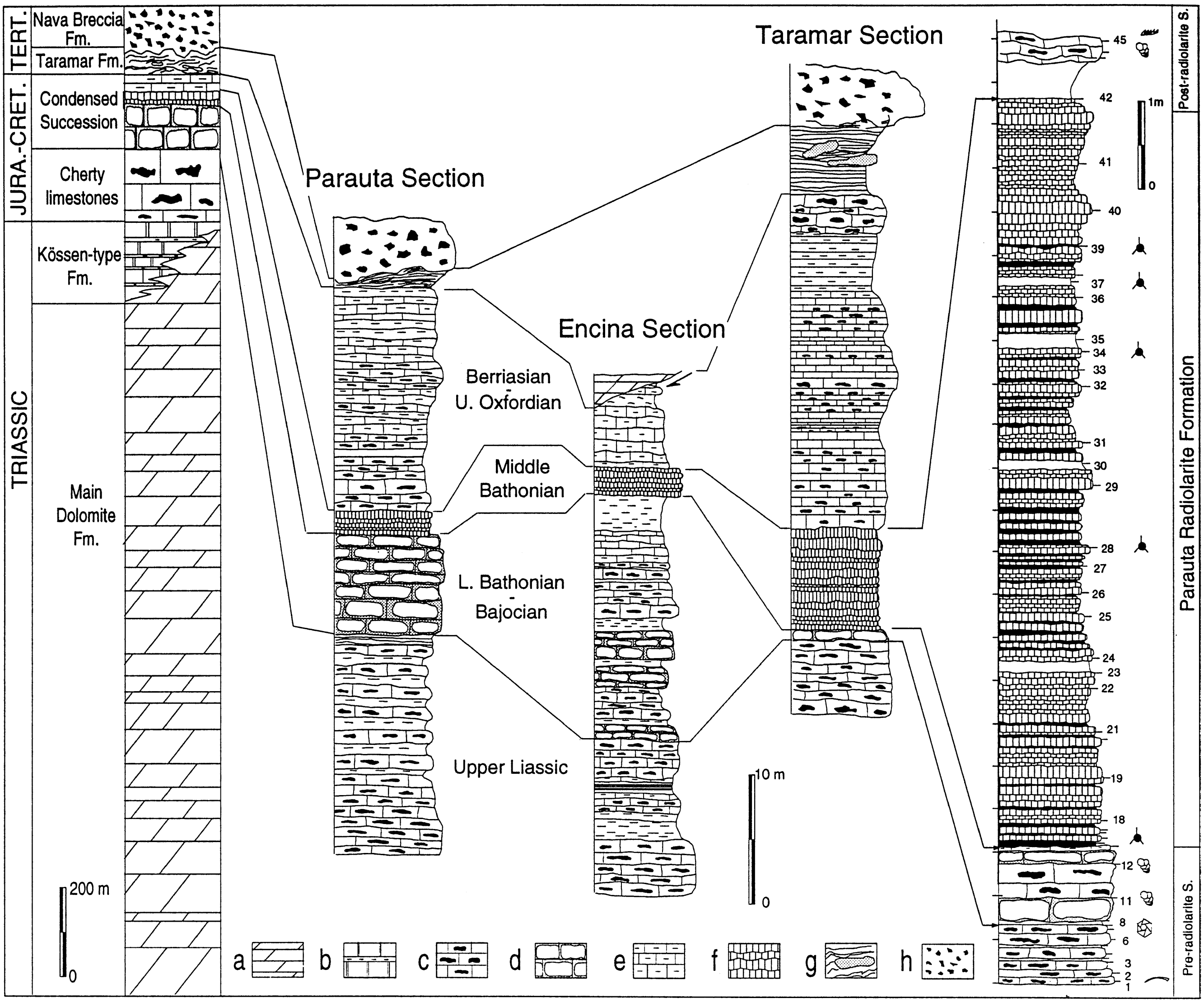


Fig. 4 Synthetic stratigraphy of the Nieves unit, stratigraphic correlation between the Mesozoic condensed successions of the Parauta, Taramar and Encina sections (location in Figs. 2 and 3), and type section of the Parauta Radiolarite Formation with indication of the position of the samples mentioned in the text (*dark interbeds* between cherts correspond to black/dark-grey shales). Lithology: *a* dolostones; *b* marlstone–limestone alternations; *c* cherty limestones; *d* nodular limestones; *e* marlstones; *f* radiolarites; *g* marls, sandstones and calcarenites; *h* carbonate breccias. Symbols for fossils as in Fig. 5

The greyish cherty limestones underlying the red nodular limestones are fine-grained and dominated by peloidal wackestone–packstone, in places laminated. Peloids are in their greatest part micritised bioclasts, mainly crinoids. Calcitised radiolarians and benthic foraminifera are typical components of these rocks that, additionally, include some crinoidal grainstones–packstones in Parauta. Crinoidal calcarenites are completely absent in Taramar, where the succession is finer grained and more terrigenous, with silt-sized quartz grains visible in thin section.

In Taramar, pelagic bivalves (*Bositra* sp.) become abundant in the top of the cherty limestones (sample 8: Figs. 4, 5B). In Parauta, pelagic bivalves appear in the base of the red nodular limestones (sample 2: Figs. 5A, 6A). These are also rich in chert nodules and show a microfacies transitional to those of the underlying cherty limestones, which are dominated by peloidal wackestone–packstone with pelagic bivalves, a few sponge spicules and, in places, abundant calcitised radiolarians (sample 4: Fig. 5A). In Parauta, the microfacies changes upsection to bioclastic packstone with abundant calcitised radiolarians, less abundant *Bositra* fragments and progressively more abundant planktonic foraminifera ("protoglobigerinids"), small ammonites (sample 7: Figs. 5A, 6C) and benthic foraminifera (sample 10: Figs. 5A, 6D). Analogous microfacies have been recognised near the top of the pre-radiolarite succession in Taramar (sample 11: Figs. 4, 5B, 6B) within a nodular limestone bed intercalated in the cherty limestones. Just below the contact with the radiolarites, a thin red nodular limestone with lami-

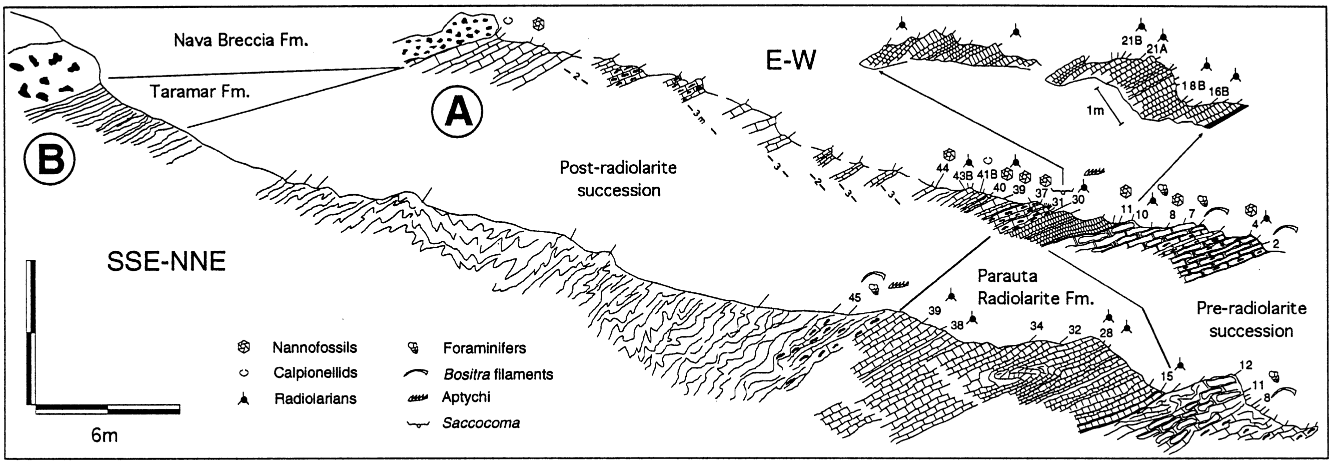


Fig. 5 Sketches of **A** the Parauta and **B** Taramar outcrops with location of samples studied and mentioned in the text. Lithologies as in Fig. 3

nated peloidal bioclastic microfacies occurs (sample 12: Figs. 4, 5B) which, however, shows strong tectonical deformation.

Parauta Radiolarite Formation

The Parauta Radiolarite Formation was formally defined by Martín-Algarra et al. (1998) based on the Taramar type section (Figs. 2A, 3), where the succession and its lower and upper boundaries are best visible (Figs. 4, 5A). The Parauta and Encina sections (Figs. 2, 4) are parastratotypes (Martín-Algarra et al. 1998). A sharp contact (paraconformity) is visible between the Parauta Radiolarite Formation and the underlying rocks, and the upper boundary of the formation is also sharp (Figs. 4, 5). The maximum thickness is approximately 10 m (Taramar section) only 2–3 m are recorded in the Parauta and Encina sections. The radiolarites are finely and rhythmically stratified alternations of decimetre- to centimetre-thick, tabular to platy beds of brown-reddish (base of Parauta), dark brown-greenish (top of Parauta and Taramar) or dark greenish (Encina) fractured ribbon chert, and millimetre- to centimetre-thick, greenish or dark-grey to black siliceous mudstones (Fig. 4). Bedding planes are generally sharp, some parallel lamination and smooth pinch-and-swell structures may be present and bioturbation is rare.

Two petrographic types of siliceous rocks are present in the radiolarites. The main type (sample 16B: Figs. 5A, 6E,F; sample18B: Fig. 5A, 6H) is a moderately recrystallised hematitic, carbonate-free radiolarian chert with a pale brownish-red colour. Subordinately, near the base of the formation in Taramar (sample 15: Fig. 5B), a grey moderately recrystallised calcareous radiolarian chert occurs (Fig. 6G) that grades into radiolarian-bearing siliceous limestone.

The radiolarian content is on average between 30 and 50% by volume, ranging from 10 to more than 60%. Variations in radiolarian content are reflected by the lamination. In thin section, the size of the roundish radiolarian tests ranges between 30 and 100 μm with a maximum of 130 μm. Most radiolarian sections are round (Fig. 6E,G,H). Relatively few radiolarians show longish-triangular contours typical for sections along the long axis of Mesozoic cone-shaped radiolarians (multicyrtid nassellarians). A few spumellarian skeletons observed in thin section can be attributed to the Emiluviinae (Fig. 6F: *Homoeoparonaella* sp.). Tectonic flattening is generally absent. However, late-diagenetic pressure dissolution of the tests may occur, especially along the frequent bedding-parallel microstylolites (Fig. 6E). Apart from radiolarians and their fragments, no other biogenic constituents have been found.

Thermal grain growth and recrystallization are moderate to strong. Many radiolarians, however, are relatively well preserved and show skeletal details even in thin section. Preservation grade decreases in radiolarian-rich laminae. The radiolarian tests are nearly exclusively preserved as microquartz (Fig. 6G) that has diagenetically replaced the organic opal A. Four types of mineralogical preservation and infillings occur:

1. Skeleton infillings with microquartz are very abundant, the skeleton being indistinguishable from the infilling as in Fig. 6H. The semicircular structures in the border between the test and the central void of the big radiolarian are made of “microquartz balls” that replaced the original lepispheres of opal CT (cristobalite–trydimite).
2. Mixtures of submicroscopically fine-grained microquartz and hematite (Fig. 6H, interior of the large radiolarian).
3. Chalcedony or chalcedony with some microquartz (Fig. 6G, filling of the radiolarians).
4. One or few megaquartz crystals (>35 μm in diameter: Fig. 6H, centre) are rare.

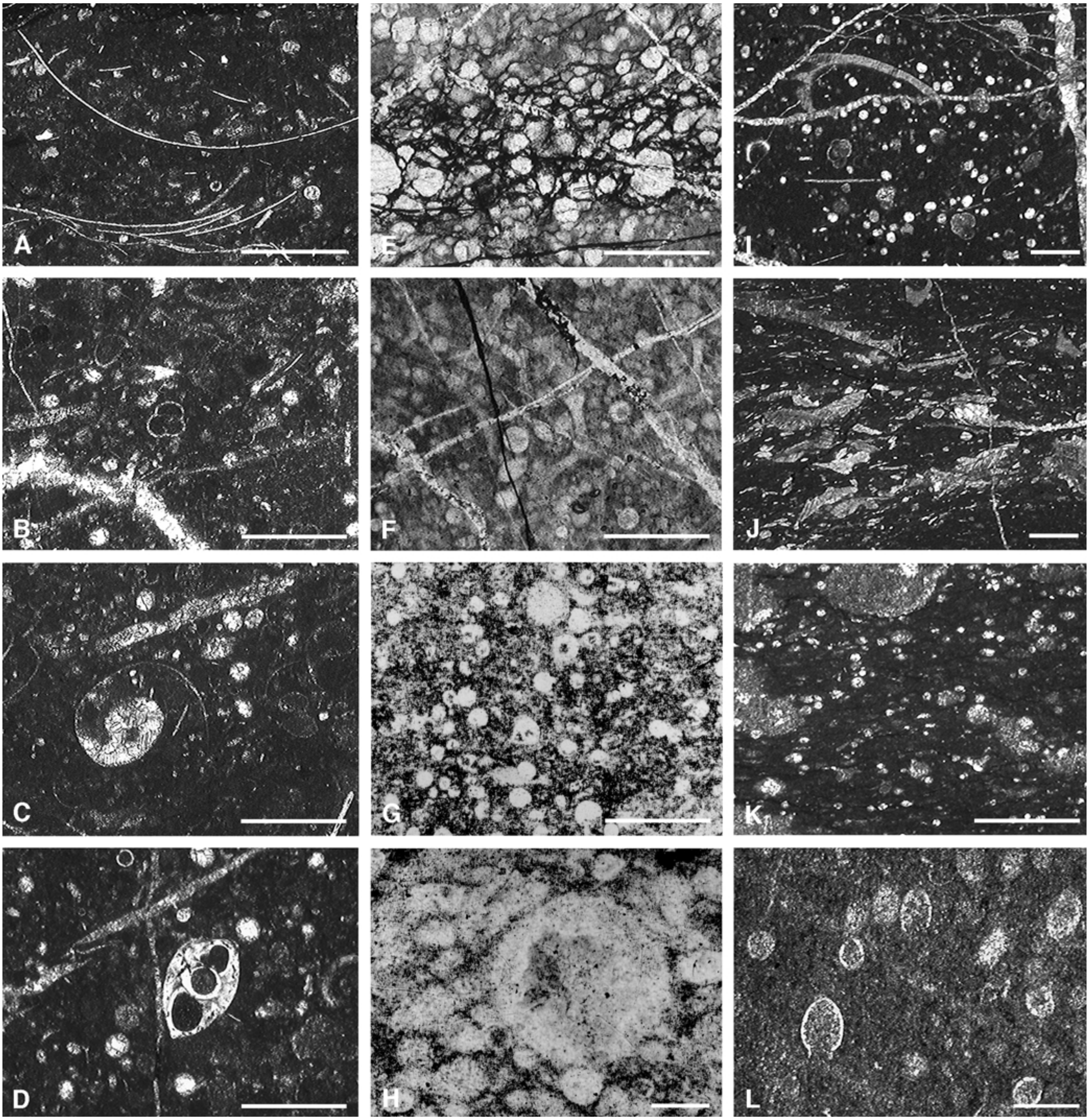


Fig. 6 Microfacies of the mesozoic condensed succession of the Nieves unit. *A–D* from the pre-radiolarite succession. *E–H* from the Parauta Radiolarite Formation. *I–L* from the post-radiolarite succession. See text and Figs. 4 and 5 for details on microfacies, petrography, sample provenance and location. *Scale bars* are 500 µm, except for *H* and *L* where bars are 10 µm

Some radiolarite beds show homogeneous texture; however, most beds are laminated on a macro- or microscopical scale. The lamination is caused by microstratigraphical variations in radiolarian content and may be diffuse or well defined. It is horizontal and mostly continuous. Radiolarian-rich or radiolarian-poor microlenses may also occur. Laminae thickness is between 100 µm and few millimetres. A few weakly graded laminae are visible except in the calcareous radiolarites, where millimetre-thick graded laminae are more typical.

Post-radiolarite succession

The radiolarites are overlain by light-coloured greyish marly limestones and marls with local chert nodules. This unit is tectonically flattened, folded and transformed to calc-schists in the Taramar outcrop, and it lies abruptly on the radiolarites (Fig. 5B). In Parauta (Fig. 5A), the top of the radiolarites is also a sharp contact and the post-radiolarite succession starts with a centimetric clay layer overlain by a 1-m-thick bundle of reddish, slightly nodular and cherty limestones (*Rosso ad Aptici* facies). These grade upwards into a 2-m-thick alternation of light-grey (sometimes pinkish) schistose marls and *Aptychus*-bearing platy limestones with some chert nodules. Upsection, greenish-greyish fine-grained platy marly limestones alternating with schistose marls and decimetre-thick intercalations of cherty and slightly nodular, greyish to pinkish limestones are present. The thickness of this unit varies from less than 10 m in the Encina outcrop to 15–20 m in Parauta, and to approximately 25 m in Taramar (Fig. 4).

The beds just above the radiolarites in Taramar (sample 45: Figs. 4, 5B) show biomicritic microfacies: radiolarian-rich packstone–wackestone with planktonic ("Protoglobigerina") and benthic foraminifera, pelagic bivalves, crinoids, sponge spicules and aptychi (Fig. 6I). The common presence of aptychi is the main difference with respect to the Protoglobigerina-bearing pre-radiolarite rocks (compare Fig. 6B,I). Nevertheless, the reddish, slightly nodular and cherty limestones that sharply overlie the radiolarites in Parauta are tectonically slightly deformed wackestone–packstone with bioclasts of the planktonic crinoid *Saccocoma* sp., aptychi and radiolarians (sample 30: Figs. 5A, 6J), in addition to benthic foraminifera and other Jurassic pelagic microfossils (*Globochaete alpina* Lombard, *Stomiosphaera* sp. and *Cadosina* sp.). Some of these rocks show packstone–wackestone microfacies very rich in radiolarians that are moderately to partially well-preserved (sample 40: Figs. 5A, 6K). Some of them have been extracted from chert nodules for a micropalaeontological study (see Biostratigraphy).

The greenish-greyish, fine-grained, platy marly limestone beds of the top of the condensed succession show micritic microfacies (mudstone to wackestone) with abundant calcitised radiolarians in some cherty beds (sample 40: Figs. 5A, 6K). Calpionellids were found in several levels, but only in the Parauta section (sample 41B: Figs. 5A, 6L) are these microfossils determined (*Calpionella alpina* Lorenz, *C. elliptica* Cadisch and *Crassicollaria* sp.).

The Mesozoic succession is overlain by strongly deformed Tertiary marls in Parauta and Taramar, but in the Encina section Norian dolostones are thrust onto the post-radiolarite succession (Fig. 4).

Biostratigraphy

Sampling and biostratigraphical criteria

The Jurassic–Cretaceous successions of the internal zones have rarely been studied in detail palaeontologically in contrast to other Middle-Upper Jurassic pelagic successions bearing siliceous rocks of the external zones of the Betic Cordillera (O'Dogherty et al. 1989a, 1989b, 1995, 1997), and of the equivalent internal zones of the Rif (De Wever et al. 1985; Maate et al. 1993).

We collected 67 samples for radiolarian preparations, but only 9 radiolarite samples yielded moderately well-preserved micropalaeontological associations useful for detailed taxonomical and biochronostratigraphical studies. Radiolarians were extracted mainly from carbonate-free radiolarian cherts following standard procedures (Baumgartner 1984). Their skeletons are composed of silica and are moderately to well preserved in the samples finally selected. Apart from radiolarians, no other biogenic constituents occur within the residues. The systematic taxonomy used in this study basically follows that proposed in the Radiolarian Catalogue published by the InterRad Working Group (Baumgartner et al. 1995a), with addition of some species not included in the catalogue. Biochronological results (Table 1) have been correlated with the most recent radiolarian zonation proposed by Baumgartner et al. (1995a) for the Tethyan Middle Jurassic–Early Cretaceous, which is based on the Unitary Association method (Guex 1991).

Twenty-three samples were collected and examined for calcareous nannofossil stratigraphy, however, only from slightly calcareous beds due to the strong tectonisation of the marliest intervals. Highly concentrated smear slides were prepared from raw material following standard procedures (Aguado 1993). Most samples are, however, barren of calcareous nannoflora and only contain significant proportions of clay minerals together with common carbonate microparticles of approximately 10–20 μm or, at most, rare identifiable nannofossils and fragments of heavily overgrown unrecognisable ones. Only five samples gave reliable biostratigraphical results. For the Mesozoic, the systematic nannofossil taxonomy and biostratigraphy used here follows the proposals by Thierstein (1976), Moshkovitz and Ehrlich (1987), Reale et al. (1992), Cobianchi et al. (1992), Aguado (1993), Bown et al. (1996) and Aguado and Rey (1996).

Age of the pre-radiolarite succession

Bositra and Protoglobigerina-bearing microfacies of the uppermost part of the pre-radiolarite rocks are commonly found in the Alpine–Mediterranean Middle and lower Upper Jurassic (e.g. Azéma et al. 1979; Sartorio and Venturini 1988; Martire 1992). In Betic suc-

Table 1 Middle Bathonian radiolarians from Parauta Radiolarite Formation. Sample locations in Figs. 4 and 5

Middle Jurassic radiolarians from the Nieves unit (Rondaide): Taramar and Parauta sections	P-16B	P-21A	P-21B	T-15	T-34	T-38	T-39
Amphipyndax tsunoensis Aita	●		●				
Archaeodictyomitra (?) *amabilis* Aita	●	●	●			●	●
Cinguloturris carpatica Dumitrica	●	●	●		●	●	●
Complexopora sp. 1.			●				
Dictyomitrella (?) *kamoensis* Mizutani and Kido				●			
Eucyrtidiellum ptyctum(Riedel and Sanfilippo)	●	●	●			●	●
Eucyrtidiellum unumaense s.l.(Yao)				●			
Gongylothorax sp. aff. *G. favosus* Dumitrica			●	●			
Guexella nudata (Kocher)	●	●	●	●	●	●	●
Kilinora (?) *spiralis* gr. (Matsuoka)	●		●	●			
Kilinora catenarum (Matsuoka)	●		●				
Kilinora oblongula (Kocher)	●		●	●	●		
Leugeo hexacubicus (Baumgartner)	●		●				
Mirifusus dianae s.l. (Karrer)	●		●		●		
Obesacapsula morroensis Pessagno	●		●				
Orbiculiforma (?) *heliotropica* Baumgartner	●		●				
Palinandromeda podbielensis (Ozvoldova)	●		●				
Pantanellium riedeli Pessagno			●				
Parahsuum sp. 1.			●				
Parahsuum sp. S in Baumgartner et al. (1995a)			●				
Parashuum izeense (Pessagno & Whalen)			●				
Parashuum officerense (Pessagno & Whalen)	●		●				
Perispyridium ordinarium gr. (Pessagno)							●
Podobursa helvetica (Rüst)	●		●				
Podobursa polyacantha (Fischli)	●		●				
Protunuma turbo Matsuoka	●		●	●			
Pseudoeucyrtis firmus Hull	●		●				
Ristola altissima s. l. (Rüst)	●		●				
R. altissima major Baumgartner and De Wever	●		●				
Sethocapsa funatoensis Aita					●		
Spongocapsula perampla (Rüst)							●
Stichocapsa convexa Yao	●	●	●	●		●	●
Stichocapsa decora Rüst	●	●	●			●	●
Stichocapsa robusta Matsuoka	●	●	●		●	●	●
Stichomitra (?) *takanoensis* gr. Aita	●		●				●
Striatojaponocapsa plicarum s.l. (Yao)	●	●	●				
S. plicarum ssp. A in Baumgartner et al. (1995a)		●				●	●
S. sp. M in Baumgartner et al. (1995a)	●		●				
Theocapsomma cordis Kocher				●			
Theocapsomma cucurbiformis Baumgartner				●			
Transhsuum brevicostatum gr. (Ozvoldova)		●		●		●	●
Transhsuum maxwelli gr. (Pessagno)	●	●	●			●	●
Williriedellum sp. A in Baumgartner et al. (1995a)	●		●				
Zhamoidellum ventricosum Dumitrica	●		●				

cessions well controlled by ammonites, *Bositra*- and Protoglobigerina-bearing microfacies coexist in the Upper Bajocian (Sandoval 1983). This is supported by the nannofossil results from two samples of the same stratigraphic levels in the Parauta section. Sample 8 (Fig. 5A) contains a poorly preserved calcareous nannofossil assemblage characterised by heavily overgrown, cosmopolitan, diagenesis-resistant taxa: *Watznaueria britannica* (Stradner) Reinhardt; *W. barnesae* (Black) Perch-Nielsen; and *Discorhabdus striatus* Moshkovitz and Ehrlich. A more impoverished and poorly preserved association was found just below the radiolarites in sample 11 (Fig. 5A): only few specimens of *W. britannica* could be identified. The presence of *W. barnesae* and the absence of other cosmopolitan and diagenesis-resistant taxa, such as *Hexalithus magharensis* Moshkovitz and Ehrlich and *Carinolithus superbus* (Deflandre) Prins *in* Grün, Prins and Zweili, or *Watznaueria manivitae* Bukry, indicate a Bathonian age for the top of the pre-radiolarite succession.

Age of the Parauta Radiolarite Formation

The radiolarites are characterised by a radiolarian association which displays high diversity values and typical Tethyan taxa. By using the protoreferential (range chart) of Baumgartner et al. (1995a) we have calculated the age of our samples (see Guex 1991 for the procedure). In the richer samples (Table 1) the faunal association is composed of 44 taxa, 41 nassellarians and 3 spumellarians. The extremely low S/N ratio (0.073) is typical for carbonate-free radiolarian cherts because of diagenesis, which obliterates many spumellarian skeletons. Nevertheless, a slightly higher proportion of spumellarians (emiluviids, hagiastrids and patulibracchiids) was observed in some thin sections (Fig. 6B) and on the surface of fragments etched by hydrofluoric acid. No complete assemblage of these radiolarian taxa has been obtained by standard sample preparation because their delicate skeletons are more susceptible to dissolution. Only a few broken specimens of spumellarians (*Higumastra* spp., *Paronaella* spp., *Emiluvia* spp. and *Tritrabs* spp.) have been recognised in the residues. The robust cryptocephalic and cryptothoracic nassellarians are the dominant morphotypes.

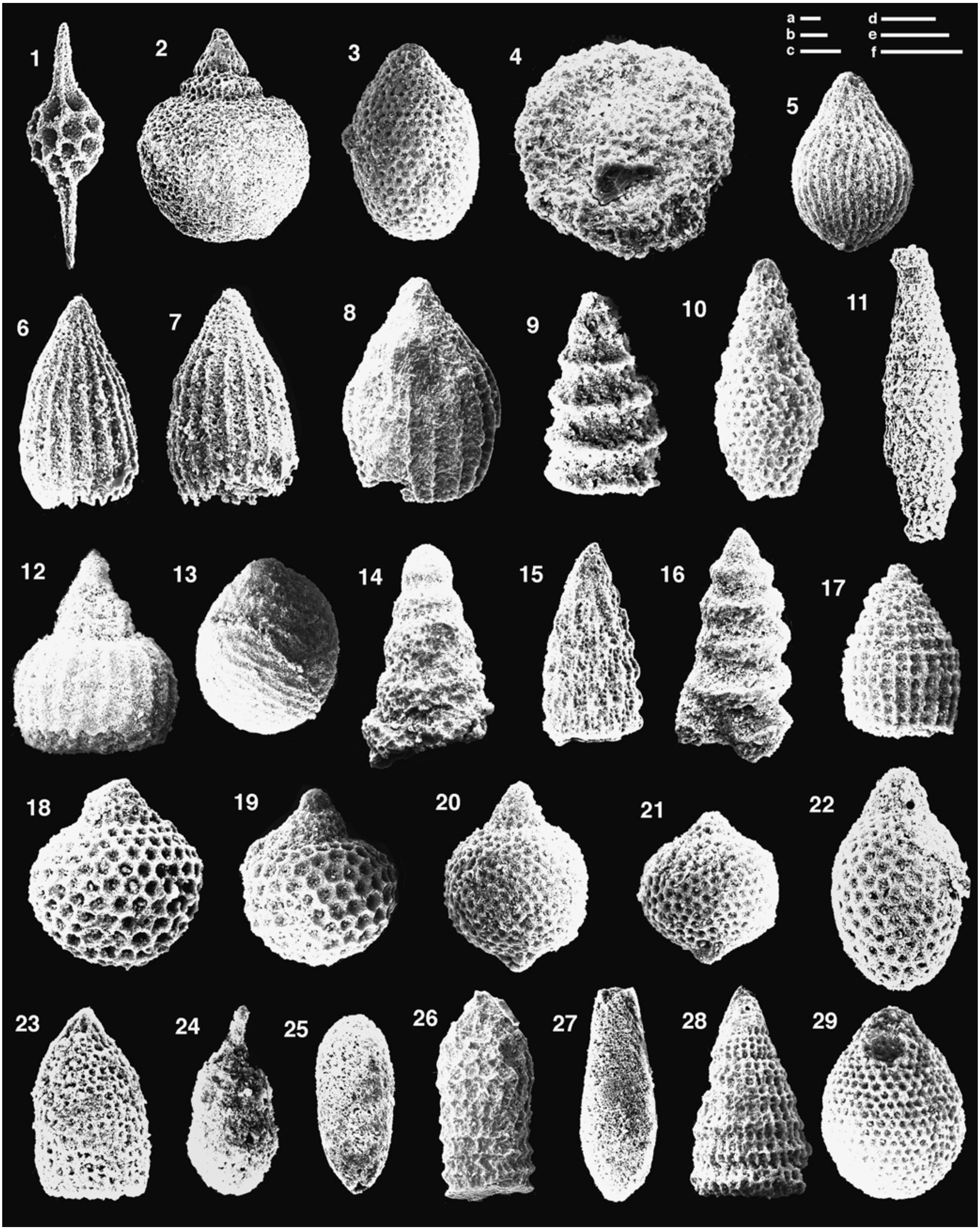
The radiolarian assemblages (Table 1) are similar in all analysed samples and include, among others: *Eucyrtidiellum ptyctum* (Riedel and Sanfilippo); *Guexella nudata* (Kocher); *Kilinora tecta* (Matsuoka); *K.* (?) *spiralis* gr. (Matsuoka); *K. catenarum* (Matsuoka); *K. oblongula* (Kocher); *Stichomitra* (?) *takanoensis* gr. Aita; *Striatojaponocapsa plicarum* s.l. (Yao); *Williriedellum* sp. A *sensu* Matsuoka; *Protunuma turbo* Matsuoka; *Hsuum matsuokai* Isozaki and Matsuda; *Dictyomitrella* (?) *kamoensis* Mizutani and Kido; and *Amphipyndax tsunoensis* Aita. This association (Fig. 7) is assigned to the UAZone 6 (Middle Bathonian).

Age of the post-radiolarite succession

Calcareous nannofossils were obtained neither from the Parauta Radiolarite Formation nor from samples taken in the levels adjacent to the radiolarites. In the Taramar section the Protoglobigerina-bearing microfacies with some aptychi directly overlying the radiolarites, suggest that the age of these beds probably is near the Middle–Late Jurassic boundary, because “Protoglobigerinids” are particularly abundant during the Callovian and, even more, during the Oxfordian (Azéma et al. 1979; Sartorio and Venturini 1988). In the Parauta section (sample 30: Fig. 5A, 6J) the cherty limestones just above the radiolarites show typical, Alpine–Mediterranean, Kimmeridgian–Lower Tithonian microfacies, characterised mainly by the abundance of *Saccocoma* sp. and other typical Upper Jurassic pelagic microfossils. This is confirmed by radiolarian associations from two chert nodules sampled from these limestones (samples 31 and 32: Fig. 5A, 6K), which contain an association of *Emiluvia orea ultima* Baumgartner and Dumitrica, *Acanthocircus trizonalis dicranacanthos* (Squinabol) and *Podobursa helvetica* (Rüst), among others. This assemblage indicates the UAZone 10 (Upper Oxfordian–Kimmeridgian).

Samples from the post-radiolarite succession in Parauta yielded scarce identifiable nannofossil remains. These are similarly preserved as in the pre-radiolarite succession. Sample 37 was taken near the base of the post-radiolarite succession (Fig. 5A) and contains *W. britannica*, *W. barnesae* and *W. manivitae* (specimens larger than 12 μm). For the first occurrence of *W. manivitae* some authors suggest an Early to Middle Callovian age (Thierstein 1976; Moshkovitz and Ehrlich 1987), and others an Early Bajocian age (Erba 1990; Reale et al. 1992). This discrepancy may be explained by the different species concept. Cobianchi et al. (1992) reported a size of approximately 9 μm for the primitive Lower Bajocian specimens of *W. manivitae* and they assumed a progressive intraspecific size increase till the Bathonian. The species concept of the authors favouring a Callovian age for the first occurrence of *W. manivitae* is restricted to the large (>12 μm) forms. In other succession of the Betic Cordillera, well dated by ammonites and radiolarians, the large forms (>12 μm) do not occur until the Early to Middle Callovian (O’Dogherty et al. 1989a; Aguado and Rey 1996); therefore, we suggest a Callovian or younger age (probably Kimmeridgian) for sample 37, taking into account also the information provided by the underlying *Saccocoma* microfacies. Thus, the existence of a stratigraphical gap, including at least the Late Bathonian (although it probably also includes the Callovian–Oxfordian), is demostrated in Parauta. An equivalent gap, but covering a lesser time span, is also present in Taramar.

Fig. 7a–f Middle Bathonian radiolarians association (UAZone 6) of the Parauta Radiolarite Formation. Location of samples in Figs. 4 and 5. *Scale bars* measure 50 μm for a magnification of **a** ×75, **b** ×100, **c** ×150, **d** ×200, **e** ×250 and **f** ×300. All specimens come from sample P-21B; otherwise, the sample is indicated in brackets. For each specimen the repository number (sn) and the magnification are given: *1 Pantanellium riedeli* Pessagno. sn:17927 (×150); *2 Obesacapsula morroensis* Pessagno. sn:17938 (×75); *3 Stichocapsa robusta* Matsuoka. sn:17934 (×200); *4 Orbiculiforma* (?) *heliotropica* Baumgartner. sn:17955 (×200); *5 Striatojaponocapsa plicarum* s.l. (Yao). sn:17931 (×250); *6 Archaeodictyomitra* (?) *amabilis* Aita. [P-16B], sn:17973 (×200); *7 Archaeodictyomitra* (?) *amabilis* Aita. sn:17932 (×250); *8 Archaeo*dictyomitra (?) *amabilis* Aita. sn:17929 (×150); *9 Dictyomitrella* (?) *kamoensis* Mizutani and Kido. [T-15], sn:17958 (×200); *10 Amphipyndax tsunoensis* Aita. sn:17946 (×200); *11 Pseudoeucyrtis firmus*. Hull. sn:17943 (×150); *12 Eucyrtidiellum ptyctum* (Riedel and Sanfilippo). [T-38], sn:17968 (×300); *13 Kilinora* (?) *spiralis* gr. (Matsuoka). sn:17935 (×250); *14 Stichomitra* (?) *takanoensis* gr. Aita. sn:17942 (×150); *15 Transhsuum brevicostatum* gr. (Ozvoldova). [P-16B], sn:17976 (×150); *16 Cinguloturris carpatica* Dumitrica. [T-34], sn:17960 (×200); *17 Parashuum izeense* (Pessagno and Whalen). sn:17936 (×200); *18 Complexopora* sp (1. sn:17940 (×200); *19 Gongylothorax* sp. aff. *G. favosus* Dumitrica. sn:17933 (×200); *20 Williriedellum* sp. A in Baumgartner et al. (1995a) sn:17954 (×200); *21 Williriedellum* sp. A in Baumgartner et al. (1995a) sn:17944 (×200); *22 Kilinora oblongula* (Kocher). [P-16B], sn:17974 (×200); *23 Parahsuum* sp. S in Baumgartner et al. (1995a) sn:17950 (×200); *24 Theocapsomma cucurbiformis* Baumgartner. [T-15], sn:17957 (×200); *25 Kilinora catenarum* (Matsuoka). sn:17948 (×200); *26 Ristola altissima major* Baumgartner and De Wever. sn:17950 (×100); *27 Guexella nudata* (Kocher). [T-34], sn:17960 (×150); *28 Parahsuum* sp 1. sn:17930 (×150); *29 Stichocapsa robusta* Matsuoka. sn:17928 (×200)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In the Parauta section, the marls of sample 39 (Fig. 5A) contain *Conusphaera mexicana* Trejo ssp. *mexicana*, very abundant *W. manivitae* >13μm and *Diazomatolithus subbeticus* Grün of the Late Tithonian (Aguado 1993). One metre above (sample 41B: Fig. 5A, 6L), the presence of *Calpionella alpina* Lorenz and *C. elliptica* Cadisch places these levels near the Tithonian–Berriasian transition (zone B of calpionellids). Upsection, sample 44 (Fig. 5A) contains *Nannoconus steinmannii* Kamptner ssp. *steinmannii*, *N. steinmannii* Kamptner ssp. *minor* Déres and Achériteguy, *D. subbeticus*, *Micrantholithus obtusus* Stradner and doubtful specimens of *Calcicalathina oblongata* (Worsley) Thierstein, of a possible Middle Berriasian or younger age (up to Early Barremian).

Sedimentation processes and depositional environment

The lower and upper boundaries of the Parauta Radiolarite Formation are sharp surfaces with a marked lithological change and correspond to breaks in sedimentation and stratigraphical hiatuses. Together with its abrupt nature, the non-depositional character of the contact below the radiolarites is suggested by the reduced thickness of the pre-radiolarite red nodular limestones and the laminated, peloidal–bioclastic, probably current-generated microfacies of their topmost bed in the Taramar outcrop. In the pre-radiolarite succession the activity of bottom currents is suggested by: (a) the lamination including particle sorting of the *Bositra* and radiolarian-bearing limestones within the red nodular limestones (Parauta) and the cherty limestones (Taramar); (b) the intercalations of crinoidal grainstones–packstones between the cherty limestones (Parauta); and (c) the fine peloidal–bioclastic microfacies of the cherty limestones, which contain fine terrigenous grains (Taramar).

Our biostratigraphical data indicate that radiolarite deposition occurred during a maximum time span of 2 million years (based on Odin's 1994 timescale). This, together with the reduced thickness of the Parauta Radiolarite Formation and its bottom and top hiatuses suggest that the minimum sedimentation rate was 1–2 mm/10^3 years in Parauta and approximately 10 mm/10^3 years in Taramar, after compaction. These values correspond to those of modern pelagic sediments (De Wever et al. 1994) and point to an extremely sediment-starved environment for the radiolarite deposition.

Sediment contribution was nearly exclusively derived from pelagic "rain" and consisted mainly of radiolarian skeletons with rare carbonate and very scarce fine-grained siliciclastic particles (clay minerals). The practically total absence of carbonate, the scarcity of terrigenous material and the dominantly siliceous character of the sedimentation indicate deposition far from continental sources, in a very distal and isolated deep basin located near or below the Jurassic CCD. The fine-grained character of the sediments, the generally homogeneous structure of the bedding and the horizontal lamination in cherts indicate deposition mainly by pelagic settling in quiet waters. Nevertheless, the presence of graded and microlenticular laminae in some radiolarite bed suggests very low-energy deep-sea currents, probably bottom currents and/or very low-concentrated turbidity currents that reworked previously deposited siliceous–calcareous sediment. The existence of such currents, together with irregular basin geometry, may also account for the minor differences in facies, thickness, colour, proportion of mudstone interbeds and time range of the bounding hiatuses between the radiolarites of the outcrops. In the Parauta succession, the colour of the radiolarites is brown to dark reddish, whereas in Taramar and Encina the cherts are darker and interbedded with dark-green to grey siliceous mudstones and minor black shales (Fig. 4). This suggests that the Parauta depositional area was probably located on a topographic high, whereas the Taramar area was a slightly deeper and more confined basin, with restricted circulation and lower oxygenation of bottom waters.

Palaeogeographical and basinal development

During the Jurassic and Cretaceous, the Nieves unit was a part of a deep basin with a slightly irregular bottom topography. After Martín-Algarra (1987), it was a narrow trough with a NE–SW orientation, at least 10 km wide and 50 km long. Within this Nieves basin the Parauta Radiolarite Formation was probably deposited at a depth of at least 1000–1500 m. This is inferred after subsidence data deduced from the great thickness of the underlying shallow water Triassic deposits and from a preliminary backstripping analysis of the whole Triassic–Cretaceous succession (Fig. 8 following Einsele's 1992 procedure), and from the deep-sea nature of the pre-radiolarite siliceous limestones and chert-nodules bearing limestones.

The Parauta Radiolarite Formation is not associated with oceanic crust but forms part of a deepening-upward Rondaide continental margin succession (Fig. 4). Its deposition started after the rifting of its continental basement resulting in a pile of thick Triassic platform carbonates (Martín-Algarra 1987). After the break-up and drowning of this platform, ammonite-bearing pelagic sediments were deposited starting near the Triassic–Liassic boundary (Braga et al. 1984). During the Lower Jurassic the Rondaide basins became progressively deeper and topographically irregular as shown by synsedimentary faulting, gravitationally triggered erosion and resedimentation in several units (Martín-Algarra 1987). Two divergent continental margins developed: the Southern Iberian margin, from which the external zones of the Betic Cordillera are derived, and the Rondaide margin. Between the two continental margins, a narrow deep

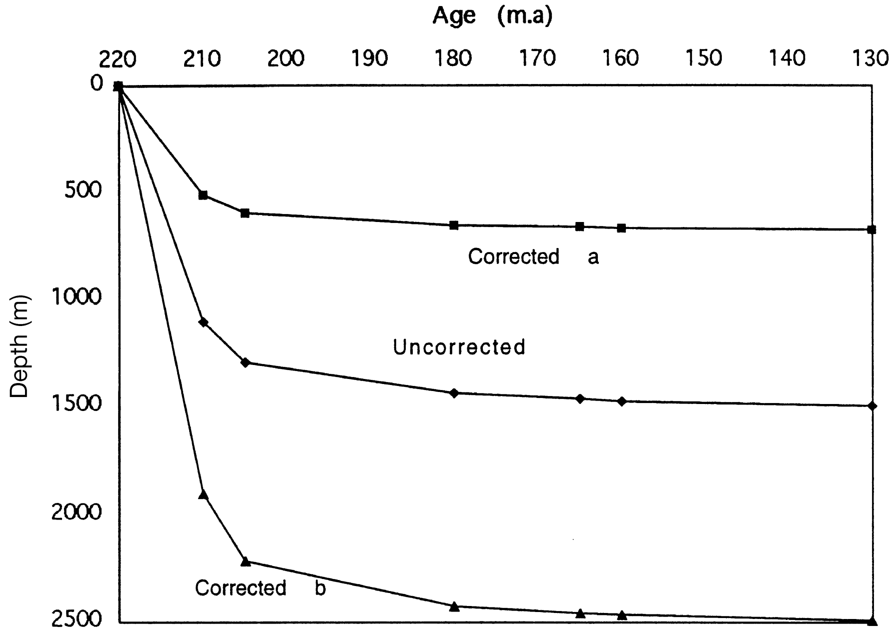

Fig. 8 Backstripping diagram of the Triassic–Cretaceous stratigraphic series of the Nieves unit. Uncorrected curve for decompaction is the original cumulated thickness. **a** The corrected curve results from removing the effect of initial subsidence due to isostatic compensation (following Einsele's 1992 procedure). **b** The corrected curve is the decompacted original thickness (following Einsele's 1992 procedure, see Palaeoceanographical implications within the Tethyan realm). Timescale according to Odin (1994)

basin opened, in which the Nieves unit, including the Parauta Radiolarite Formation, was deposited.

During the Middle Jurassic, the Nieves unit was located in the distal slope of the rifted Rondaide margin. Carbonate turbidites and breccias of Late Jurassic–Early Cretaceous age in other Rondaide units (Martín-Algarra 1987) indicate that synsedimentary tectonic movements were still active in the distal zone of the Rondaide margin; therefore, we infer that the Nieves basin was confined by topographic highs and that the Parauta Radiolarite Formation is the sedimentary infill of a "perched" slope basin that was located in the distal zone of the rifted Rondaide continental margin.

The Southern Iberian margin is generally interpreted as the southern and southeastern edge of the Iberian plate, the Rondaide margin as the northwesternmost edge of the Mesomediterranean Microplate (Durand-Delga and Fontboté 1980) or Terrane (Martín-Algarra 1987; Martín-Algarra et al. 1992; Guerrera et al. 1993). This continental block was separated in Jurassic times from the major plates of Iberia and Africa–Adria during an eastward shift of Africa relative to Iberia, noted as a major rifting episode in the Betic external zones and in many other areas of the Alpine–Mediterranean margins (García-Hernández et al. 1980, and references therein). The oceanic basins of the Central Atlantic and Piedmont-Ligurian opened contemporaneously and were linked by narrow deep basins between the Southern Iberian and the Rondaide margins. The sediments of these basins are partly presented in the Campo de Gibraltar Complex and in some ophiolite-bearing, Nevado-Filabride units of the Betic internal zones (Tendero et al. 1993). We conclude that the Rondaide margin represents a segment of the transitional zone between the Mesomediterranean Terrane and a narrow oceanic basin (Fig. 9). This situation can be compared, for example, to the Austroalpine units of the Alps, which are interpreted as the continental margin of the Adria plate in transition towards the Piedmont-Ligurian oceanic basin (Trümpy 1975; Manatschal and Nievergelt 1997).

Palaeoceanographical implications within the Tethyan realm

Main features of the Parauta Radiolarite Formation include: (a) strong stratigraphic condensation; (b) strictly siliceous character; and (c) dark colour including intercalated black shales. These features distinguish the Parauta Radiolarite Formation from radiolarites in the external zones of the Betic Cordillera, which are calcareous and were probably deposited at shallower depths (Ruiz-Ortiz et al. 1989; O'Dogherty et al. 1997; Molina et al. 1999). In Jurassic times the Tethyan calcite compensation depth (CCD) was at 2–3 km water depth (Bosellini and Winterer 1975), or at 1.5–2 km (Jenkyns and Winterer 1982; Baumgartner 1987, 1990; De Wever et al. 1994; Santantonio et al. 1996). We assume that the CCD in the Parauta basin was not more than 2 km deep due to: (a) the high plankton productivity of the Tethyan surface waters (De Wever et al. 1994); (b) the high rates of dissolved silica in marine waters during the Mesozoic (Kastner 1981); and (c) the irregular topography of the Tethyan realm.

Typical Tethyan radiolarites usually show relatively light, greenish or reddish colours (De Wever et al. 1994; Gorican 1994; O'Dogherty et al. 1997; among others). Dark radiolarian cherts, like in the Parauta Radiolarite Formation, are rare in the Jurassic,

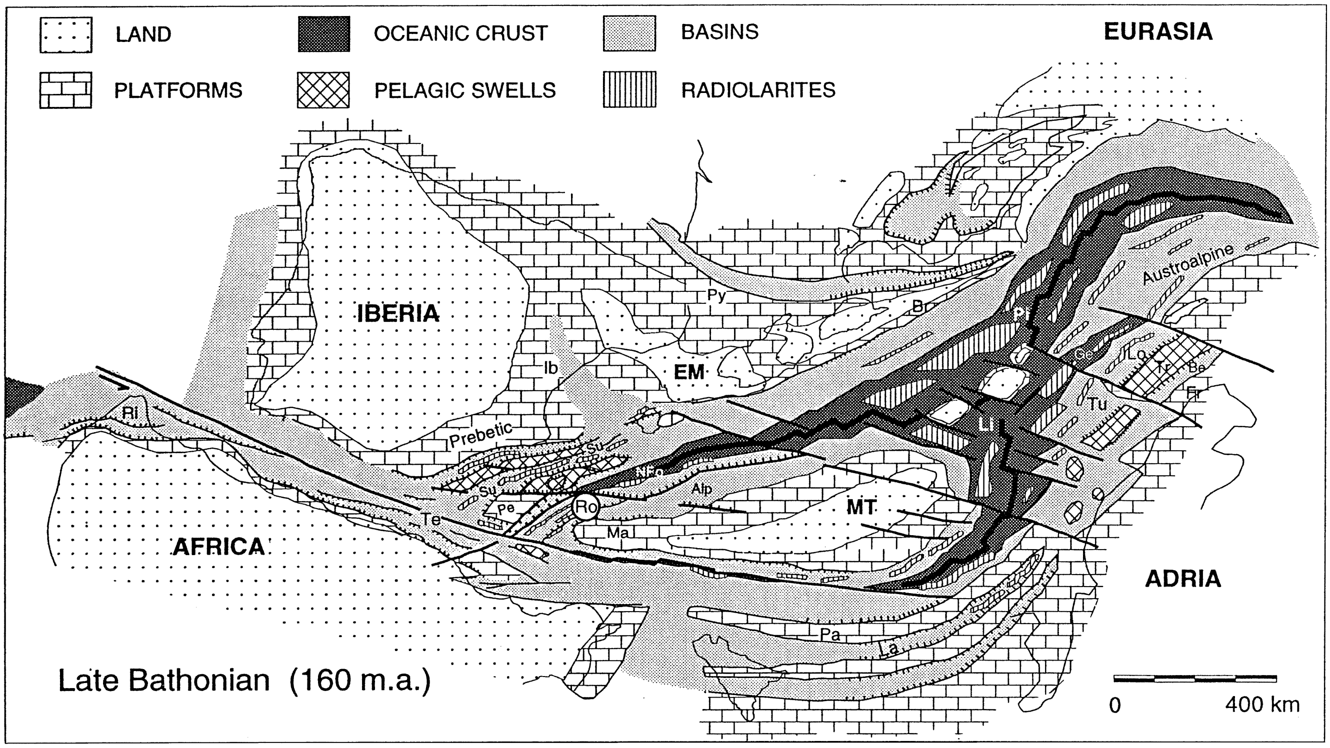

Fig. 9 Paleogeographic map from the Central Atlantic to the Central Tethys areas during the Middle Jurassic (Bathonian), and location of the sedimentary basin of the Parauta Radiolarite Formation and other radiolarite deposits. *Alp* Alpujarride; *Be* Belluno Through; *Br* Briançonnais; *EM* Ebro Massif; *Fr* Friuli Platform; *Ge* Gets; *Ib* Iberian Chain; *La* Lagonegro; *Li* Ligurian; *Lo* Lombardian basin; *Ma* Malaguide; *MT* Mesomediterranean Terrane; *NFO* Nevado Filabride Ophiolite; *Pa* Panormide; *Pe* Penibetic; *Pi* Piedmont; *Py* Pyrenees; *Ri* External Rif; *Ro* Rondaide; *Su* Subbetic; *Te* Tell; *Tr* Trento Plateau; *Tu* Tuscan. (Modified from Martín-Algarra 1987)

whereas green colours are most typical for the early radiolarites of the Tethys (Baumgartner 1984). In general, siliceous and organic-rich marine sediments are not associated in Jurassic times, and siliceous sediments are found in more oceanic positions than organic-rich ones (De Wever and Baudin 1996). However, in restricted basins, such as the Nieves basin, siliceous deposits were formed in poorly oxygenated bottom waters. Mid-Jurassic dark radiolarites with striking facies and palaeogeographical analogies to the Parauta Radiolarite Formation occur in, for example, the Gets and Simme nappes of the French–Swiss Prealps (Bill et al. 1998), and in some Austroalpine Juvavic nappes (Northern Calcareous Alps south of Salzburg; Gawlick 1996; Gawlick and Suzuki 1999; Gawlick et al. 1999). These Alpine radiolarites were formed either in the southern continental margin of the Piedmont-Ligurian Ocean (Austroalpine nappes) or in its most internal zone (Gets nappe). Along with the Parauta Radiolarite Formation, they are basinal deposits that record long periods of basin starvation and restricted water circulation during the late Middle-early Late Jurassic and were probably deposited in confined, tectonically controlled depressions in the lower slope of the rifted continental palaeomargin. The perched basins of the Gets, Juvavic and Parauta radiolarites developed after rifting and slow sea-floor spreading between Europe and Adria (<10 mm/year; Lagabrielle and Lemoine 1998) and were preferential sites for anoxic conditions during the onset of siliceous sedimentation. Contemporaneous laminated organic-rich siliceous mudstones occur overlying the oldest basalts of the Atlantic Ocean (DSDP Site 534, Blake Bahama Basin; Sheridan 1983). The Bathonian age attributed to these sediments (Baumgartner and Matsuoka 1995) is equivalent to those of the Parauta Radiolarite Formation, the Prealpine radiolarites of the Gets Nappe (Bill et al. 1998) and the Strubberg Formation (Gawlick and Suzuki 1999).

Conclusion

The Mesozoic succession of the Nieves unit was a segment of the Rondaide continental margin of the Betic Cordillera. It shows striking similarities in facies, stratigraphy and palaeogeographic evolution to coeval Tethyan series in, for example, the northeastern sectors of the Adriatic plate. The Parauta Radiolarite Formation consists of siliceous deep-sea deposits found in a narrow, tectonically controlled slope basin that developed simultaneously with neighbouring sea-floor spreading processes in the deep Tethys. The Parauta radiolarites and their Alpine equivalents record relatively long periods of basin starvation with contemporaneous restricted oceanic circulation. This favoured the development of poorly oxygenated bottom waters at the beginning of the Jurassic siliceous sedimentation in the basins and margins of the Western Tethys.

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