

# Age and genesis of Tethyan Jurassic Radiolarites

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# Age and genesis of Tethyan Jurassic Radiolarites

BY PETER O. BAUMGARTNER<sup>1)</sup>

## ABSTRACT

This paper has two parts: The first part (chapter 2) provides new biostratigraphic data to further constrain the calibration of the radiolarian zonation proposed by BAUMGARTNER (1984b) to the Middle–Late Jurassic stages. Correlation with western North American radiolarian zonations is discussed. New radiolarian data from an ammonite-bearing section in the Sierra de Ricote (Subbetic Zone, Spain) indicate that the limit between radiolarian zones A0 and A1, previously placed within the early Callovian, must be placed in the Bathonian, and that zone C1 reaches the base of the Kimmeridgian. New data from Bosso (Umbria, Italy) show the base of Zone D well below calpionellid zones A/B boundary in the Late Tithonian.

Zone A0 to A2 can be correlated with zones MH-3 to MH-4, established by MURCHEY (1984) for the Marin Headlands (California), and zones D to E2 correspond to MH-5. The age of several Franciscan Central Belt terranes can now be specified and a hiatus comprising the entire Late Jurassic can be confirmed.

The correlation of zones A0 to B with the zonation by PESSAGNO et al. (1987b) shows an overlap of the upper part of their superzone 1 with their zone 2, owing to a co-occurrence of species defining upper superzone 1 with *Mirifusus* PESSAGNO sp. The first appearance of this genus, defining the base of Pessagno's zone 2, occurs below the first occurrence of *Ristola turpicula* PESSAGNO & WHALEN and has to be placed in the Bajocian-Bathonian, based on Tethyan data.

The second part (chapter 3) discusses new aspects of the genesis of Tethyan Jurassic radiolarites in the light of new detailed age data. Comparison of coeval Middle-Late Jurassic Atlantic and Tethyan facies suggests that Tethys had a estuarine circulation causing high surface fertility, drawing nutrients from the Paleopacific, while the Jurassic Atlantic was a "mediterranean" restricted basin, with indirect connections to the world ocean, possibly with a lagoonal circulation, causing low surface fertility.

Pre-Cretaceous calcareous plankton productivity was scarce. Since productivity of radiolarians is mainly limited by the available nutrients (and not especially by silica), any area of high plankton productivity in the Jurassic ocean may have produced sufficient radiolarians to result in a regional occurrence of radiolarites. While the Gulf of California model fits well to Western Tethys, the Jurassic equatorial convergence zone may be a likely origin of other Tethyan and Circumpacific radiolarites.

In Western Tethys basinal Middle Jurassic radiolarites are coeval with condensed pelagic limestones on swells. This facies contrast is not a function of the presence of a CCD. The absence of silica on the swells can obviously not be explained by the dissolution of carbonate at depth. Moreover, basinal facies are not solution residues of less deep swell facies, because radiolarites have higher sedimentation rates than coeval condensed limestones. The intrabasinal dispersal of radiolarians determined the local occurrence and age span of radiolarites: Persistent bottom currents prevented radiolarians from accumulation on the swells, and carried them into the basins. Scarcity of calcareous plankton is responsible for the formation of condensed limestones on swells and for a low carbonate input, as compared to silica, to the basins, resulting in shallow, irregular and sharply defined ACD and CCD.

Radiolarites are considered as the normal pelagic sediment for most of the Mesozoic, if a number of inhibiting factors are not effective.

## RÉSUMÉ

Ce travail est divisé en deux parties. La première (chapitre 2) fournit des nouvelles données biostratigraphiques apportant des précisions sur la calibration de la zonation à radiolaires proposée par BAUMGARTNER (1984b)

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avec les étages jurassiques. On discutera la corrélation de cette zonation avec celles établies pour l'ouest de l'Amérique du Nord. De nouvelles données sur la distribution des radiolaires dans une série de la Sierra de Ricote (Zone Subbétique, Espagne), datée par des ammonites, montrent que la limite entre les zones à radiolaires A0 et A1, préalablement placée dans le Callovien, peut être datée du Bathonien. La base de la zone C1 correspond à la base du Kimméridgien. Des données nouvelles établies à Bosso (Ombrie) montrent d'autre part que la base de la zone à radiolaires D se situe dans le Tithonique supérieur, en dessous de la limite A/B de la zonation standard des calpionelles.

Les zones A0 à A2 sont corrélées avec les zones MH-3 à MH-4 établies par MURCHEY (1984) dans les Marin Headlands (Californie), et les zones D à E2 correspondent à MH-5. Ce résultat permet de préciser l'âge des terrains Franciscains du Central Belt et de confirmer l'existence d'un hiatus recouvrant la totalité du Jurassique supérieur.

La corrélation des zones A0 à B avec la zonation de PESSAGNO et al. (1978b) montre un chevauchement de la partie supérieure de leur superzone 1 avec leur zone 2, grâce à l'association de *Mirifusus* PESSAGNO sp. avec des espèces caractéristiques de la partie supérieure de la superzone 1. La première apparition de *Mirifusus*, définissant la base de la zone 2, est antérieure à la première apparition de *Ristola turpicula* PESSAGNO & WHALEN et elle doit être placée dans le Bajocien-Bathonien, selon les données téthysiennes.

La deuxième partie (chapitre 3) traitera de nouveaux aspects de la genèse des radiolarites, en fonction de datations nouvelles et plus précises de ce faciès. Pour l'Atlantique et la Téthys la comparaison des faciès jurassiques contemporains suggère: 1. une circulation estuarienne pour la Téthys, apportant des nutriments du Paléopacifique et causant une haute fertilité de surface. 2. une circulation lagunaire pour l'Atlantique engendrant une basse fertilité de surface. L'Atlantique jurassique était un bassin «méditerranéen» restreint, n'étant connecté qu'indirectement avec l'océan mondial.

La production de plancton calcaire était peu abondante avant le Crétacé. N'importe quelle zone à haute productivité de plancton dans l'océan jurassique peut avoir produit suffisamment de radiolaires pour former des dépôts de radiolarites à l'échelle régionale, puisque la productivité des radiolaires est principalement limitée par les nutriments (et non pas par la silice, en particulier) et puisque les radiolaires n'entraient pas en compétition avec du plancton calcaire abondant. Alors que le modèle du Golfe de Californie reflète certainement bien la situation de la Téthys occidentale, la zone de convergence équatoriale Jurassique pourrait être la source probable de radiolarites dans la Téthys orientale et dans les terrains circumpacifiques.

Les radiolarites du Jurassique moyen des bassins de la Téthys occidentale sont contemporaines de calcaires condensés de hauts-fonds profonds dans lesquels la silice est pratiquement absente. Ce contraste de faciès n'est pas dû à la CCD (niveau de compensation de la calcite) parce que l'absence de silice sur les hauts-fonds ne peut évidemment pas être expliquée en ces termes. En outre, les faciès des bassins ne sont pas des résidus de dissolution des faciès moins profonds, car les radiolarites ont des taux de sédimentation supérieurs à ceux des calcaires condensés. C'est la distribution des radiolaires par des facteurs hydrodynamiques qui déterminait la présence locale, l'épaisseur et l'âge des radiolarites. Des courants de fond permanents ont empêché l'accumulation de radiolaires sur les hauts-fonds et les ont emportés dans les bassins. La rareté du plancton calcaire est responsable de la formation de calcaires condensés des hauts-fonds; dans les bassins, elle explique également le faible apport de carbonates par rapport à la silice. Il en résulte que l'ACD et la CCD sont peu profondes, irrégulières et bien définies.

Les radiolarites sont considérées comme le sédiment pélagique normal pendant tout le Mésozoïque, à l'exception du Crétacé supérieur, si certains facteurs (tab. 1) n'empêchaient pas leur formation.

## RESUMEN

Este trabajo se compone de dos partes. La primera parte (capítulo 2), aporta nuevos datos bioestratigráficos para la correlación de la zonación en base a radiolarios propuesta por BAUMGARTNER (1984b) con respecto a los pisos del Jurásico medio y superior. Se compara esta zonación con las que se han propuesto para el oeste de Norteamérica. Se presentan nuevos datos de radiolarios de una secuencia datada en base a amonites en la Sierra de Ricote (Zona Subbética, Prov. Murcia, España). Estos datos muestran que el límite entre las zonas A0 y A1 tiene que ser ubicado en el Bathoniense. Además, muestran que la base de la zona C1 corresponde con la base del Kimmeridgiense. Los nuevos datos de Bosso (Umbria, Italia) indican que la base de la zona de radiolarios D se encuentra en el Tithoniense superior, por debajo del límite A/B de la zonación estandar de los calpionellides.

Las zonas A0 a A2 son correlacionados con las zonas MH-3 a MH-4 establecidas por MURCHEY (1984) en Marin Headlands (California), y las zonas D a E2 corresponden con MH-5. Este resultado permite precisar la edad de los terrenos del "Franciscan Central Belt" y confirma un hiatus que abarca todo el Jurásico superior.

La correlación de las zonas A0 a B con la zonación de PESSAGNO et al. (1987b) muestra que la parte superior de la superzona 1 de estos autores se traslapa con la zona 2 de los mismos. Esto se comprueba gracias a una co-ocurrencia de especies características de la superzona 1 con *Mirifusus* PESSAGNO sp. La primera aparición de este género, definiendo la base de la dicha zona 2, se encuentra por debajo de la primera aparición de *Ristola turpicula* PESSAGNO & WAHLEN y se ubica en el Bajociense-Bathonense, según los datos del Tethys.

La segunda parte de este trabajo (capítulo 3) expone nuevos aspectos de la génesis de las radiolaritas, basado en las dataciones más precisas obtenidas en estas facies. Se hace una comparación de las facies contemporáneas del Jurásico del Atlántico y del Tethys sugiriendo: 1. una circulación estuarina para el Tethys atrayendo nutrientes del Paleopacífico y causando una alta fertilidad en la superficie. 2. una circulación lagunar para el Atlántico, dando como resultado una baja fertilidad en la superficie. El Atlántico del Jurásico era una cuenca «mediterránea» restringida e indirectamente conectada con el océano mundial.

La producción del plancton calcáreo era escasa antes del Cretácico. Cualquier zona de alta productividad planctónica en el océano Jurásico puede haber producido suficientes radiolarios para llegar a formar depósitos regionales de radiolaritas, ya que la productividad de los radiolarios es principalmente limitada por la cantidad de nutrientes (y no por el sílice en particular). Además, los radiolarios no estaban en competencia con el plancton calcáreo abundante. Mientras que el modelo del Golfo de California refleja bien la situación en el Tethys occidental, la zona de convergencia ecuatorial del Jurásico podría ser el origen de radiolaritas en el Tethys oriental y la región circumpacífica.

En el Jurásico medio del Tethys occidental las radiolaritas de las cuencas son contemporáneas con las calizas condensadas de altos fondos profundos, en las cuales el sílice es casi ausente. Este contraste de facies no es un resultado de la CCD (nivel de compensación de la calcita), porque la ausencia del sílice en los altos fondos evidentemente no se explica con la disolución del carbonato en la profundidad. Además, las facies radiolaríticas de las cuencas no pueden ser residuos de disolución de las facies calcáreas de los altos fondos, porque las primeras tienen tasas de sedimentación más altas. Es la distribución hidrodinámica de los radiolarios que determinaba la presencia local, el espesor y la edad de las radiolaritas en cada lugar. Corrientes de fondo permanentes no permitieron la acumulación de los radiolarios en los altos fondos, sino los transportaron a las cuencas. Es la escasez del plancton calcáreo que es responsable de la formación de calizas condensadas en los altos fondos. Además, en las cuencas explica el aporte escaso de carbonatos en comparación con el aporte silíceo. El resultado de esta situación es una CCD poco profunda, irregular y bien definida.

Las radiolaritas son consideradas como el sedimento pelágico normal durante todo el Mesozoico (con excepción del Cretácico superior), si ciertos factores (tab. 1) no inhibieron su formación.

## ZUSAMMENFASSUNG

Diese Arbeit besteht aus zwei Teilen: Teil 1 (Kapitel 2) vermittelt neue biostratigraphische Daten, die der genaueren Kalibrierung der von BAUMGARTNER (1984b) vorgeschlagenen Radiolarienzonierung bezüglich der Stufen des Mittel- und Oberjuras dienen. Die Korrelation mit West-Nordamerikanischen Radiolarienzonierungen wird diskutiert. Neue Radiolariendaten von einem Ammoniten-führenden Profil in der Sierra de Ricote (Subbeticum, Spanien) zeigen auf, dass die Grenze zwischen Radiolarienzonen A0 und A1, bisher als Unter-callovian datiert, jetzt ins Bathonian gestellt werden muss. Die Zone C1 erreicht die Basis des Kimmeridgian. Neue Daten von Bosso (Umbrien, Italien) zeigen, dass die Basis der Zone D unterhalb der Calpionellen-Zonengrenze A/B, d. h. in das Obertithon zu liegen kommt.

Zonen A0 bis A2 können mit den von MURCHEY (1984) für die Marin Headlands (Kalifornien) aufgestellten Zonen MH-3 und MH-4 verglichen werden und Zonen D bis E entsprechen MH-5. Dadurch kann das Alter mancher Terranes des Franciscan Central Belt genauer gefasst und eine Schichtlücke, die den ganzen Oberjura umfasst, bestätigt werden.

Die Korrelation der Zonen A0 bis B mit der von PESSAGNO (1987b) aufgestellten Zonierung belegt eine Überlappung ihrer oberen Superzone 1 mit ihrer Zone 2, durch die Tatsache, dass Arten, welche die obere Superzone 1 definieren, mit *Mirifusus* sp. PESSAGNO vergesellschaftet sind. Das Erstauftreten dieses Genus – es bildet die Definition der Basis der Zone 2 – tritt unterhalb des Erstauftretens von *Ristola turpicula* PESSAGNO & WAHLEN auf. Es muss deshalb in das Bajocian-Bathonian gestellt werden.

Der zweite Teil dieser Arbeit (Kapitel 3) diskutiert neue Aspekte der Genese der Radiolarite unter Berücksichtigung der neuen genaueren Datierungen. Die Gegenüberstellung gleichaltriger Fazies des Juras des Atlantiks und der Tethys lassen vermuten, dass die Tethys eine estuarine Zirkulation aufwies, welche eine grosse Oberflächenfertilität zur Folge hatte, während der Atlantik, als «mediterranes» Becken mit indirekten Verbindungen zum Weltmeer, eine lagunäre Zirkulation aufwies, die geringe Oberflächenfertilität zur Folge hatte.

Die Produktivität des kalkigen Planktons war vor der Kreidezeit unbedeutend. Da die Radiolarienproduktivität hauptsächlich durch die zur Verfügung stehenden Nährstoffe (nicht durch die Kieselsäure im Speziellen) begrenzt ist, könnte jede Zone mit grosser Oberflächenfertilität im Juraozean genügend Radiolarien hervorgebracht haben, um zu einem regionalen Vorkommen von Radiolariten geführt zu haben. Während das Modell des Golfs von Kalifornien gut der Situation der Westtethys entspricht, mag die Jurassische äquatoriale Konvergenzzone ein möglicher Ursprung mancher anderer Radiolarite der Osttethys und des Zircumpazifischen Raums sein.

In der Westtethys entsprechen Mitteljurassische Radiolarite in den Becken heteropen kondensierten pelagischen Kalken auf den Schwellen. Dieser Fazieskontrast ist nicht primär eine Funktion des Vorhandenseins einer Kalzit-Kompensationstiefe (CCD). Das Fehlen von Kieselsedimenten auf den Schwellen kann nicht mit der Karbonatauflösung in der Tiefe erklärt werden. Zudem stellen die Beckenfazies nicht lösungsfeste Residuate der seichteren Schwellenfazies dar, da die Radiolarite höhere Sedimentationsraten als die kondensierten Kalke aufweisen. Die hydrodynamische Sedimentverteilung innerhalb der Becken bestimmte das lokale Auftreten und die Zeitspanne der Radiolarite: Andauernde Bodenströmungen auf den Schwellen verhinderten die Ablagerung der Radiolarien und verfrachtete sie in die Becken. Die Seltenheit an kalkigem Plankton ist verantwortlich für kondensierte Kalke auf den Schwellen und einen niedrigen Karbonat-Input in den Becken, welcher zu seichten, unregelmässigen aber scharf definierten ACD und CCD Anlass gab.

Die Radiolarite werden als das pelagische Normalsediment während fast des ganzen Mesozoikums betrachtet, sofern eine Anzahl von Faktoren (Tab. 1) deren Bildung nicht verhinderte.

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## 1. Introduction

Radiolarians have been found in a vast amount of sedimentary rocks of deep water origin such as cherts, siliceous shales and mudstones, pelagic and turbiditic limestones. These rocks are, especially in the Jurassic, otherwise poor in age-diagnostic fossils and have therefore remained approximately dated. In the last fifteen years we have been able to establish a Mesozoic radiolarian biostratigraphy (FOREMAN 1973, 1975; RIEDEL & SANFILIPPO 1974; PESSAGNO 1976, 1977a, b; BAUMGARTNER et al. 1980; NAKASEKO et al. 1979; YAO et al. 1980, 1982; SCHAAF 1981, 1985; YAO 1983, 1984; BAUMGARTNER 1984a, b; PESSAGNO et al. 1984, 1987b; SANFILIPPO & RIEDEL 1985, only to mention a few) which allows to date these sediments to stage or substage level. These newly obtained ages open a new era in the understanding of the geologic history of the Mesozoic oceans and mountain belts.

Despite the effort of a rapidly growing group of scientists all over the world, the biochronologic potential of Mesozoic radiolarians is far from being exhausted and the systematic search in all deep-water sediments has just begun. Zonations are constantly being created and revised and the number of new Mesozoic radiolarian taxa described every year amounts to hundreds. Any published account is therefore preliminary, zonations and their calibration to the stages are perfectible.

This paper is divided into two parts. *The first part* provides new data to further constrain the ties between Middle and Late Jurassic stages and the radiolarian zonation proposed by BAUMGARTNER (1984a, b, 1986). Furthermore, a correlation to Western North American zonations is attempted and discrepancies are discussed in detail.

The occurrence of many Cenozoic radiolarian species is known to be related to specific oceanographic conditions and a number of studies have demonstrated that the radiolarian assemblages preserved in the surface sediments of the oceans reflect the major zooplankton distribution provinces (HAYS 1965; PETRUSHEVSKAYA 1967; NIGRINI 1967, 1968, 1970; GOLL & BJØRKLUND 1971, 1974; KLING 1976, 1979; McMILLEN & CASEY 1978 etc.) Both the latitudinal and the bathymetric zonations proposed in these studies are now widely confirmed. It is now clear that Mesozoic radiolarians also show significant faunal provincialism which may provide a basis for paleogeographic and paleoceanographic reconstructions. PESSAGNO & BLOME (1986) defined simple criteria to differentiate radiolarian assemblages of the Tethyan from those of the Boreal realm and to subdivide these realms into provinces. Their differentiation remains, however, hypothetical for two reasons: 1. Their criteria are largely based on observations in Western American displaced or suspect terranes, the paleolatitudinal and paleogeographical setting of which is unknown or highly interpretive. No reference sections of known paleobiogeographic affinity and/or paleolatitude have been studied yet for the Lower and Middle Jurassic, in order to confirm the proposed criteria. 2. A pure paleolatitudinal interpretation of radiolarian faunal provincialism should be cautioned by the fact that Jurassic paleolatitudinal (temperature) gradients may have been less important than those in the glacial

world of the Cenozoic. In turn, other factors, such as basin configuration and current pattern may have been more important for Jurassic oceanic environments and radiolarian distribution than they are in the Present.

*The second part of this paper* reevaluates genetic interpretations of Tethyan radiolarian-rich sediments in the light of the new age data. A number of studies have dealt with the genesis of Tethyan radiolarites (BOSELLINI & WINTERER 1975; STEINBERG et al. 1977; FOLK & MCBRIDE 1978; MCBRIDE & FOLK 1979; KÄLIN et al. 1979; WINTERER & BOSELLINI 1981; BARRETT 1982; JENKYN & WINTERER 1982, etc.). At that time no exact age control was available on the radiolarites. Therefore no precise chronostratigraphic correlation was possible between sediments deposited in basins and those deposited on seamounts of western Tethyan ancient margins. Common to all cited papers (except for Folk in FOLK & MCBRIDE 1978 and MCBRIDE & FOLK 1979) is the acceptance of a calcite compensation depth (CCD) at a relatively shallow level (as compared to today) as proposed by BOSELLINI & WINTERER 1975. It is believed that the presence of sharply defined dissolution levels is responsible for the observed spatial distribution of calcareous and noncalcareous pelagic facies.

As more precise age control on Tethyan radiolarites is now available, the image becomes more complex. Start and duration of radiolarite sedimentation is a function of basin history (BAUMGARTNER 1984b). There is no general Tethyan radiolarite age span. Radiolarites may be deposited at any time during the Late Triassic – Early Cretaceous, if certain conditions are given. What are these conditions? While the CCD-model may be valid to explain the absence of pelagic carbonates in basins it does not explain the partial or total absence radiolarites on adjacent seamounts. The small scale facies pattern of coeval chert and pelagic limestone observed along Tethyan ancient margins calls for a reevaluation of the dissolution model. The distribution of siliceous sediment is a problem that has to be dissociated from the dissolution of carbonate at depth. If the planktonic carbonate input to Tethyan basins was very scarce, then dissolution zones would have been very shallow and irregular. Consequently, the CCD-model would have lost much of its bathymetric argument.

Chapter 3 of this paper analyses the spatiotemporal distribution of radiolarites and coeval pelagic sediments in the early Atlantic and Tethys in order to extract possible paleoceanographic signals. On the other hand, the transport properties of radiolarians are discussed to provide a basis for a hypothesis of radiolarian sediment dispersal in the Tethyan Jurassic.

## **2. Dating radiolarites: Middle Jurassic-early Cretaceous radiolarian zonation**

### **2.1. The method: Unitary Associations versus probabilistic Procedures**

The Bathonian to Hauterivian radiolarian zonation recently proposed by BAUMGARTNER (1984b) is defined by means of Unitary Associations (U.A., GUÉX 1977, 1987). A database consisting of first and final appearances of 110 species in 245 samples at 51 localities was used to establish a system of 15 successive U.A. (grouped in 9 zones), each of which is defined by a number of characteristic species or species pairs (like concurrent range zones). The studied localities are situated in a low paleolatitude belt

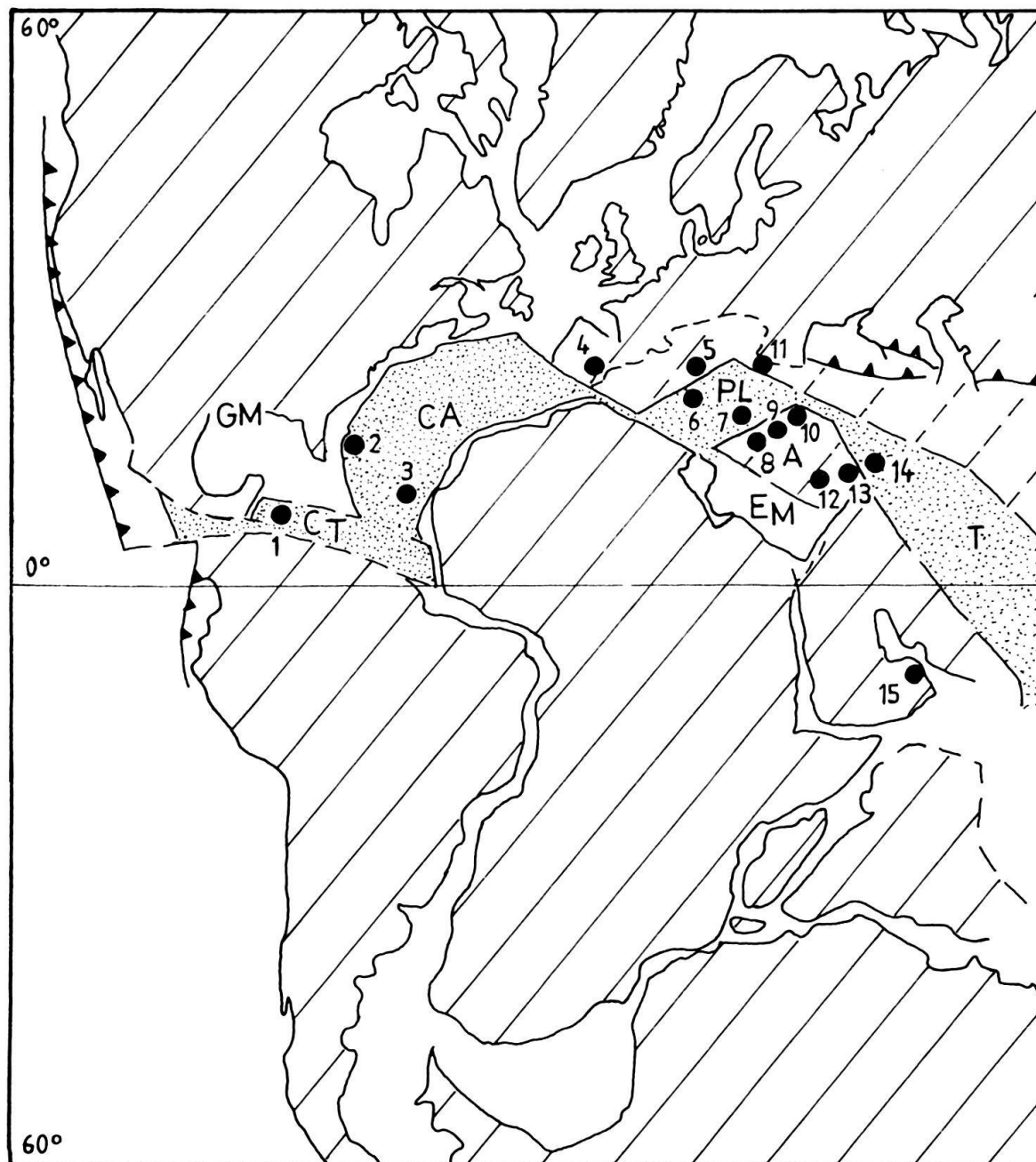


Fig. 1. Tentative restoration of the Late Jurassic Tethys after BERNOULLI & LEMOINE (1980) with locations of the principal areas studied for the present radiolarian zonation: 1. Nicoya Complex, Costa Rica; 2. DSDP-Site 534, Blake Bahama Basin; 3. DSDP-Site 367, Cape Verde Basin; 4. Sierra de Ricote, Prov. Murcia, Spain (see Text-Figs. 3, 4); 5. Ultrahelvetic of the Swiss Alps; 6. Schistes lustrés of the Western Alps; 7. Ligurian Ophiolite units; 8. Tuscan and Umbrian margin; 9. Lombardy Basin and Trento Plateau; 10. Northern Calcareous Alps (Austria); 11. Romanian Carpathians; 12. Pindos Trough, Central Greece; 13. Pelagonian Zone s. l. of Eastern Greece; 14. Vardar Ophiolite units, Eastern Greece; 15. Hawasina Nappes, Oman. GM. Gulf of Mexico, CT. Caribbean Tethys; CA. Central Atlantic; PL. Piemont-Ligurian Ocean (Western Tethys); A. Apulian Block; T. Eastern Oceanic Tethys from the Vardar Zone eastwards.



(Fig. 1) reaching from the Caribbean Tethys and early Central Atlantic (including DSDP-Site 534, Blake Bahama Basin) to the Mediterranean Tethys.

Establishing Unitary Associations following the procedures exposed by GUEX & DAVAUD (1984) and BAUMGARTNER (1984a) has proven to be a very effective way of integrating a large amount of radiolarian data into a biochronologic framework. The resulting species co-occurrence chart formed by vertically ordered Unitary Associations (Fig. 2) displays maximum ranges of each species with respect to all other species. These ranges are produced by stacking co-occurrence data from all sections and therefore compensating for local gaps in the record due to patchy preservation of radiolarians along each section. Only the Unitary Associations that prove to have a sufficient lateral reproducibility over the studied area (see BAUMGARTNER 1984b, Fig. 1) are of chronologic significance and may be used to define biochronozones.

In comparing the results of the Unitary Associations method with those of probabilistic strategies applied to the same database (BAUMGARTNER 1984a) it became clear that the results of the two approaches are very different. A probabilistic range chart does not reflect the actual co-occurrences of species encountered in the samples and may therefore lead to wrong results when used as a basis for dating. The following comments and Fig. 3 should give some explications.

Probabilistic methods like ranking and scaling (AGTERBERG & NEL 1982a, b) assume a symmetrical random scatter of the first and final appearance events around "average" endpoints of the taxon-range, which necessarily implies a consistent occurrence of the taxon in the interior of its range. These assumptions are almost never met by real fossil data, because:

1. – The scatter of local first and final appearances along an arbitrary (hypothetical time-) scale is not random, but predictable; ranges are shortened essentially due to the incompleteness of the fossil record, but cannot be lengthened beyond the maximum range of a taxon except for reworking, misidentification or contamination. These latter effects are generally less important than the effect of lack of preservation and can be discerned by other means. The probability curves for observing first and final occurrences of a taxon will therefore be distinctly asymmetrical (Fig. 3 c) with steep slopes near the maximum endpoints of the range and gentle slopes towards the inside of the range (see also EDWARDS 1982, Fig. 1). It follows that «average» ranges calculated in assuming a symmetrical (normal) probability distribution of observed tops and bottoms are necessarily shorter than maximum ranges and are easily contradicted by well preserved assemblages. Two radiolarian zonations for the Lower Cretaceous published recently (SANFILIPPO & RIEDEL 1985; SCHAAF 1985) are based on a probabilistic procedure. The sequence of first and final appearances proposed in the range charts of these authors not only differ markedly from each other but also are contradicted by radiolarian occurrences in Lower Cretaceous land sections from the Southern Alps and Umbria (Italy), where well preserved samples are available at many levels (JUD, work in progress). Zoning of fossil assemblages based on a probabilistic range chart, taken at face value, may be an exercise of very limited reliability; a statistical procedure considering the "event-range" (range of probable occurrence of each event, see AGTERBERG & NEL 1982a and Fig. 3 c) of all involved taxa would be necessary to find the most probable "age-range" of an assemblage.



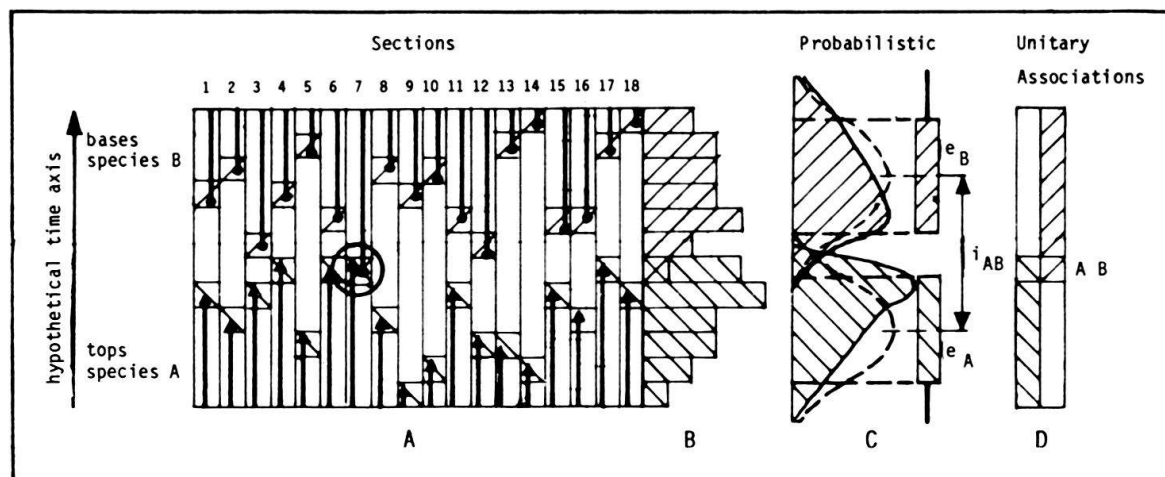


Fig. 3. a: Hypothetical last appearance of species A and first appearance of species B in 18 sections. Note that A and B are actually co-occurring in section 7. b: Bar-graphs representing the distribution of last and first appearances. c: Smoothed curves showing the probabilities of last and first appearance. Note the pronounced asymmetry of curves. Stippled curves represent normal distributions assumed by some probabilistic methods (e.g. ranking),  $e_B$  and  $e_A$  are deduced event-ranges of the last appearance of A and the first of B.  $i_{AB}$  is the interfossil distance used in ranking. Note that despite an actual co-occurrence found in section 7, species A and B are assumed to be stratigraphically succeeding. As a consequence assemblages containing A but lacking B are interpreted as being older than assemblages containing B but lacking A, which may be true in many cases but is contradicted at least in section 7. d: Unitary Associations show the co-occurrence of A and B and indicate maximum ranges.

2. – Mesozoic radiolarian data are especially incomplete owing to a limited number of lithologies favorable to radiolarian preservation. The probability of a species not being preserved at any sample level is equally high throughout its range. Dissolution acts selectively on certain taxonomic groups after death and at the seafloor (TAKAHASHI & HONJO 1981). After burial, preservation of a radiolarian test is dependent of the diagenetic environment, size, shape and other unknown factors. Therefore, local first and final appearances may typically occur anywhere along the entire range of a taxon and are not necessarily clustered near the endpoints of the range.

“Average” ranges for Mesozoic radiolarians calculated by ranking and scaling under the above assumptions are generally much shorter than those indicated by Unitary Associations for the same database (BAUMGARTNER 1984a). These ranges serve at best to confirm which of the species are dissolution-resistant.

GRADSTEIN (1985) cited in extenso the procedures of establishing the Unitary Associations of the present zonation as well as its comparison to results of ranking after BAUMGARTNER (1984a). However, he failed to also cite the most critical remarks about the pitfalls of ranking and scaling and makes the reader believe (p.277) that the present zonation is based on U.A. and ranking, which is incorrect. The ranking solution illustrated by BAUMGARTNER (1984a, Fig.4) and reproduced by GRADSTEIN (1985, Fig.6) shows several pairs of species as not co-occurring but apparently stratigraphically succeeding, whereas in the database (published in both papers) these pairs are actually found co-occurring in several samples (see also hypothetical example in Figure 3). Such results have not been considered in the present zonation.

The inclusion of more and more samples into the database has confirmed the maximal ranges and the assemblages defined by Unitary Associations; no conflicting data as to

their superposition have been found. It is expected that future work may considerably refine, but not fundamentally alter the established zonation.

The ties between Unitary Associations and chronostratigraphy are a separate problem, depending on the correlation with other fossil zonations, especially the ammonite zonation, dealt with in the next chapter.

## 2.2. Calibration in the middle and late Jurassic: New data from the Sierra de Ricote (Prov. Murcia, Spain)

BAUMGARTNER'S (1984b) radiolarian zones were tentatively tied to the standard stages by means of co-occurring microfossils (calpionellids, nannofossils, dinoflagellates) rather than ammonites. The studied sections of the central Tethyan realm generally are very siliceous, consisting of sediments deposited at least below the local aragonite compensation depth (see chapter 3) and are thus, in general, devoid of ammonites.

The exceptional presence of displaced ammonites in the pelagic Middle and Upper Jurassic of the Subbetic Realm exposed in the Sierra de Ricote (Prov. Murcia, Spain; SEYFRIED 1978; BAUMGARTNER 1984b, loc. 45, p. 799; Fig. 1, loc. 4 herein) led us to study several sections in greater detail for radiolarians and paleomagnetic reversals (BAUMGARTNER & CHANNELL, in preparation).

The Subbetic is presently a 40–80 km wide belt of Jurassic and Cretaceous pelagic sediments which extends 500 km across southern Spain from Cadiz to Alicante. This region is interpreted as a passive margin which began active foundering during the Early Jurassic and remained for most of its area in the pelagic realm until initiation of tectonic shortening in the Eocene. The Prebetic realm to the north remained a shallow marine carbonate platform throughout this time. The Subbetic is bounded to the south by the allochthonous units of the Betic, emplaced during the Tertiary.

During the Jurassic, the Subbetic was divided into submarine swells and a median trough which experienced local volcanic extrusions. This general topography and the irregular, possibly fault-controlled relief on each swell led to considerable variation in the Jurassic facies (VERA et al. 1979; SEYFRIED 1979; COMAS et al. 1981). The local topographic highs are characterized by a condensed Bathonian to Early Oxfordian sedimentation of nodular limestones often rich in ammonites. More continuous pelagic sedimentation commenced in the late early Oxfordian with red marl or nodular marly limestone. The basinal sections exposed in the Sierra de Ricote comprise Upper Liassic to Upper Cretaceous pelagic and intermittent calciturbiditic sediments similar to other basins along the Tethyan margins (e.g. Lombardy Basin). The radiolarites, however, are distinctly more calcareous and, especially in the upper red part, more clay-rich.

The studied sections include 110 m of Bathonian grey siliceous limestones (Fig. 4, unit 1) with occasional dark grey replacement chert interbedded occasionally with greenish grey siliceous marls. Thin-shelled bivalves (*Bositra* sp.?) form an important fraction of these limestones. Radiolarians occur sporadically concentrated in thin beds often accompanied by bands and nodules of replacement chert. Ammonites are only rarely and poorly preserved. Towards the top of this unit radiolarian-rich beds become more abundant. SEYFRIED (1978) found *Cadomites* cf. *C. daubenyi* (GEMMELLARO) indicating a Bathonian age in the upper part of this unit. Extracted radiolarian assemblages are assignable to

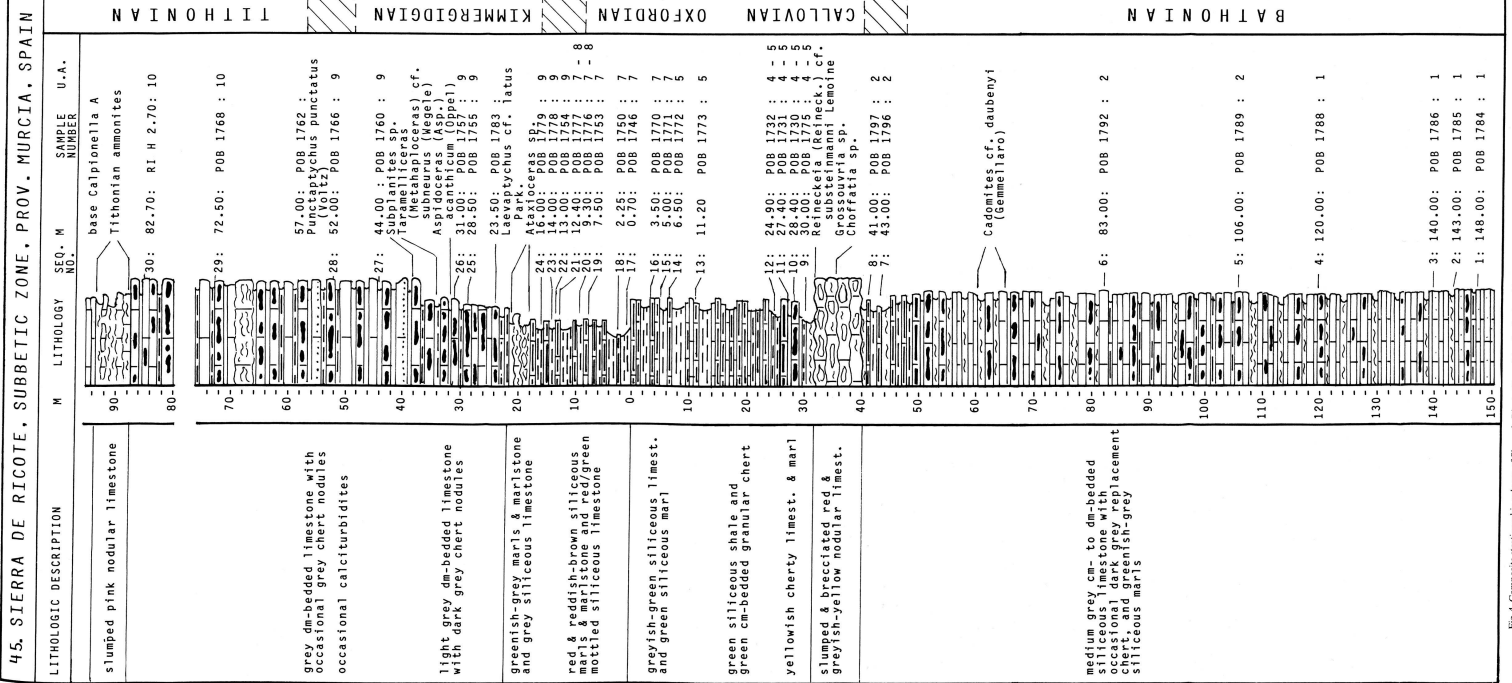


Fig. 4. Composite stratigraphic column of Sierra de Ricote (Prov. Murcia, Spain, with position of 30 zoned radiolarian samples and ammonite data.

zone A0 (U.A. 1) in the lower part and to zone A1 (U.A. 2) in the upper 70 m of this formation.

This unit is overlain by about 8 m of red and grayish-yellow nodular limestone (Fig. 4, unit 2) with clear features of penecontemporaneous gravitative resedimentation and slumping. This bed can be followed over several km and shows identical microfacies characteristics as some nodular limestones in condensed sections on the swells. A rich ammonite assemblage extracted from the upper part of this unit by SEYFRIED (1978) comprises *Reineckeia* (*Reineckeia*) cf. *substeinmanni* LEMOINE, *Grossouvria* sp., *Choffatia* sp. and others, indicative of an early or middle Callovian age. Preliminary paleomagnetic data (CHANNELL & BAUMGARTNER, work in progress) show no effect of slumping, suggesting that the sediment was sufficiently unconsolidated to reset its remanent magnetisation during or after gravitative emplacement. Considering the fact that these facies show frequent early lithification on the swells (JENKYNS 1974), the paleomagnetic data confirm a penecontemporaneous emplacement of this unit and validate its ammonites for calibration of radiolarian assemblages found above and below this unit.

The following unit (Fig. 4, unit 3) comprises the transition from yellowish cherty limestone at the base to the green basal radiolarites, here developed as green 2–5 cm bedded calcareous chert and interbedded siliceous shales. Towards the top grayish-green siliceous limestones replace the cherts. Except for rare belemnite rostra, no macrofossils have been found. Radiolarians are very abundant but preservation is moderate. The radiolarian assemblages of the lower part of this unit are assignable to zone A1–A2 (U.A. 4–5) or to zone A2 (U.A. 5). The uppermost 5 m of this unit are assignable to zone B (U.A. 7).

The contact with the next unit (Fig. 4, unit 4) is a sharp color change from green to red, which is found throughout the Subbetic and is dated on the swells (where the ammonite control is better) as Early Oxfordian (VERA et al. 1979). Unit 4 comprises red siliceous marls and marlstones and red/green mottled siliceous limestones rich in moderately well preserved radiolarians. Only primary calcitic macrofossils have been reported (rhyncholiths, aptychi, belemnites, characteristic of the Oxfordian). Radiolarian assemblages of the lower red part of this unit are assignable to zone B (U.A. 7). Limestone beds become rapidly more abundant upsection where a few beds of nodular marls mark the transition to the white cherty limestone of the next unit (Fig. 4, unit 5). Some of these nodular marls show lenticular disrupted bedding and suggest penecontemporaneous redeposition. SEYFRIED (1979) cites a basal Kimmeridgian *Ataxioceras* sp. from these beds. Radiolarian assemblages from this upper part of unit 4 are assignable to zone C1 (U.A. 9).

Unit 5 (Fig. 4) consists of dm-bedded light grey siliceous limestones with bands and layers of dark grey replacement chert every couple of meters. Many of these beds show faint grading of redeposited carbonate debris. Radiolarians are preserved sporadically in the more siliceous beds showing chert nodules.

Kimmeridgian and up-section Tithonian ammonites are abundant in certain beds. Radiolarian assemblages are assignable to zone C1 (U.A. 9) and in the upper part to zone C2 (U.A. 10).

In contrast to similar paleogeographic situations in the Southern Alps and the Apennines, the Subbetic basin appears to have been shallower and possibly more directly connected to shallow shelf areas from where periplatform carbonate ooze and calcitur-

		45. SIERRA DE RICOTE SUBBETIC ZONE, PROV. MURCIA, SPAIN	
30:	RI H2.70		(0) <i>Ristola turpicula</i>
29:	P08 1768		(2) <i>Unuma echinatus</i>
28:	P08 1766		(10) <i>Andromeda praecrassa</i>
27:	P08 1760		(9) <i>Tricolocapsa plicarum</i>
26:	P08 1757		(14) <i>Mirifusus fragilis</i>
25:	P08 1755		(17) <i>Eucyrtidiellum unumaensis</i>
24:	P08 1779		(18) <i>Podobursa helvetica</i>
23:	P08 1778		(19) <i>Emiluvia premyogii</i>
22:	P08 1754		(61) <i>Stichocapsa convexa</i>
21:	P08 1777		(20) <i>Tetraditryma corralitosensis</i>
20:	P08 1776		(24) <i>Acanthocircus suboblongus</i>
19:	P08 1753		(23) <i>Hsuum brevicestatum</i>
18:	P08 1750		(36) <i>Tetratrabs zealis</i>
17:	P08 1746		(29) <i>Triactoma jonesi</i>
16:	P08 1770		(7) <i>Guexella nudata</i>
15:	P08 1771		(13) <i>Higumastra imbricata</i>
14:	P08 1772		(87) <i>Praeconocaryomma (?) hexacubica</i>
13:	P08 1773		(90) <i>Parvicingula dhimenaesis</i>
12:	P08 1732		(43) <i>Homoeoparonaella argolidensis</i>
11:	P08 1731		(50) <i>Spongocapsula palmerae</i>
10:	P08 1730		(16) <i>Andromeda podbielensis</i>
9:	P08 1775		(25) <i>Triactoma blakei</i>
8:	P08 1797		(32) <i>Ristola altissima</i>
7:	P08 1796		(31) <i>Perispyridium ordinarium</i>
6:	P08 1792		(33) <i>Emiluvia sedecimporata salensis</i>
5:	P08 1789		(30) <i>Triactoma tithonianum</i>
4:	P08 1788		(37) <i>Mirifusus guadalupensis</i>
3:	P08 1786		(35) <i>Bernoullius dicera</i>
2:	P08 1785		(41) <i>Emiluvia (?) sp. P.</i>
1:	P08 1784		(49) <i>Staurosphaera antiqua</i>
			(89) <i>Triactoma cornuta</i>
			(76) <i>Mirifusus mediodilatatus s.l.</i>
			(54) <i>Tritrabs ewingi</i>
			(45) <i>Ristola procera</i>
			(62) <i>Tetratrabs bulbosa</i>
			(55) <i>Diboloachras chandrika</i>
			(64) <i>Podobursa spinosa</i>
			(60) <i>Emiluvia orea</i>
			(75) <i>Archaeodictyomitra apiaria</i>
			(69) <i>Podocapsa amphitreptera</i>
			(68) <i>Sethocapsa cetia</i>
			(81) <i>Triactoma echiodes</i>
			(99) <i>Mirifusus mediodilatatus minor</i>

Fig. 5. Selected occurrence data of radiolarian species in samples 1–30 of Text-Fig. 3. *Ristola turpicula*, though not used in the present zonation, is included to serve as a faunal link to North American sections.

bidites could enter the basin. Abundance of clays starting possibly in the late Early Oxfordian (unit 4) may indicate start of basinward transport of unconsolidated clay-rich shelf deposits owing to a lowering of the sealevel (cf. HAQ et al. 1987).

### Results

Figure 4 shows a composite lithologic column with the most important ammonite data and 30 physically superposed radiolarian samples which are assigned to U.A. on the basis of the selected species-occurrence data given in Figure 5.

In the light of this new data, a readjustment of some zonal boundaries to the stages is possible (Fig. 6):

The boundary between zones A0 and A1, thus far believed to lie within the basal Callovian, is now found more than 30 m below the occurrence of *Cadomites* sp. cf. *C. daubenyi*, a Bathonian ammonite. This boundary must therefore be placed at least within the Bathonian. Since the Bathonian sediments are at least 100 m thick at this locality, it is likely that this boundary occurs somewhere in the upper Bathonian. This new calibration casts some doubt about the middle to late Callovian age originally assigned to the oldest sediments at DSDP Site 534 (SHERIDAN, GRADSTEIN et al. 1983); the age was based on dinoflagellates and nannofossils and was the principal basis for the Callovian age assignment of zone A1 (see BAUMGARTNER 1984b, p. 742 and loc. 30, Pl. 12 A). Alternatively, U.A. 2 of zone A1 must represent a rather long time interval reaching from at least late Bathonian to early or middle Callovian.

The penecontemporaneous slump unit (fig. 4, unit 2), of pelagic limestone containing ammonites of early or middle Callovian age is bracketed by radiolarian samples assignable to U.A. 2 (zone A1) and to U.A. 4–5 (zones A1–A2). This is a clear indication for an early-middle Callovian minimum age of zone A1. The age of the boundary A1/A2 is still poorly defined. Unfortunately radiolarians extracted from the lowermost green cherts of unit 3 are too poor to allow a precise assignment to either U.A. 4 or 5. The first sample definitely assignable to U.A. 5, almost 20 m above the base of unit 3, may already be basal Oxfordian in age. It seems nevertheless clear that at least part of U.A. 5, and therefore part of Zone A2 corresponds to the late Callovian. U.A. 6 has not been recognized in this section, it is so far only known from the Lombardy Basin and its biostratigraphic value continues to be questionable (see BAUMGARTNER 1984a, p. 744).

Regional lithostratigraphic correlation shows that the boundary between units 3 and 4 (Fig. 4) occurs within the early (probably late early) Oxfordian. The first assemblages assignable to U.A. 7 (zone B) are found 5 m below this contact. It is therefore likely that the A2/B boundary occurs within the early Oxfordian.

The presence of an *Ataxioceras* sp. in the transitional beds between the red radiolarian marls (Fig. 4, unit 4) and the white pelagic limestones (Fig. 4, unit 5) indicates a basal Kimmeridgian age of this transition. The base of zone C1 is reached in the uppermost red marls (unit 4) just below this transition and suggests that the boundary between zones B and C1 coincides approximately with the Oxfordian/Kimmeridgian boundary at this locality.

Joint biostratigraphic work on various fossil groups and paleomagnetic work in the same sections (BAUMGARTNER & CHANNEL, in prep.) is necessary to confirm the above calibrations and those of the remaining boundaries, especially the base of zones B and Zone C2.



### 2.3. Calibration at the Jurassic/Cretaceous boundary: New data from Umbria

New radiolarian samples collected from the Bosso section (Loc 26, BAUMGARTNER 1984b) in Umbria allow to define a more precise correlation between magnetostratigraphy (LOWRIE & CHANNELL 1984), calpionellid zones and radiolarian zone C1/D boundary.

LOWRIE & CHANNELL (1984) and BAUMGARTNER (1984b) both used the calpionellid stratigraphy by MICARELLI et al. (1977) to relate their data of the basal part of the Maiolica at Bosso to the stages. Both the calpionellid zonation and the definition of the Tithonian/Berriasian boundary used by MICARELLI et al. (1977) differ significantly from the Rome standard calpionellid zones (ALLEMANN et al. 1971; REMANE 1978, 1985; REMANE et al. 1986). This fact prompted a comment on Lowrie & Channell's paper by OGG (1984) in which the different definitions were discussed. During work in progress (Baumgartner, Remane & Jud) we reexamined the calpionellids at the base of the Maiolica and found the boundary between Rome standard calpionellid zones A and B to lie at 311 m [Remane, personal communication, m-levels of LOWRIE & CHANNELL (1984) and BAUMGARTNER (1984b)], which places the Tithonian/Berriasian boundary (COLLOQUE 1975 definition) in the middle or marine magnetic anomaly M-19n of LOWRIE & CHANNELL (1984). Thus the discrepancies discussed by OGG (1984) are eliminated.

New radiolarian samples show radiolarian zone D (U.A. 11) as low as 304 m, thus clearly below the calpionellid zone A/B boundary. At present the radiolarian zone C2/D boundary is to be found between 299.5 m and 304 m, or within magnetic anomaly M-20n. New observations (Remane, personal communication) suggest that subzone A1 of REMANE (1963) = *Remanei* subzone of REMANE et al. (1986) is lacking or disturbed in the Bosso section. Samples between 303 and 305 m show only *Saccocoma*. Further work is needed to decide whether the radiolarian C2/D boundary lies within, below or above the *Remanei* subzone.

### 2.4. Correlation with western North American radiolarian Zonations

#### 2.4.1. Introduction

Radiolarians are open marine planktic organisms that should have a wide distribution within certain paleoceanographic domains and a correlation of biozonations established in two different areas should therefore be possible. There are, however three potential obstacles to correlation:

1. *Faunal provinciality.* – There are clear indications of Jurassic radiolarian faunal provinces, possibly related to the Jurassic paleoceanography. These faunal provinces have been linked by PESSAGNO & BLOME (1986) to paleolatitudinal (Tethyan – Boreal) belts. Biostratigraphic correlation between faunal provinces is likely to be more difficult than within them.

2. *Preservation.* – Different paleogeographic and paleoceanographic settings may result in different sedimentary facies which in turn have variable preservation potentials for certain radiolarian groups. This may cause absence of certain species from certain levels without any paleobiogeographic significance.

3. *Biostratigraphic concept.* – Correlation of two zonations is only possible, where both are based on a similar concept of zones and if a number of species (and their

HAQ ET AL. 1987 TIMESCALE		BAUMG. 1984b		THIS PAPER		CALP.
M.Y.	STAGES	U.A.	ZONE	U.A.	ZONE	ZONES
120	HAUTERIVIAN					
		14	E 2	14	E 2	
125	VALANGINIAN	XXXXXXXXXXXXXX		XXXXXXXXXXXXXX		-----
		13	E 1	13	E 1	E
		XXXXXXXXXXXXXX		XXXXXXXXXXXXXX		-----
130	BERRIASIAN	12	D	12	D	D
		11		11		C
						B
135	TITHONIAN	XXXXXXXXXXXXXX		XXXXXXXXXXXXXX		-----
				10	C 2	A
		XXXXXXXXXXXXXX		XXXXXXXXXXXXXX		
140	KIMMERIDGIAN	9	C 1			
		XXXXXXXXXXXXXX		9	C 1	
145	OXFORDIAN	8	B	XXXXXXXXXXXXXX		
		7		8	B	
		XXXXXXXXXXXXXX		7		
150	CALLOVIAN	6		XXXXXXXXXXXXXX		
		5	A 2	5 6	A 2	
		XXXXXXXXXXXXXX		XXXXXXXXXXXXXX		
155	BATHONIAN	4 3	A 1	XXXXXXXXXXXXXX		
		2		3	A 1	
		XXXXXXXXXXXXXX		2		
160	BAJOCIAN	1	A 0	XXXXXXXXXXXXXX		
		0		1	A 0	
165				0		
170						

Fig. 6. Updated correlation of Zones A0 to E2 with the stages, based on the data discussed in text. For comparison, the calibration of BAUMGARTNER 1984b is also given. Calpionelid zones A-E are after REMANE 1985, the timescale is from HAQ et al. 1987. "XXXX" represent zones of uncertainty.

taxonomic definitions) are common to both zonation. It has been documented (BAUMGARTNER 1984b) that the present zonation can be easily correlated to the various Japanese zonation, since these are also based on an assemblage concept in which each zone is defined by a number of characteristic species or species pairs having a concurrent

range. Considerable difficulties of correlation arise if one tries to compare concurrent range zones with interval zones based on first or last appearances of one marker taxon, especially when taxa defining different interval zones are found co-occurring in an "incompatible" way.

No matter how difficult the correlation of biozonations may be, it is essential for the understanding of global sedimentation processes and it also reveals the amount of local stratigraphic uncertainty. In order to be valid, correlation should be based on certain principles, already sketched in BAUMGARTNER (1984b, p. 737):

1. If a correlation of radiolarian zones is sought, correlation should be based on radiolarians only. The relation of radiolarian zones with ammonite stratigraphy and the stages is the problem of calibration that has to be dealt with separately.
2. The correlation should be strictly based on species that are represented in both range charts or on a reexamination of original sample material in order to find common species. The morphologic delimitations of these species have to be the same, as far as this can be defined in descriptions, synonymy and illustrations.
3. A zonation based on maximum ranges compiled from co-occurrences in a large number of samples is likely to demonstrate partial or total overlap of zones established on the basis of local or incomplete ranges.
4. A zonation in which the superposition of zones is demonstrated in a reproducible way in many sections is likely to show overlap of zones established in different areas, where the superposition of zones has to be inferred from other fossil data and/or circumstantial evidence.

#### 2.4.2. Correlation with the zonation by MURCHEY (1984)

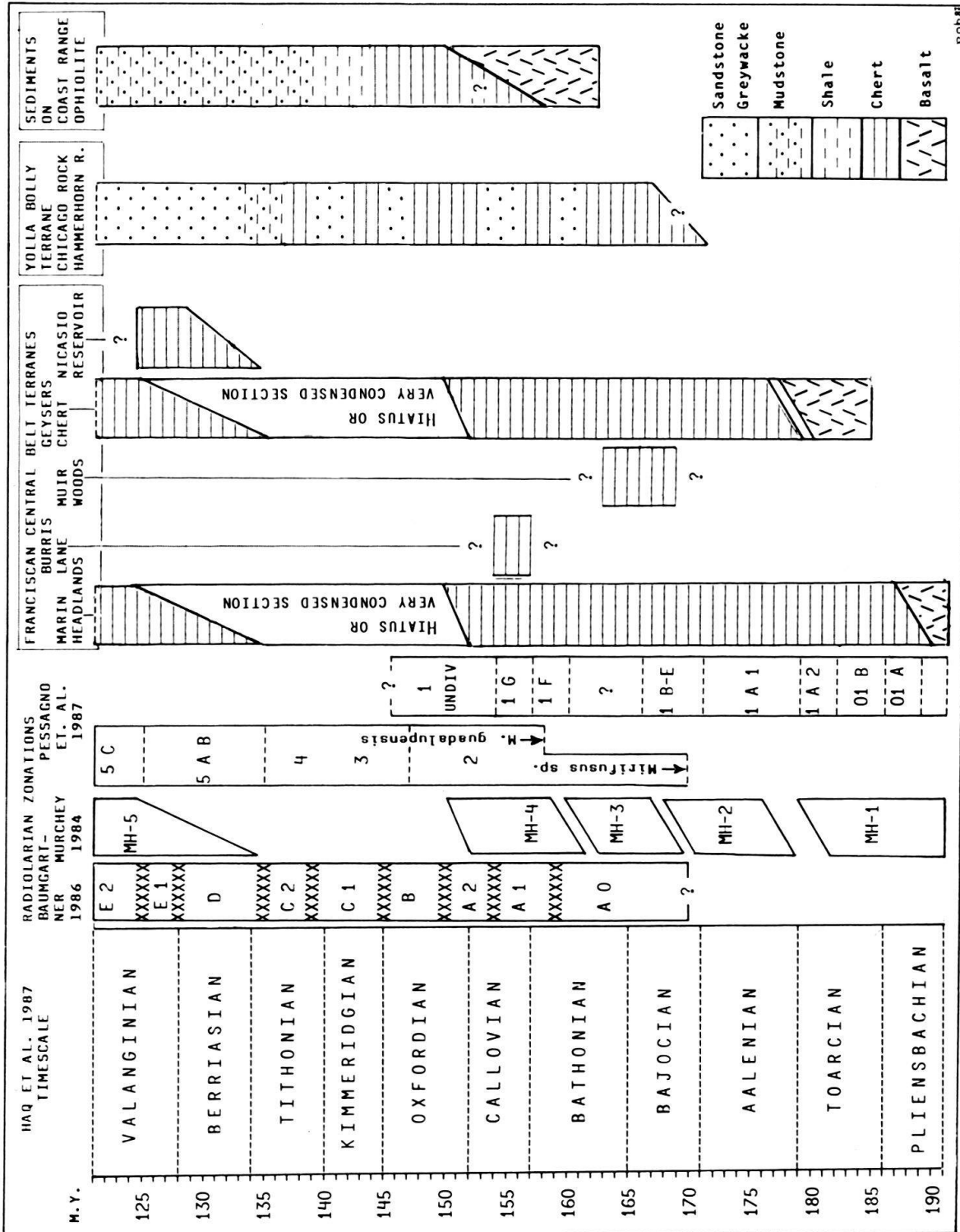
MURCHEY (1984) has analyzed several continuous radiolarite sections in the Marin Headlands and other Franciscan Central Belt terranes (see also data in MURCHEY and JONES 1984). Based on radiolarian occurrences mainly in the Marin Headlands she was able to define a sequence of 7 assemblages. Except for assemblage MH-6 which differs from MH-5 only by the absence of a number of species, all other assemblages are defined by the total local range of a number of characteristic species along with concurrent, longer ranging species. Although the state of radiolarian preservation in Franciscan samples is generally moderate and the zonation may appear rather coarse, its definition by assemblages eases the determination of zones and makes a correlation to the Tethyan zonation possible.

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Fig. 7. Correlation of Tethyan and W-North American Jurassic radiolarian zonations and age of some Franciscan terranes (after BAUMGARTNER & MURCHEY 1987).

The ties between A0–A2 (Atlantic–Tethys) and MH-3–4 (MURCHEY 1984, Marin Headlands) are established by the occurrence of *Andromeda* spp. *Unuma echinatus*, *Mirifusus fragilis*, *M. guadalupensis*, *Ristola turpicula*, *Archaeohagistrum munitum*, *Triactoma cornuta*, and other species in both areas. The age of several Franciscan terranes can now be specified. Note that clastic intercalations occur in the Yolla Bolly Terrane since the Middle Jurassic and can therefore not be derived from the Nevadan orogen.

Zone 2 of PESSAGNO et al. (1984, 1987b), the base of which is defined by the first appearance of *Mirifusus* sp., shows an overlap with the upper part of superzone 1 of PESSAGNO et al. (1987). The defining species of both zones co-occur in Franciscan and Atlantic–Tethyan samples. Data showing the stratigraphic superposition of the overlapping zones in one section, have in fact not been published by these authors. For details, see chapter 2.4.3.



Joint work with B. Murchey allowed to find a sufficient number of common forms in order to correlate zones MH 3–5 established by MURCHEY (1984) with zones A0 to E2 of the present zonation (see Figure 7, from BAUMGARTNER & MURCHEY 1987).

MH3 is defined amongst other species by the presence of *Mirifusus* sp. A = *Mirifusus fragilis* BAUMGARTNER and *Trillus* sp. cf. *T. seiderse* PESSAGNO & BLOME with co-occur in zone A0, U.A. 0 of the present zonation. In addition, *Unuma echinatus* ICHIKAWA & YAO has been identified in samples assigned by MURCHEY (1984) to the MH-3 assemblage. Other forms like *Unuma* sp. A and *Unuma* sp. B, and several forms of *Hsuum* sp. common in MH-4 and in zone A0 allow further comparison.

The limit between MH-3 and MH-4 is not yet clearly defined: It has to be placed at the limit between A0 and A1, or alternatively within A0, between U.A. 0 and U.A. 1. In Tethyan sections *Ristola turpicula* PESSAGNO & WHALEN co-occurs with *Unuma echinatus* (Sierra de Ricote, Figure 5) and has its base therefore at least in U.A. 1. This would put the base of MH-4 in U.A. 1, since *R. turpicula* is one of the defining species of this assemblage. In the Franciscan, however, the range of *Unuma echinatus* is difficult to establish because it is a very rare form. Recent reexaminations of Murcheys Marin Headland samples (BAUMGARTNER & MURCHEY in prep.) assigned to assemblage MH-3 reveal several species which have their base in U.A.1 like *Higumastra imbricata*, *Praeconocaryomma* (?) *hexacubica* BAUMGARTNER and *Parvicingula dhime-naensis* BAUMGARTNER. The presence of these species is a clear indication that at least the uppermost part of MH-3 may be correlative with U.A. 1, i.e. the Upper part of zone A0.

MH-4 is defined by the presence of *Ristola turpicula* and *Tricolocapsa* sp. C, in co-occurrence with a number of forms ranging up from MH-3. The range of *R. turpicula* is so far poorly known in Tethyan sections, because it seems to be a very rare form which was not included in present zonation (BAUMGARTNER 1984b). Nevertheless it may be an excellent species for the correlation to the North American zonations and a reexamination of Tethyan sections may eventually establish its total range in that area. So far this species is known from U.A. 1 and U.A. 2, i.e. from the top of zone A0 and the base of zone A1. Fortunately, the MH-4 samples from Marin Headlands, the Geysers Chert and the Muir Woods block (Fig. 7) are amongst the best preserved Franciscan samples and allow a very good correlation of the MH-4 assemblage to the Tethyan zones: The following species have been found co-occurring with *R. turpicula* in various Franciscan localities (U.A. range in parenthesis): *Eucyrtid.* gen. et sp. indet. (BAUMGARTNER 1984b, U.A. 0–3), *Mirifusus fragilis* BAUMGARTNER (U.A. 0–5), *Emiluvia premyogii* BAUMGARTNER (U.A. 0–8), *Praeconocaryomma* (?) *hexacubica* (U.A. 1–7), *Paranoella kotura* BAUMGARTNER (U.A. 4–9), *Triactoma cornuta* BAUMGARTNER (U.A. 4–9), *Ristola procera* (PESSAGNO) (U.A. 5–8). It can therefore be established that the top of *R. turpicula* in Californian sections must be at least in U.A. 5. Hence, MH-4 is correlative at least with zone A1 (U.A. 2–4) and part of zone A2 (U.A. 5 and possibly 6?).

MH-5 is defined, amongst others by the concurrent range of *Acanthocircus dicranacanthos* (SQUINABOL) (U.A. 9–14), *Mirifusus mediodilatatus* (RÜST) = *Mirifusus mediodilatatus minor* BAUMGARTNER (U.A. 10–14), *Archaeodictyomitra apiaria* (RÜST) = *Archaeodictyomitra excellens* (TAN SIN HOK) (U.A. 11–14), *Pseudodictyomitra* sp. A. = *Pseudodictyomitra depressa* BAUMGARTNER (U.A. 11–14) and *Cecrops septemporatus* (PARONA) (U.A. 14). The presence of *Cecrops septemporatus* would restrict MH-5 to zone

E2, but this species is not present in all samples. It is therefore possible that some samples assigned to MH-5 may be correlative with zones D and E1.

These correlations allow us to be more specific about the age assignment of the Californian assemblages MH-3-5: MH-3 covers at least part of the Bajocian and tops in the middle or late Bathonian. MH-4 is of middle to late Bathonian to late Callovian (early Oxfordian?) age. MH-5 may be late early Valanginian to Hauterivian–Barremian in age, but it cannot be excluded that in places the lowest samples assigned to MH-5 are in fact older – perhaps as old as Berriasian.

An important stratigraphic gap discovered by MURCHEY (1984) in many Franciscan Central Belt terranes can thus be confirmed as covering at least the entire Late Jurassic but more probably also part of or the entire Neocomian.

This gap does not exist on top of the Coast Range Ophiolite nor in the Yolla Bolly belt (Fig. 7, BAUMGARTNER & MURCHEY 1987), where all zones A0 to C2 can be recognized. Consequences of these observations will be discussed in forthcoming papers.

#### 2.4.3. Comparison to the Jurassic zonation by PESSAGNO et al. (1984, 1987a, b)

##### General remarks

PESSAGNO et al. (1984) redefined zones 1 to 4 of the PESSAGNO (1977a) zonation of the North American Late Jurassic. In PESSAGNO et al. (1987b) “formal” definitions of radiolarian zones for the entire Jurassic of North America are established. Zonal Units are defined on the basis of first or final appearances of “primary marker taxa” and “supplementary marker taxa”.

The characteristics of the zonation proposed by PESSAGNO et al. (1987b) are such that the obstacles mentioned in the introduction to this chapter (2.4.1.) make a correlation to the Tethyan zonation extremely difficult:

1. *Faunal Provinciality.* – The zonation is composed of parts which are established in different areas, belonging to different faunal provinces:

The Upper Pliensbachian to lower Callovian part of the zonation is mainly based on samples from the Mesozoic Clastic Terrane, Blue Mountains Province, east-central Oregon. This terrane is believed by PESSAGNO & BLOME (1986) and by PESSAGNO et al. (1987b) to have moved northwards during the early and middle Jurassic from the Tethyan to the southern Boreal realm.

The upper Kimmeridgian to upper Tithonian part of the zonation makes reference to observations in east-central Mexico (see PESSAGNO et al. 1987a) and in the volcano-pelagic sequence overlying the Coast Range Ophiolite (Great Valley Supergroup, see PESSAGNO et al. 1984).

The upper Callovian to lower Kimmeridgian interval remains unzoned and no data is given as to the superposition of Superzone 1 and zones 2–4 in one section.

2. *Preservation.* – For this discussion which focuses on the problems in the Middle and Late Jurassic part of the zonation, it is important to note that Zones 1B through 1G (Bajocian–lower Callovian, Fig. 7) of PESSAGNO et al. (1987b) have been found superposed in east-central Oregon only. The absence of certain taxa like *Mirifusus* sp. PESSAGNO in that area may be controlled by local paleoenvironmental and preservational factors, reflected by the organic-rich mudstone facies so much unlike other North American and European radiolarian-bearing facies. Unless there is control from other sections

of different lithofacies, located in other faunal realms, the conclusion that *Mirifusus* sp. is generally absent from the Middle Jurassic is not warranted. In addition it should be noted that the superpositional control of the spot samples collected by Pessagno and his colleagues is entirely dependent on the ammonite biostratigraphy. From this area, no physical section with the relative position of samples has been published by the authors.

3. *Biostratigraphic concept.* – Since Unitary Associations and the resulting zones have the practical character of concurrent range zones, they are not directly comparable with interval zones (superzone 1 and zones 2, 2alpha, 2beta, 3alpha and 4alpha of PESSAGNO et al. 1987b). The correlation attempted in the following is based on concurrent ranges of species which are used in both zonations.

#### Correlation of zones and discussion of their chronostratigraphic assignments

*Zone 4.* – The top is defined by the final appearance of *Ristola altissima* (RÜST) and *R. procera* (PESSAGNO). It can be correlated with the top of U.A. 10, zone C2 of the present zonation, although this is also the top for *Eucyritidiellum ptyctum* (RIEDEL & SANFILIPPO) and *Perispyridium ordinarium* (PESSAGNO) which are said to terminate below the top of zone 4. An equation of the top of zone 4 with the top of zone C2 would be in agreement with the correlation of the base of next higher zones: The base of zone 5 of PESSAGNO (1977b), which is defined by the first occurrence of *Obesacapsula rotunda* (HINDE), correlates with the base of U.A. 11, zone D.

The base of zone 4 is defined by the first appearance of *Valupus hopsoni* PESSAGNO & BLOME and *Acanthocircus dicranacanthos* (SQUINABOL). The former species occurs in one of our samples (POB 986, loc. 8, Theokafta, Argolis Peninsula, Greece) assigned to U. A. 9, zone C1 of the present zonation. *A. dicranacanthos* has its first appearance also within U. A. 9, but it generally does not occur at the very base of zone C1. Hence, zone 4 can approximately be correlated with the upper part of zone C1 and C2.

*Discussion of chronostratigraphic assignments.* – PESSAGNO et al. (1987a) made reference to BAUMGARTNER et al. 1980 for the base of zone 5/zone D, and PESSAGNO et al. (1987b) arbitrarily correlated the top of zone 4 with the top of the Tithonian. We have presented new data in this paper (p. 844) that indicate the lowest zone D samples clearly below the calpionellid zone A/B boundary and therefore clearly within the late Tithonian. It is possible that the C2/D boundary comes to lie close to or even below the base of calpionellid zone A (i.e. the first occurrence of Calpionellidae with fully hyaline wall). Obviously, this is in conflict with the correlation by PESSAGNO et al. (1987a, b): Based on data from east-central Mexico, they equate the base of zone 4 (defined by the first occurrence of *A. dicranacanthos*) with the first occurrence of *Crassicollaria intermedia*. As noted already by KOCHER 1981, the first occurrences of *A. dicranacanthos* are irregular in Tethyan sections. It is possible that the local first occurrences are not representative for the maximum range. It is therefore likely that the first appearance of this species is in one place as early as Kimmeridgian and in other places as late as late Tithonian. Unitary Associations always show the maximum range.

*Zone 3.* – Whereas the top of zone 3 (and subzone 3beta) cannot be recognized in our zonation, the top of zone 3alpha, defined by the last appearance of *Mirifusus guadalupensis* (PESSAGNO), corresponds to the top of zone B (U. A. 8).

*Discussion of chronostratigraphic assignments.* – PESSAGNO et al. (1987b) assign a Tithonian age to the top and a late Kimmeridgian or early Tithonian age to the base of zone 3 (based exclusively on data from east-central Mexico). We have presented new data in this paper (p. 843) that suggest the top of zone B to lie close to the Oxfordian/Kimmeridgian boundary in the Subbetic realm. The resolution of these discrepancies is seriously hampered in that, except for pantanelliids and *Napora* sp. PESSAGNO, no radiolarian occurrence data have been published by PESSAGNO et al. (1984, 1986, 1987a, b) of their samples from east-central Mexico. It is presently impossible to compare the Mexican assemblages that led to these age assignments with their Mediterranean analogues. Like their reports on Oregon, none of the cited papers presents an illustration of a stratigraphic column that would show the physical superposition of samples. The reader is faced with complicated descriptions that relate radiolarian spot samples to ammonite localities.

*Zone 2.* – The top of zone 2 is difficult to recognize in our zonation. The base of Zone 2 is defined by the first appearance of *Mirifusus* PESSAGNO and thus has to be placed at the base or below Zone A0 of the present zonation, since our data show occurrences of *Mirifusus* throughout zones A0 to C2. The different conclusions about the first appearance of *Mirifusus* are the main obstacle to the correlation of the two zonations. This topic will be discussed in a separate paragraph below.

*Superzone 1.* – The top of Superzone 1 is defined as immediately below the first occurrence of *Mirifusus*. It should therefore be placed at or below the base of or Zone A0.

*Discussion.* – PESSAGNO et al. (1987b) did not subdivide the uppermost part of their superzone 1 (late Callovian–Oxfordian–early-Kimmeridgian?). However, they mention that the radiolarian assemblage from this interval contains, amongst others, *Acanthocircus variabilis* (SQUINABOL), *Bernoullius* sp. aff. *B. dicera* BAUMGARTNER (straight spined form), *Hsuum maxwelli* PESSAGNO, *Eucyrtidiellum ptyctum* (RIEDEL & SANFILIPPO) and *Ristola turpicula* PESSAGNO & WAHLEN. This assemblage, especially the co-occurrence of *Eucyrtidiellum ptyctum* with *Ristola turpicula* is characteristic of Unitary Associations 4–5, which we correlate with a Callovian–early Oxfordian age. Hence, there is an approximate agreement on the age assignment of these assemblages, if we ignore the presence/absence of *Mirifusus* sp. Upper superzone 1 assemblages are said to occur (PESSAGNO et al. 1987b, p. 7) in the lowermost strata (Galice Formation, HARPER 1983) above the Josephine Ophiolite in northwestern California. SALEEBY et al. (1982) obtained from plagiogranites within the Josephine Ophiolite an U/Pb age of  $157 \pm 2$  my, and from a keratophyre sill within the Galice an age of  $150 \pm 2$  my. This interval corresponds to the Callovian–early Oxfordian in the timescale by HAQ et al. 1987, which is in agreement with our age assignment.

#### Comments on the first appearance of *Mirifusus* PESSAGNO

PESSAGNO et al. (1984) attempted to show that the biostratigraphic data presented by BAUMGARTNER et al. (1980) were not sufficient to prove the occurrence of *Mirifusus* sp. in strata older than Kimmeridgian. For both the Cape Verde Basin (DSDP Site 367) and some sections of the Jasper Beds of the Romanian Carpathians a Kimmeridgian age of the *Mirifusus*-occurrences recorded by BAUMGARTNER et al. (1980) was in fact not ex-



cluded. It is difficult in Tethyan radiolarites to document an age older than Kimmeridgian by ammonites because of a general lack of aragonitic fossils in these facies.

However, all the biostratigraphic information presented by PESSAGNO et al. (1984, p. 13–18) serves no other purpose than to confirm a Kimmeridgian age of North American and European *Mirifusus*-occurrences, but does not help to establish its base. The work by PESSAGNO and his collaborators (1977–1987) contains no sequential sample data whatsoever that would establish the consistent presence/absence of *Mirifusus* in strata older than Kimmeridgian: In the Californian sections, PESSAGNO et al. (1984, p. 12) admit that the absence of *Mirifusus* in the lowermost samples at Point Sal and in Alamo Creek “may be controlled diagenetically”.

When carefully reading the descriptions of their sample localities of the Taman Formation in east-central Mexico (PESSAGNO et al. 1984, p. 14), one finds that the absence of *Mirifusus* in one sample (MX-82-3) is taken as evidence to place the base of *Mirifusus* in the upper lower Kimmeridgian.

In PESSAGNO (1987a, fig. 10) two more samples (MX-84-48, MX-82-6) are assigned to superzone 1 apparently because the lack *Mirifusus*. However, the order in which these samples are presented in Figure 10, has no relationship to their geographic location as described in the locality descriptions (ibid. p. 32). Since no structural data are given, one is left with the doubt that the arrangement of the samples was based on their radiolarian content and does not represent a stratigraphic section. [Example: MX-82-8 contains *Mirifusus mediodilatatus* (ibid. p. 32). Both the samples MX-82-6/MX-82-3, located about 50 m west of MX-82-8 and MX-84-48 situated 200 m east of MX-82-8 do not contain *Mirifusus* and are therefore classified as superzone 1 and grouped to the left in Figure 10]. Unless PESSAGNO and his colleagues publish measured, physical sections in which the stratigraphic superposition of samples is indicated, we have serious doubts about the biostratigraphic relevance of their data.

In addition PESSAGNO et al. (1986, 1987b) presented geochronometric arguments for a Kimmeridgian age of the zone 1/2 boundary: It is said to be younger than  $157 \pm 2$  my but older than  $150 \pm 2$  my (see above p. 851). Considering the choice of recent geochronologic timescale propositions this range may represent: the Callovian (ODIN et al. 1982), the Callovian and earliest Oxfordian (HAQ et al. 1987), the Oxfordian to earliest Kimmeridgian (HARLAND et al. 1983) or the Oxfordian to earliest Tithonian (KENT & GRADSTEIN 1985, DNAG 1983). PESSAGNO et al. (1987b, p. 7) favor HARLAND et al. (1983), we favor HAQ et al. (1987), for reasons exposed above.

There is now sufficient published data to show that *Mirifusus guadalupensis* PESSAGNO ranges down to the base of the Callovian and that *Mirifusus fragilis* BAUMGARTNER makes its first appearance further down in the Middle Jurassic (Bathonian–Bajocian?):

### 1. Evidence based on radiolarian co-occurrences

*Mirifusus guadalupensis* PESSAGNO has been found to co-occur with *Ristola turpicula* in Costa Rica (loc. 41 of BAUMGARTNER et al. 1984b, U. A. 3–5) and with *Bernoullius* sp. aff. *B. dicera* (straight spined form = *Bernoullius* sp. B, GORICAN, in press) at Site 534A, Core 125 (U. A. 4), and in the Traversiera Massive (DE WEVER et al. 1987, Pl. 1, table, U. A. 4–5). These two latter species are considered typical for upper superzone 1 by

PESSAGNO et al. (1987b, p. 8, see above). By us, the cited samples are assigned to zones A1 or A2 (U. A. 3 to 5) indicating a late Bathonian to early Oxfordian age.

*Mirifusus fragilis* BAUMGARTNER co-occurs with *Unuma echinatus* ICHIKAWA & YAO, *Trillus* spp. PESSAGNO & BLOME and *Zartus* spp. PESSAGNO & BLOME in Japan (YAO et al., 1982; YAO 1983; KIDO et al., 1982; AITA 1982; BAUMGARTNER 1984b In 7), Greece, Northern Italy, Umbria (BAUMGARTNER 1984b), Calabria (DE WEVER & MICONNET 1986) and in California (Marine Headlands: MURCHEY 1984, and many other localities, BAUMGARTNER & MURCHEY, work in progress). These assemblages are currently being studied (DE WEVER & BAUMGARTNER, in prep.) and are believed to be no younger than Bathonian in age (Zone A0).

## 2. Evidence based on co-occurrences with other fossil groups

In the Blake-Bahama Basin (DSDP Site 534) *Mirifusus fragilis* occurs in samples from Core 126 to Core 122, and *Mirifusus guadalupensis* occurs from Core 125 to Core 120. Samples from these cores are dated by dinoflagellates and nannofossils as middle and late Callovian to earliest Oxfordian (SHERIDAN, GRADSTEIN et al., 1983; BAUMGARTNER 1984 loc. 30). In the Sierra de Ricote (Figs. 4, 5, p. 841) *Mirifusus guadalupensis* is found immediately above beds containing lower and middle Callovian ammonites and *M. fragilis* is found at least 80 m below beds containing Bathonian ammonites.

In summary, it appears that in European, Japanese and some Californian sections *Mirifusus* ranges down to the upper Middle Jurassic.

## Conclusions

It is unfortunate that Pessagnos zone 1/2 boundary is defined by the first appearance of *Mirifusus*. Disregarding the *Mirifusus* problem, there is a general agreement between upper superzone 1 of PESSAGNO et al. (1987b) and zones A0 to A2 of BAUMGARTNER (1984b) (see Fig. 7). *Ristola turpicula*, for instance, defining by its first appearance the base of zone 1F and ranging to the top of superzone 1 (PESSAGNO et al. 1987b), has been found to range from U. A. 1 (zone A0) to U. A. 5 (zone A2, see p. 848). However, *R. turpicula* and other species considered characteristic of upper superzone 1 by PESSAGNO et al. (1987b) have also been found co-occurring with *Mirifusus guadalupensis* and *M. fragilis*. The first appearance of the latter species is, in fact, found below the one of *R. turpicula*.

The base of zone 2 of PESSAGNO et al. (1987b), as presently defined by the first appearance of *Mirifusus* has to be placed at the base or below zone A0, or, in the Bajocian–Bathonian. This results in an important overlap of the top of superzone 1 and zone 2 (Fig. 7). We do not doubt, that the samples used in their reports to redefine Zone 2 are of late Kimmeridgian age. However, there are other samples containing *Mirifusus* that may be of Bathonian to Oxfordian age and have not been recognized as such. A reevaluation of these samples in view of the Tethyan Middle–Late Jurassic experience urges, since many interpretations of the geology of western North America depend on radiolarian ages based so far on a Kimmeridgian first appearance of *Mirifusus*.

Correlation of the PESSAGNO and the BAUMGARTNER zonations is possible, if the succession of assemblages, rather than the occurrence of single marker species is dis-

cussed. This will only be possible if PESSAGNO and his collaborators start to publish their stratigraphic raw data, including physical superposition of samples and complete faunal lists, which led to their interpretations.

### 3. New aspects of the genesis of Tethyan Jurassic Radiolarites

#### 3.1. Introduction

Recent advances in radiolarian biostratigraphy have allowed an increase of precision in dating the radiolarite formations throughout Western Tethys, both on ancient continental margins and on the ophiolites which presumably formed a rather small oceanic seafloor during the Late Jurassic. When we first attempted to date the radiolarite formations of Lombardy, the Pindos and some other localities (BAUMGARTNER et al. 1980) we had very little ammonite biostratigraphic data, especially for the base of the radiolarites, that would have allowed a correlation of radiolarian zones to the stages. Based on a preliminary database including 30 species we obtained a Zone A that typically covered an important part of the radiolarites s. str. Although we could discern faunal differences within this zone (Unitary Associations 1–3) we ignored their biostratigraphic importance. We recognized for instance that the basal Green Radiolarites of the Lombardy Basin yielded radiolarians assignable to U.A. 1 whereas the basal Angelokastron Chert, deposited on an ancient plateau, contained radiolarians that were assigned to U.A. 3. We ignored, however, whether this result was of biochronologic significance and whether it could be generalized.

Speculations existed about the age of the base of Tethyan radiolarites. Most geologists believed that they would probably start in the Upper Callovian or Oxfordian, based on the youngest fossils found beneath them, typically in Ammonitico Rosso facies on submarine highs. KÄHLIN et al. (1979) presented biostratigraphic data on aptychi from a section in Tuscany which suggested a latest Callovian onset of radiolarite deposition at that locality.

The study of very well preserved radiolarians at DSDP-Site 534 in the Blake Bahama Basin (Central Atlantic) was decisive in the approach towards a better resolution of the Callovian–Oxfordian. This time interval, corresponding in western Tethys to the basal Green Radiolarites, known for a rather moderate radiolarian preservation, is at Site 534 represented by a sequence of over 15 cores of mainly claystones yielding superbly preserved pyritized radiolarians. Many species could be accurately described and subsequently also recognized in poorer preserved Tethyan material. This better resolution has permitted a detailed biostratigraphic correlation of coeval sedimentary sequences in Atlantic and Tethys.

The correlation between Atlantic and Western Tethyan basinal sediments reveals a much more siliceous facies evolution in Tethys: No equivalent of the Tethyan radiolarites has been drilled in the Atlantic. Within Tethys, it becomes clear that a good part of the basinal radiolarites is older than the first beds on ancient plateaus (see BAUMGARTNER 1983, Fig. 1). The data presented in BAUMGARTNER (1984b) document a systematic diachronism of the basal onset of radiolarites on Tethyan continental margins, spanning at least the Bajocian–Bathonian to Oxfordian (Fig. 8). Recent studies in Triassic troughs oriented towards eastern Tethys (Lagonegro, southern Pindos, Antalya ?, Oman, Fig. 8)

suggest that the radiolarite facies is still longer ranging and may encompass the Late Triassic, the entire Jurassic and early Cretaceous (see chapter 3.2.2.).

The occurrences of Jurassic radiolarites in Tethys and elsewhere have two aspects which have to be treated separately in the light of the new data:

1. *The regional (basin-wide) occurrence of radiolarites* must be controlled by physical paleoceanographic parameters which in turn control radiolarian productivity. The proposed models (JENKYN & WINTERER 1982; HEIN & KARL 1983) involve narrow, marginal ocean basins (like the Gulf of California) or ocean margins in which a vigorous circulation causes upwelling, making deep water nutrients available to surface dwelling radiolarians and therefore provoking high radiolarian productivity. These models must be reevaluated under the aspect of ecologic data on recent radiolarians and on the basis of the Atlantic–Tethys correlation (see chapter 3.2.).

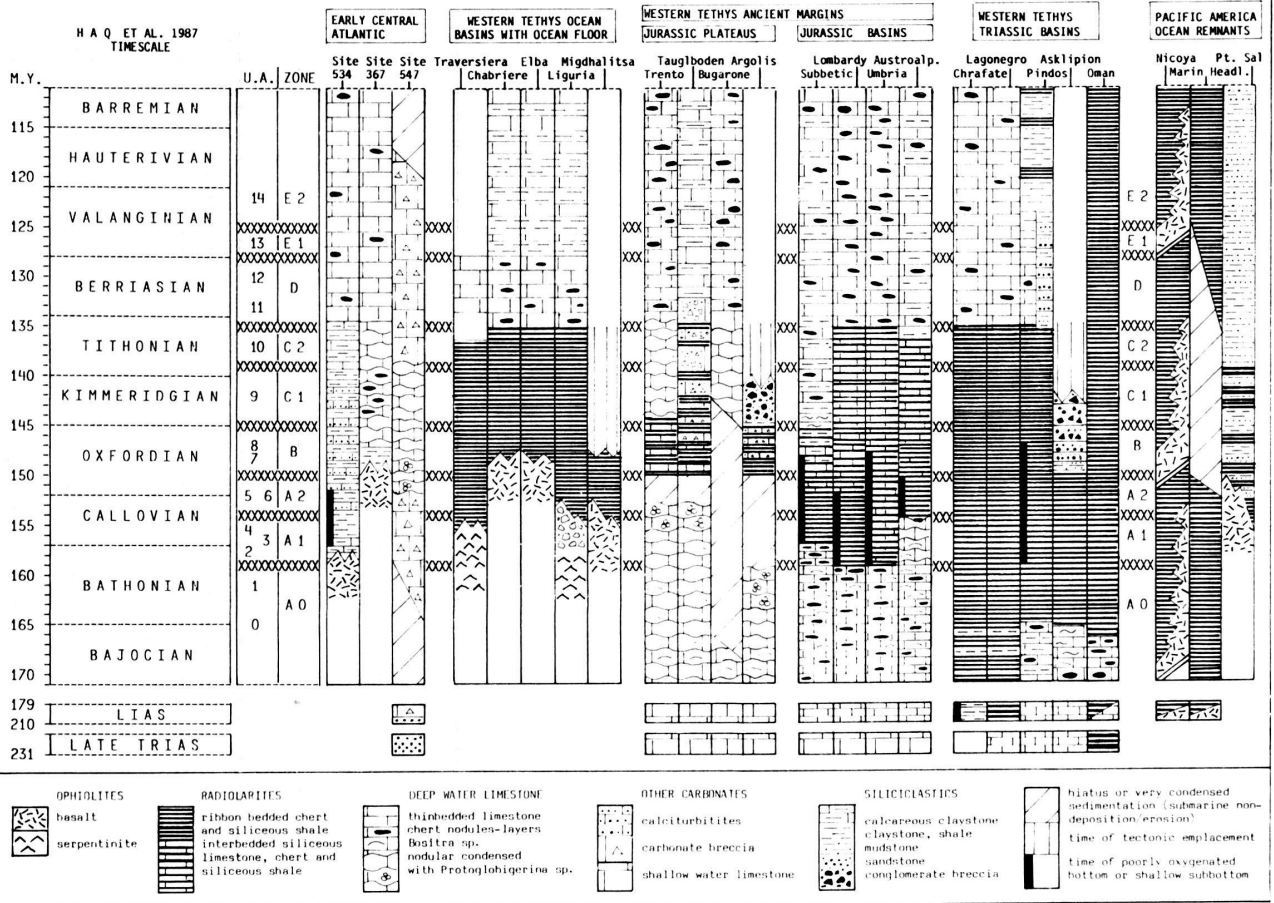
2. *The local (intrabasinal) facies distribution* of calcareous vs. siliceous sediments cannot be explained by regional paleoceanographic concepts alone. The sharply defined, relatively shallow calcite and aragonite compensation depths as proposed by BOSELLINI & WINTERER (1975) may account for the observed vertical facies successions from an actualistic point of view. However, detailed age control reveals a small scale facies pattern of coeval chert and pelagic limestone which imply mechanisms other than just carbonate dissolution at depth. General productivity and local dispersal of calcareous and siliceous pelagic sediment at any time as well as diagenetic processes must be considered to reasonably explain the small scale picture (see chapter 3.3.).

### 3.2 Lithology and spatiotemporal distribution of Radiolarites and coeval pelagic sediments in Tethys and Atlantic

#### 3.2.1. *Jurassic of the Atlantic compared to the Jurassic of western Tethyan basins*

Jurassic sedimentary rocks were recovered by the Deep Sea Drilling Project at a number of Sites: Site 99, 100, 105 (HOLLISTER, EWING et al. 1972), Site 391 (BENSON, SHERIDAN et al. 1978) and Site 534 (SHERIDAN, GRADSTEIN et al. 1984) are located in the North American Basin. Site 367 (LANCELOT, SEIBOLD et al. 1978), Site 416 (LANCELOT, WINTERER et al. 1980) and Sites 544, 545 and 547 (HINZ, WINTERER et al. 1984) are located in the eastern Central North Atlantic. Of these, Site 416 recovered predominantly clastic and calciturbiditic sediments representing a lowermost continental rise depositional environment. Sites 544 and 545 recovered relatively shallow seamount (544) and shallow carbonate platform sediments (545). These Sites are therefore not examined here. Of the remaining Sites, only 534, 367 and 547 have been studied for radiolarians, with 547 being completely devoid of determinable specimens (HINZ, WINTERER et al. 1984, Site report p. 249). The faunal correlations are thus based on one Site (534) in the western and one Site (367) in the eastern Central Atlantic. Complete data were presented in BAUMGARTNER (1984).

The similarity of Central Atlantic and Western Tethyan sedimentary facies has been stressed in several classical papers by BERNOULLI (1972), BERNOULLI & JENKYN (1974), BOURBON (1978), which mainly considered the post-Oxfordian carbonate-rich sediments in both areas. BERNOULLI & KÄLIN (1984) extended this comparison to the Liassic and Middle Jurassic deep water limestones drilled at Site 547 off the Mazagan escarpment



(NW African margin). The inferred Jurassic position of this Site along an unstable faulted slope compares well with similar situations along western Tethyan ancient margins. The condensed sequence at this site is, however, not a suitable record of the late Middle and Late Jurassic *basinal* facies evolution of the Atlantic.

While the Eastern Atlantic, more calcareous facies of the Oxfordian-Kimmeridgian compare somehow to limestones deposited on foundered Tethyan plateaus, the pre-Ti-tonian sediments of the western Atlantic basin have little in common with the radiolarite facies in Tethyan basins. We will examine first the Callovian of Site 534 and compare it to the coeval Tethyan sedimentation, and then do the same with the Oxfordian-Kimmeridgian sediments recovered at various sites. Description of facies from Site 534 is mainly based on OGG et al. 1983. For all radiolarian data used here and for detailed illustration of the discussed sections see BAUMGARTNER (1984 b).

### Callovian of Site 534 compared to Tethyan basal Green Radiolarites

Only at Site 534 pre-Oxfordian basinal sediments have been cored in the Atlantic. Cores 127 to 120 of Hole 534B recovered dark green to black claystones with thin layers of radiolarian sand, interbedded with lightcolored pelmicritic lime-turbidites rich in radiolarians (OGG et al. 1983). The radiolarians of this interval are assigned to Unitary Associations 2–5, or zones A1–A2 (Callovian and earliest Oxfordian). Coeval sediments in many Tethyan basins include the basal Green Radiolarites, a ribbon-bedded sequence of 5–8 cm thick chert beds with mm to cm thick siliceous shale interbeds. This formation is almost lime-free in old basins which, at this time were relatively deep like most Triassic troughs as Lagonegro and Pindos, but also the Lombardy and some Austroalpine basins, to slightly calcareous in less deep basins like Umbrian and Subbetic realms (Fig. 8).

The microfacies of claystones of Cores 127–120 of Hole 534B (OGG et al. 1983) shows an upwards declining abundance of nannofossils (from 20 to 0%), some terrigenous silt, about 1–2.8% organic carbon in plant debris and clay-sized organic material and radiolarians as the only microfossils. Radiolarians generally comprise less than 5% of the total volume of sediment, they are all replaced by pyrite. In the radiolarian sand layers and in calciturbidites radiolarians are generally replaced and filled by silica. Radiolarians may comprise up to 40% of the sand layers, attributed by OGG et al. (1983) to periodical winnowing on the sea floor. On the whole, radiolarians represent certainly less than 5%

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Fig. 8. Chronostratigraphic correlation of Central Atlantic and Western Tethyan sequences principally based on radiolarian dating. Note the Bajocian-Bathonian (or earlier) onset of radiolarite deposition in basins existing since the Triassic, late Bathonian-early Callovian onset in basins individualized since the early Liassic and Oxfordian onset on seamounts and plateaus. Note also a minimum late Middle Jurassic age for oceanic crust in Greece (Migdhallitsa, Argolis Peninsula, Pelagonian s. l.), Liguria and Western Alps and Late Jurassic nappe emplacement in Eastern Greece (Pelagonian s. l.). Apart from radiolarian data and own field observations the following sources were consulted for lithology and age information: Site 534: SHERIDAN, GRADSTEIN et al. (1983). Site 367: LANCELOT, SEIBOLD et al. (1978). Site 547: HINZ, WINTERER et al. (1984). Traversiera, Cottian Alps, Italy: DEWEVER et al. (1987). Chabrière, Western Alps (Schistes lustrés): DEWEVER & CABY (1981). Argolis Peninsula (Migdhallitsa, Ophiolite, Askliopion Nappe and Basal Sequence): BAUMGARTNER 1985. Trento Plateau: STURANI 1964, FOGELGESANG 1975. Bugarone, Monte Nerone, Umbria: CECCA et al. 1987. Subbetic: SEYFRIED 1978. Chrafate, Rif, Morocco: DEWEVER et al. 1985b. Lagonegro: DEWEVER & MICONNET (1986). Pindos: FLEURY (1974, 1975), DEWEVER & THIEBAULT (1981). Oman: BERNOULLI & WEISSERT (1987). For further explanation see text. "XXXX" represent zones of uncertainty.

of the sediment volume, compared to up to 80% in some chert beds and an estimated average of 40–50% for coeval (zone A) Tethyan chert sections.

In order to compare radiolarian productivity and/or preservation between the Jurassic Atlantic and Tethys, estimates of dilution by detrital sediment and the amount of redeposition are necessary. Redeposition of radiolarians, both by turbidity currents and by winnowing due to bottom currents have been invoked to explain radiolarian sand layers both in the Atlantic (MCCAVE 1979; OGG et al. 1983) and Tethys (NISBET & PRICE 1974; FOLK & MCBRIDE 1978; MCBRIDE & FOLK 1979; KÄHLIN et al. 1979; BARRETT 1982). In the Callovian Interval at Site 534, these layers form less than 10%, compared to 40–80% in coeval Tethyan sections.

Based on radiolarian biostratigraphy, average accumulation rates in cores 126–92 are only 4 to 6 times higher than in coeval Tethyan radiolarite sections (BAUMGARTNER 1983). Taking into account that for some cores lime-turbidites constitute nearly half of the sediment volume, sedimentation rates of the interturbidite claystones may perhaps be twice as high as those of radiolarites, but certainly less than 4 times as high. Thus, even if we account for a dilution of 0.5 to 0.25, the resulting accumulation/preservation rate of pure radiolarians in the Atlantic is at best half, but more probably some 10–25% of that in Tethys.

Silica-contents (expressed as SiO<sub>2</sub> of bulk rock, i.e. including SiO<sub>2</sub> of clays) show the same situation: radiolarian-bearing claystones from Cores 127–123 gave SiO<sub>2</sub>-values between 43 and 65% (OGG et al. 1983) whereas a variety of Tethyan radiolarites have values between 85 and 100%, with a maximum between 90 and 95% SiO<sub>2</sub> (STEINBERG et al. 1977). It is not conceivable that diagenetic processes alone are responsible for these differences, unless one would assume that large amounts of silica have passed from the sediment column into the water. It seems more likely that radiolarian productivity and/or preburial preservation was significantly higher in Tethys than it was in the Atlantic.

#### Oxfordian–Tithonian Cat Gap Formation compared to Tethyan Radiolarite and Rosso ad Aptychi

*Western Atlantic Cat Gap Formation.*— Reddish brown and greenish gray marls and marly limestones recovered from Sites 99, 100, 105 and 391 in the North American Basin were described as the Cat Gap Formation by LANCELOT et al. (1972) and JANSÁ et al. (1979). The type section at Site 105 shows upwards increasing carbonate content from a lower calcareous claystone to marl into marly limestone above. Similar trends were observed at Sites 391 and 534.

At Site 534, Cores 119–111 (zone A2, probably late Callovian to early Oxfordian in age), the basal reddish greenish and black claystones are virtually devoid of any microfossils, have very low (10–15%) carbonate contents, relatively high organic carbon contents (0.2–3.9%) and have estimated sedimentation rates as low as 2–3 m/my. OGG et al. (1983) suggested a deposition close to the CCD in a low fertility zone, with an increased preburial dissolution rate to explain the absence of radiolarians.

In the following Cores 110–104 (zone B ?–C1, late Oxfordian–Kimmeridgian) the greenish-gray marls (averaging 30% CaCO<sub>3</sub>) are rich in fine pelagic bivalve shells (probably *Bositra* sp.) and in some layers calcified radiolarians are abundant. The presence of rare aragonite, fine pelagic bivalve shells and an increase in Carbonate content suggest that

CCD and ACD were dropping during the deposition of this unit. OGG et al. suggested a late Oxfordian CCD depth of 3300 m and a Kimmeridgian ACD depth of 3300 m.

Red marls characterize the upper part of the Cat Gap Formation at Site 534, Cores 103–92 (zone C1 ?–C2 ?, Kimmeridgian–Tithonian). A transition to white nannofossil limestones of the Blake Bahama Formation marks the top (in Core 92). Carbonate contents is steadily increasing upwards from 15–20% up to 50–70% in Core 93 to 92. Aragonite was identified in Cores 100 and 95. Microfossils include common calcified radiolarians and *Saccocoma*. The transition to the white nannofossil limestone is due to a steady increase of the lime/clay ratio through Cores 94–92, mainly owing to more and more abundant nannofossils, and the color change may be attributed to a decrease of total Fe from about 5% to 1% in the white limestones (MURDMAA et al. 1978).

*Eastern Atlantic.* – Two Sites in the Eastern Atlantic show similar Late Jurassic lithofacies but are distinctly more calcareous. At Site 367 (LANCELOT, SEIBOLD et al. 1978) in the Cap Verde Basin, 55.5 m of reddish brown partly nodular marly limestones were recovered. They are in the lower part interbedded with greenish gray claystone. Three distinct microfossil facies were recognized (JANSA et al. 1978): A radiolarian microfacies with abundant radiolarian molds filled with calcedony and calcite (Cores 37 and 38-1, zone B: middle–late Oxfordian), a “filament” microfacies with abundant parallel oriented pelagic bivalves (Cores 36 and 35-3, zone B, or base zone C1, late Oxfordian, or part of Kimmeridgian), and a *Saccocoma* facies, also rich in aptychi (Cores 35-2 to 32-5, zone C1, Kimmeridgian–early Tithonian). A sharp boundary marks the upper contact of the reddish brown marly limestone lithofacies with the light gray nannofossil limestone facies above. A zone C2 assemblage indicating a middle to late Tithonian age was determined in the basal beds of the nannofossil limestones in Core 32-4.

At Site 547 (HINZ, WINTERER et al. 1984), off the Mazagan Escarpment, off NW-Africa, the Jurassic sediments are dominantly limestone slope breccias. A few cores show, however, condensed pelagic limestone facies in which rare nannofossils and benthic foraminifers provided some biostratigraphic control. In Core 11B, 50 cm of green and red micrite near the base contain Pliensbachian nannofossils and benthic foraminifers. At the base of Core 10, some 2 m of reddish brown and greenish gray nodular limestone contain a Bajocian to Callovian assemblage of benthic foraminifers and some calcified radiolarians. These nodular limestones of Ammonitico Rosso type contain also abundant fragments of thin shelled “pelagic” bivalves (BERNOULLI & KÄLIN 1984). Core 9B recovered limestone breccias and Core 8B and the base of Core 7B contain reddish and greenish nodular limestones with abundant *Bositra?*, some *Protoglobigerina* and Oxfordian benthics. Rare traces of calcified radiolarians were found. In the upper part of Core 7B a *Lamellaptychus* and common *Saccocoma* make a Kimmeridgian age probable. In Core 6 there is only one more m of nodular limestone before calpionellids indicate a late Tithonian–Berriasian age starting in section 3. The entire late Jurassic is represented by less than 20 m of cored interval in which more than half of the recovered rocks are limestone breccias. This sequence compares well to some condensed sections on ancient submarine swells in the Southern Alps and Tuscany (see BERNOULLI et al. 1979; KÄLIN et al. 1979).

*Western Tethys.*– The Western Tethyan basinal sediments deposited during the Oxfordian–Tithonian interval are much more siliceous than those of the Atlantic. A number of different facies successions can be distinguished (Fig. 8):



1. Lime-free, siliceous mudstones and radiolarian cherts are usually the first sediment deposited on newly formed oceanic crust in the Ligurian–Piemont oceanic zone (FOLK & MCBRIDE 1978; BARRETT 1982) as well as in the southernmost Vardar ocean, represented by the Ophiolites of Eastern Greece (BAUMGARTNER 1985). The oldest recovered radiolarian assemblages, usually from the first few meters above pillow lavas or ophicalcites, can be assigned to zone A2 (late Callovian–early Oxfordian) or zone B (middle–late Oxfordian) depending on the area (Fig. 8).

2. Triassic basins (e.g. Lagonegro, DEWEVER & MICONNET 1986; Pindos, Asklipion, BAUMGARTNER 1984b, 1985) show a lime-free radiolarite deposition throughout this time interval.

3. In Jurassic basins (e.g. Lombardy Basin) the time equivalent of the Atlantic Cat Gap Formation is represented by two formations: first the Knobby Radiolarites (BOSELLINI & WINTERER 1979), a now almost lime-free to lime-poor chert sequence with discontinuous, wavy bedding probably representing coalesced (early diagenetic ?) replacement chert nodules. The variation in “bed”-thickness may vary from a few cm to 50 cm. Because of this particular diagenetic alteration the original  $\text{CaCO}_3$ -content is difficult to estimate – it may have been some 20% (WINTERER & BOSELLINI 1981). This facies usually starts with a knife-sharp contact above the basal Green Radiolarites. The contact is dated as late zone A2 (probably about Callovian/Oxfordian boundary) in the Lombardy basin.

The Knobby Radiolarites pass through a very gradual increase of carbonate up-section into the Rosso ad Aptychi (PASQUARE 1965), in which layers of red chert nodules alternate with pink siliceous limestone beds. Visible chert decreases steadily upsection from some 60–70% in the uppermost knobby beds to some 20% near the top of the formation. Carbonate contents increase accordingly and limestone color turns from dark red to light pink. The boundary to the overlying Maiolica Formation (WEISSERT 1979) is usually placed where any trace of red color disappears and bedding thickness increases to regular 1–2 dm beds of white nannofossil limestone. The uppermost part of the Rosso ad Aptychi is frequently lacking due to submarine slumping and/or redeposition (WEISSERT 1979). Radiolarians are very abundant and often well preserved in all three formations. The gradual transition from the knobby chert to the even bedded Rosso ad Aptychi falls close to the boundary between zones A2 and B (lower–middle Oxfordian) and the gradual increase of carbonate throughout the Rosso ad Aptychi extends through Zones B, C1 and C2 (middle Oxfordian to middle or late Tithonian).

The first beds of white Maiolica limestone sometimes contain *Crassicollaria* sp. or, in many cases already abundant *Calpionella alpina* indicating a late Tithonian age for the base of this formation. This base is remarkably isochronous throughout Atlantic (Blake Bahama Formation) and Western Tethys.

The gradual increase of carbonate in the Knobby Radiolarite and the Rosso ad Aptychi parallels the evolution seen in the Atlantic Cat Gap Formation, carbonate concentrations may even be quite similar. The main difference is the remaining fraction of the sediment: it is mainly detrital clays in the Cat Gap Formation but mainly silica in Western Tethys. Except for the radiolarites and siliceous mudstones deposited on oceanic crust, clay contents is generally low in Tethys. The minor amount of biogenous silica from radiolarians found in the Cat Gap must have been taken up entirely by the clays during diagenesis leaving only calcite-filled molds of the radiolarians. It should be noted that in

Tethys there is a considerable variation of the above general facies scheme from basin to basin. The example of the Subbetic realm has been discussed in chapter 2.2. Although trends of carbonate and silica contents parallel those of the example described above, concentrations may vary considerably. In the Umbrian zone, for example, no lime-free radiolarites have been found. The knobby facies (which develops during diagenesis if a specific silica/carbonate ratio is given) is therefore displaced in age downwards to zones A1 and A2, when maximum silica concentrations were reached. Also the age of the major color boundaries (green/red) is basin specific.

4. On Jurassic plateaus (e.g. Trento Plateau, Fig. 8) radiolarite sedimentation starts not before zone B (middle-late Oxfordian), probably after a hiatus of variable importance. The facies closely resemble the lime-rich radiolarites found in the basal middle and upper Rosso ad Aptychi with some 20–40% visible chert in wavy layers. Soon after zone B sedimentation becomes again predominantly calcareous and the Kimmeridgian–Tithonian rocks closely resemble the sediments drilled at Site 367 in the Eastern Atlantic. Sedimentation of the Cat Gap Formation remains comparably more clayrich for most of this time and becomes not really calcareous until the late Tithonian. In view of the greater average sedimentation rates in the Western Atlantic this difference must, in part, be due to dilution by detrital clays.

While the upper Tithonian–lower Cretaceous Atlantic Blake Bahama Formation and the Tethyan Maiolica Formation are similar in microfacies, it should be noted, that the Maiolica is much more siliceous. Radiolarian-rich layers and associated chert bands and nodules occur at least every couple of meters in the basal Maiolica Formation, whereas in the Blake Bahama Formation chert and radiolarian layers are very sporadic, occurring perhaps every few tens of meters.

### *3.2.2. Age of Radiolarites in eastern Tethys and some circumpacific terranes*

Recent studies indicate that the age range of limefree ribbon radiolarites is by no means restricted to the Middle and Late Jurassic, as it would appear from the Western Tethyan observations. In Triassic troughs oriented towards eastern Tethys (Lagonegro, southern Pindos, DEWEVER & DERCOURT 1985, Fig. 8) radiolarites may range in age through the Liassic and perhaps even into the late Triassic. In the sequence of the Antalya Nappes, the basal radiolarites are alternating with halobian bearing (redeposited) limestones and seem to range up at least into the Hettangian–Sinemurian (DEWEVER & DERCOURT 1985). In the Havasina Nappes of Oman (BERNOULLI & WEISSERT 1987) ribbon bedded radiolarites are now dated from the Late Triassic (Halfa Radiolarites, Haliw Formation) the Liassic, and Middle Jurassic to early Cretaceous (Al Aridh and Ibra successions). BERNOULLI & WEISSERT (1987, Fig. 9) show that during the early Cretaceous the Maiolica facies is restricted to the sunken Arabian platform, whereas the entire Havasina basin is the site of radiolarite deposition during that time. A similar situation was suggested for the southern Pindos basin (DEWEVER & THIEBAULT 1981). These observations raise the question, of how general the change from siliceous to calcareous sedimentation at the close of the Jurassic may be. Perhaps nannofossil limestone occurrences of early Cretaceous age are especially important in Atlantic and Western Tethys but are restricted to shallower depth in Eastern Tethys and Paleopacific.

Likewise, no Late Jurassic drop of the CCD (as inferred in Atlantic and Western Tethys) can be confirmed for these realms.

Several recent studies from Japan, Western North America and Central America indicate that ribbon radiolarites are perhaps the normal pelagic sediment in Circumpacific terranes throughout the late Triassic to Early Cretaceous. Two examples are illustrated in Figure 8: 1. Costa Rica (BAUMGARTNER 1984c; DEWEVER et al. 1985a), where radiolarites constitute the only pelagic sediment from Late Liassic-Dogger through early Late Cretaceous (Santonian). – 2. The Marin Headlands (MURCHEY 1984) as an example of Franciscan terranes, where radiolarites constitute a conformable sequence ranging in age from Pliensbachian to Albian–Cenomanian (see also Fig. 7). No pelagic limestone of early Cretaceous age is known from western North America.

### 3.2.3. *Paleoceanographic discussion*

#### General Considerations

Models proposed for the origin of ribbon radiolarites (JENKYN & WINTERER 1982; HEIN & KARL 1983; see also MARCOUX & RICOU 1979) involve narrow, marginal ocean basins (like the Gulf of California) or ocean margins in which a vigorous circulation causes upwelling making deep water nutrients available to surface dwelling radiolarians and therefore provoking high radiolarian productivity. The Gulf of California model (JENKYN & WINTERER 1982) is certainly well tailored for the Mediterranean Tethys which has been compared to extant small ocean basins for geological reasons independent from the radiolarite occurrences (eg. KELTS 1981; BERNOULLI & LEMOINE 1980; WEISSERT & BERNOULLI 1985). On the other hand, MURCHEY (1984) has provided convincing arguments for an equatorial, open ocean origin of the Marin Headland cherts.

The marginal ocean basin model is an actualistic model that views radiolarite basins as ancient chemical analogues of Cenozoic and Modern diatomite basins, assuming a similar ocean chemistry and a radiolarian productivity comparable to the one of modern diatoms.

A few considerations of the ecology of radiolarians and diatoms are necessary to evaluate this analogy: Modern diatoms are major primary producers comprising more than 70% and sometimes over 90% of the suspended silica in the water column (LISITZIN 1972). Diatom growth and reproduction is very rapid, with populations capable of doubling in about one day. Modern radiolarians have much slower reproduction cycles, estimations ranging from several days to several weeks (CASEY 1971) or even 1 to 3 months (BERGER 1976). Modern diatoms therefore largely dominate as producers of biogenic silica. The limiting factor for productivity of diatoms and radiolarians is not, as commonly believed, the degree of undersaturation of seawater in silica, but the availability of phosphates and nitrates as it is for other planktonic organisms (RENZ 1976; KENNETT 1982, p.474–475). Sedimentation patterns for modern radiolarians closely match those areas with high biological fertility and high nutrient concentrations due to upwelling and surface mixing. The density distribution of modern radiolarians parallels the one of planktonic foraminifers and calcareous nannoplankton showing highest abundances in the equatorial regions, whereas diatoms dominate in the high-latitude upwelling areas. This distribution may be caused by an advantage of adaptation of

high-latitude diatom species with respect to radiolarian species and perhaps also by increased predation pressure on diatoms in low latitudes.

The above considerations lead to the following conclusions:

1. The productivity of radiolarians and hence the regional occurrence of radiolarites is not a silica problem, but a general nutrient problem. The chemical analogy to modern areas of *siliceous* sedimentation is therefore not a primordial requisite of a radiolarite model. The legitimacy of chemical analogies is furthermore questioned by the fact the the Jurassic ocean had much lower latitudinal gradients and, as a consequence, a generally less vigorous circulation and recycling of nutrients.

2. The composition of Jurassic pelagic sediments suggests major differences in the composition of Jurassic plankton communities, which make an actualistic chemical model even more speculative.

a. – The record of calcareous plankton in pre-Tithonian deep-water sediments is scarce. Coccoliths are rare, *Schizosphaerella* DEFLANDRE & DANGEARD, though ubiquitous, generally never becomes volumetrically important (KÄLIN 1980; KÄLIN & BERNOULLI 1984; BERNOULLI & KÄLIN 1984). The preserved occurrences of globigerinids (e.g. *Protoglobigerina* sp.) are restricted to condensed facies suggesting a low and/or sporadic productivity of these foraminifers compared to the one of their recent relatives. Thin-shelled bivalves (e.g. *Bositra* sp.), possibly occupying a pseudoplanktonic habitat (attached to unfossilized floating algae?) become locally rock forming in the Middle and Upper Jurassic of the Central Atlantic and the Mediterranean Tethys.

b. – Radiolarians are the only preserved siliceous planktonic organisms in the Jurassic.

It is therefore conceivable that radiolarians dominated the microplankton food chain, feeding on a variety of plant and animal, non skeletal plankton. At least they were the only skeleton bearing, massproducing planktonic organisms. They did not have to compete with organisms of similar size and organisation, as do the modern radiolarians with the planktonic foraminifers.

*Conclusion.* – There is no reason for us to assume that Jurassic radiolarites must have formed in small ocean basins only. Any area of high surface fertility and hence high plankton productivity may have produced sufficient radiolarians to result in a regional occurrence of radiolarites. While we believe the Gulf of California model provides a good explanation for the radiolarite occurrences in Western (Mediterranean) Tethys, we think that the Jurassic equatorial convergence zone (possibly much broader and less well defined due to the low latitudinal gradients) is a likely origin of many other Tethyan and Circumpacific Mesozoic radiolarites (see also MURCHEY 1984).

### The Atlantic-Tethys correlation

In the foregoing description we have tried to establish the differences in basinal facies evolution between the Jurassic Atlantic and Western Tethys. The Atlantic–Tethys coupling, stressed by many authors, applies only to the gradual increase of carbonate during the Kimmeridgian–Tithonian and the final dominance of nannofossil limestones in the early Cretaceous, it does not apply to silica. Average silica accumulation rates in cored Atlantic Jurassic sequences reach at best an estimated 10–25% of those in coeval

Tethyan sections. In turn, the generally higher total accumulation rates in the Atlantic can easily be explained by a documented higher input of detrital clays and redeposited carbonate.

If the high silica accumulation rate of Tethys is related to a paleoceanographic situation causing high surface fertility, then the conclusion is that the Jurassic Atlantic had a different paleoceanography resulting in an area of relatively low surface fertility. Several features, independent from the silica distribution, support this conclusion (see Fig. 9):

1. – The occurrence of laminated organic-rich claystones in the Callovian-Oxfordian of Site 534 suggests local anoxic conditions at the seafloor, which could imply a stratified watermass with a slow turnover rate and hence little or no recycling of nutrients to the surface. The basal Green Radiolarites in Tethys suggest poor oxygenation of the seabottom at the same time. No preservation of organic matter is, however, recorded from Western Tethys and the green color may be merely a result of mildly reducing diagenetic conditions.

2. – Carbonate dissolution: The inferred paleodepths for the late Oxfordian CCD differ significantly in the two basins: WINTERER & BOSELLINI (1981) give an estimate of 2000 m for the Lombardy Basin, whereas OGG et al. (1984) conclude on a paleodepth of 3300 m at Site 534. If we assume that the Oxfordian productivity of calcareous plankton was following equal trends in both basins (see above), then this difference has to be interpreted in terms of corrosiveness of bottom waters and circulation patterns: In the pre-late Tithonian Tethys the circulation could have been estuarine (BERGER 1970; WINTERER & BOSELLINI 1981), with nutrient and carbonic acid-rich bottom waters flowing in from the Paleopacific via Eastern Tethys and welling up to the surface, while nutrient depleted surface waters could have flown out into the Atlantic, for instance. Such a circulation would have enhanced the dissolution of the already low input of calcareous plankton in Tethys. Circulation in the Atlantic, in turn, could have been lagoonal (BERGER 1970), with nutrient-poor, normal saline waters flowing in at the surface (from Tethys, for instance) and more saline surface waters sinking down and possibly causing some density stratification.

3. – Basin configuration: Recent paleogeographic reconstructions (LEPICHON et al. 1977; SHERIDAN 1983 and others) depict the Late Jurassic Atlantic as a narrow “mediterranean” basin (meaning: “surrounded by land masses”) in which exchange of intermediate and deep waters with Western Tethys via a seaway between Iberia and Africa or with the Caribbean-Pacific via the Gulf of Mexico and a hypothetical seaway across Yucatan is probably very limited.

*Conclusion.* – Several lines of reasoning let us believe that the Late Jurassic Atlantic was a restricted “mediterranean” basin with indirect connections to the world ocean. Rather than being affected by the global equatorial current system, the basin would be characterized by a sluggish local circulation of lagoonal affinity, causing low surface fertility and hence, a general low plankton productivity. This situation contrasts markedly with that of the Late Jurassic Western Tethys, which had at least since the Middle Jurassic a direct, deep connection with Eastern Tethys and Paleopacific, from where, via periequatorial currents and upwelling nutrients were constantly available triggering a high radiolarian productivity. Old, corrosive bottom waters would have increased disso-

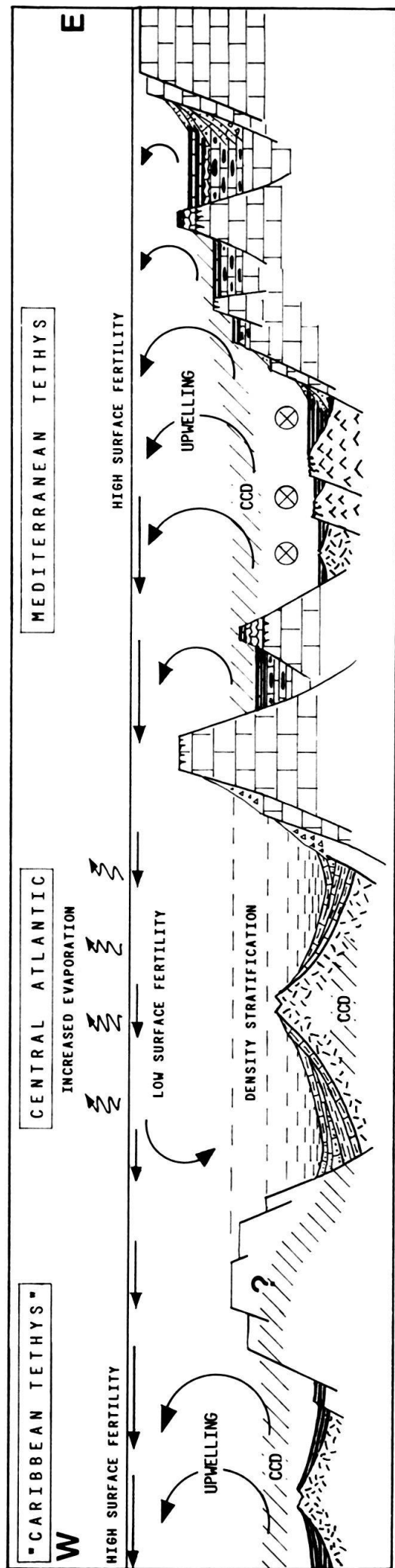


Fig. 9. Diagrammatic E-W trending cross-section from the "Caribbean Tethys" just south of Yucatan across the Early Central Atlantic to the Western Tethys, not to scale, strong vertical exaggeration. Surface waters are driven by seasonally changing SE and NE tradewinds into the Western Tethyan sea-way and cause strong, seasonally variable upwelling, making deepwater nutrients available to surface dwelling radiolarians (estuarine circulation after BERGER 1970, Gulf of California model after JENKINS & WINTERER 1982). Relatively nutrient-depleted surface waters reach the Central Atlantic, where circulation is sluggish and increased evaporation may even lead to local downwelling of saline waters (lagoonal circulation is suppressed. In the "Caribbean Tethys", offshore winds cause again upwelling and high surface fertility).

lution of the already low calcareous plankton input and caused a very shallow depth of the CCD.

The change to a unified calcareous nannofossil sedimentation at the close of the Jurassic in Atlantic and Western Tethys has been interpreted in various ways: HSÜ (1976) and WEISSERT (1979) supposed, based on paleomagnetic evidence, that the Mediterranean Tethys moved by the end of the Jurassic from a position affected by the equatorial current system into a position where a weak surface circulation was controlled by the subtropical gyres. Predominant coccolith sedimentation is viewed as the result of relatively low surface fertility compared to the one of the Late Jurassic.

DEWEVER et al. (1986) come to a contrary conclusion. For them, the Late Triassic to Late Jurassic radiolarite record in Tethys is the result of a triangular trap, open to the east, closed to the west, forcing deep waters to the surface and therefore creating high surface radiolarian productivity. By the end of the Jurassic the gaps between Africa and Iberia and between Yucatan and South America would have widened enough to permit the establishment of a global equatorial current system. Surface fertility and CCD would have changed in the Tethys–Atlantic seaways as a consequence, whereas continued upwelling along the Arabian margin would be responsible for the prolonged radiolarite sedimentation until the Late Cretaceous in that area.

We favor the early Cretaceous scenario by WEISSERT (1979), because: 1. – We consider the equatorial current system as a likely area for radiolarite deposition throughout the Mesozoic. 2. – Both Western Tethyan and Atlantic Early Cretaceous paleoenvironments have been characterized as of low to medium fertility, sluggish thermohaline circulation with a periodical tendency towards a density stratification perhaps leading to an extended oxygen minimum zone and/or to poorly oxygenated bottom waters resulting in the preservation of fine laminations and organic matter (WEISSERT 1979; ROBERTSON & BLIEFNICK 1983).

### 3.3. Intrabasinal diachronism of Tethyan Radiolarites and their sedimentary relationship to coeval calcareous facies

#### 3.3.1. *New data*

As detailed age control both on radiolarites and on the seamount facies is available, it becomes evident that basinal radiolarite facies must have coexisted with pelagic calcareous seamount facies in a small scale pattern implying drastic lateral facies changes over distances of a few km. Three examples, illustrated in Figure 8, will be mentioned:

1. *Trento Plateau – Lombard Basin.* – On the Trento Plateau sparse ammonite evidence indicates that red nodular limestone (the Ammonitico Rosso Inferiore) continued to accumulate at least in places until the middle or late Callovian (STURANI 1964; FOGELGESANG 1975; WINTERER & BOSELLINI 1981; STURANI & BERNOULLI unpubl.). In the Lombard basin, radiolarian Unitary Association 1 is present just below the base of the basal Green Radiolarites in the Breggia Gorge and just above the base in the first few m of chert at Saltrio (BAUMGARTNER 1984b, pl. 12A) indicating a (late?) Bathonian age for this transition. Thus, limefree basinal radiolarites accumulated during at least part of the Bathonian and Callovian while ammonite-bearing nodular limestones became deposited on the Trento plateau.

2. *Upper Austroalpine nappes.* – In the Tauglboden area, red ammonite-bearing limestones reach the Oxfordian (DIERSCHÉ 1980; VECSEI & PIRZER 1987). In the Glasenbach Gorge, radiolarian samples from basal green cherts yielded U. A. 4–5, indicating a Callovian age (KOCHER 1981, p. 42; BAUMGARTNER 1984b, loc. 36).

3. *Umbrian Zone, Monte Nerone (Bugarone quarries) – Bosso Gorge.* – In the Bugarone quarries, beds with upper Bajocian ammonite faunas are directly overlain by beds containing lower Kimmeridgian ammonites (CECCA et al. 1987, see also FARINACCI et al. 1981 for the Campo al Bello section nearby), indicating a hiatus corresponding to the lower three quarters of the basinal Calcari Diasprigni at Bosso (BAUMGARTNER 1984b, loc. 26). Condensed pelagic nodular limestones (now silica-free and dolomitized) of the upper Kimmeridgian–lower Tithonian at Bugarone contrast with coeval red, thin-bedded siliceous limestones with an estimated 30–40% visible chert at Bosso.

### 3.3.2. *Distribution of carbonate and silica – reevaluation of the CCD-model*

BOSELLINI & WINTERER (1975) and WINTERER & BOSELLINI (1981) proposed sharply defined, relatively shallow calcite and aragonite compensation depths to explain the lateral facies changes between seamount/plateaus and adjacent basins. As no age control was available, especially for the basinal sequences, these authors suspected a possible hiatus at the base of the radiolarites (WINTERER & BOSELLINI 1981, Fig. 5), in order to avoid the radiolarite–Ammonitico Rosso facies heteropy. Insignificant radiolarian productivity during the Bathonian and early Callovian would have allowed a virtually silica-free accumulation of Ammonitico Rosso. The Oxfordian basinal Radiolarites were considered as a solution resistant residue deposited between ACD and CCD or below the CCD for the lime-free occurrences. Although BOSELLINI & WINTERER (1975) were clear about the complexity of the ACD and CCD surfaces, the absolute bathymetric significance of inferred Jurassic ACD and CCD has been largely overestimated in the literature of the past decade.

The new data make a reevaluation of the above model necessary. Little is known about the physical facies relationships between swell and basin. While detailed paleotectonic, sedimentologic and biostratigraphic studies of the seamount-basin transition are underway in Umbria (ALVAREZ, BAUMGARTNER et al., work in progress), we may attempt to answer the following questions from a theoretical point of view:

1. – If pelagic and minor amounts of benthic carbonate particles were accumulating on the swells, *why aren't there more swell-derived calcareous turbidites deposited in the coeval basins?*

2. – The record in the basins suggests that the late Middle Jurassic Western Tethys was an area of high radiolarian productivity. *Why are no Bathonian–Callovian radiolarites preserved on the swells?*

3. – By the late Oxfordian basinal radiolarites tend to become slightly calcareous (Knobby Radiolarites of BOSELLINI & WINTERER 1975). At the same time, the radiolarite facies encroaches on many seamounts and deep plateaus [Trento, Tauglboden, Argolis Basal Sequences (BAUMGARTNER 1985), Fig. 8], where cherty thinbedded limestones with clayrich partings are deposited. *Why, in contrast to the Middle Jurassic, are late Oxfordian radiolarites sometimes preserved on the swells?*



1. – *Why aren't there more swell-derived calcareous turbidites deposited in the late Middle Jurassic basins?* – The microfacies of the uppermost calcareous facies in the swells is very characteristic and may provide some clues to answer the first question. Typical condensed sequences comprise a substrate of Early or early Middle Jurassic shallow water limestone that shows submarine early cementation, erosion and sometimes extensive ferromanganese crusts. The pelagic limestones themselves typically have thicknesses of one to a few meters and rarely exceed tenths of meters. They are mainly constituted by red microbioclastic pack- or wackestones. Bioclasts include abundant fragments of pelagic bivalves (*Bositra?*), crinoid ossicles, benthic foraminifers like *Lenticulina* sp., and in some cases abundant *Protoglobigerina* sp. Calcified radiolarians and sponge spicules are always present but volumetrically insignificant. Ammonites and belemnites are often concentrated in layers, bored and corroded on their upper surface and ammonites reveal in their chambers complex histories of early diagenetic dissolution, cementation and geopetal infill of diagenetic and pelagic sediment (WENDT 1970). There are many examples of sediment trapping and fixation by cyanobacterial and serpulid crusts (STEIGER & JANSÁ 1984). Many microfacies include extensive ferromanganese crusts and nodules in layers or just a diffuse impregnation with oxides. Current activity is indicated by lenses and layers of winnowed biosparite, overturned ammonites and graded infill of neptunian dykes.

These swells must have been a largely non-depositional setting in which carbonate dissolution, precipitation and Fe-Mn-oxide incrustation could take place as on Recent seamounts and plateaus (JENKYN 1986). This scenario gives a first answer to our question: There was not much unconsolidated carbonate to be resedimented in adjacent basins – neither as turbidites nor as diffuse nepheloid carbonate oose. Very shallow carbonate compensation levels most probably resulted from a scarcity of carbonate supplied to the basins; Late Middle Jurassic Tethys and Atlantic (and probably the rest of the World Ocean) were starved in pelagic carbonate, because calcareous plankton was scarce. Detrital and/or volcanic clays (in the Atlantic) and biogenous silica (in Tethys) must be considered as the default pelagic sediment.

2. – *Why are no Bathonian–Callovian radiolarites preserved on the swells?* – To answer the second question, we must consider the settling properties of radiolarians. TAKAHASHI (1982) measured mean weight, dimensions and sinking speed in seawater of specimens of 55 Recent radiolarian species and calculated volumes and density contrasts. He found density contrasts, relative to sea water, to be relatively independent of radiolarian size, between 0.01 and 0.5 g/cm<sup>3</sup>, which are very low compared to other sediment particles (massive opal bioclasts, for instance, have a density contrast of about 1.2 g/cm<sup>3</sup> and quartz grains have about 1.65 g/cm<sup>3</sup>). Measured settling speeds vary from 0.015 to 0.48 cm/sec, they are much lower than the values calculated by BARRETT (1982) and those for other sediment particles of comparable size (a solid silica sphere of 200 micron diameter in seawater at 5°C would have a settling speed of about 1.7 cm/sec, a sphere of 400 micron diameter a speed of about 6.8 cm/sec! [values from BARRETT 1982]). The consequences of these values are obvious: Radiolarians are transported over large distances by currents. In a moderate bottom current (10 cm/sec) even the fastest settling radiolarians would be laterally transported more than 20 times their vertical displacement. For a current thickness of 100 m this would imply a lateral displacement of 2 km for the densest/fastest settling radiolarians and 67 km for the less dense/slowest settling forms!

Winnowing of radiolarians by resuspension from a sediment surface is greatly facilitated by the fact that the surface of a radiolarian test has a minimal adhesion to the sediment due to its spines. Given the scarcity of clay-sized particles deposited with the radiolarians on swells that would "bind" them to the substrate, minimal fluid shear is sufficient to overcome drag and put the tests in suspension.

It seems therefore likely that radiolarians could not effectively accumulate on current swept highs but were transported eventually into current protected basins. Highly variable radiolarite thickness levelling out ancient submarine topography in the Ligurian oceanic realm confirm this process (see also BARRETT 1982). Size sorting and grading frequently observed in radiolarite beds may be a product of minimal variation in current velocities. If radiolarian turbidites existed as suggested by many authors, they must have been of very low density in order to allow the settling of small radiolarians.

3. – *Why, in contrast to the Middle Jurassic, are late Oxfordian radiolarites sometimes preserved on the swells?* – This question has a number of possible answers: In order to deposit radiolarians on the swells we may: decrease the current activity, or decrease the contrast in relief between swell and basin, or increase the production of clay-sized particles in order to "bind" the radiolarian tests by adhesion to sediment surface. Perhaps it is the increased input of terrestrial clays in the Oxfordian combined with the gradual waxing of nannoplankton productivity (well documented in the Atlantic, see p. 859) that helped to "stick" the radiolarians to the substrate and allowed a slow deposition of calcareous (and often clayey) radiolarites on many deeply submerged Tethyan plateaus and seamounts. It is interesting to observe the differences in faunal composition of coeval swell and basin assemblages: Sponge spicules and large "massive" radiolarians with a low sphericity and a lot of "hooks" like *Podobursa spinosa*, large *Emiluvia* sp. large *Hagiastrids*, and the heavy *Andromeda*, are relatively more abundant on swells than in basins – suggesting a hydrodynamic sorting, by which the smoother, less dense forms were winnowed away and deposited in the basins, whereas the heavier and hookier forms became entangled with others and fixed on the swells.

On the other hand, there are clear indications of cessation of faulting activity in the early Late Jurassic (WINTERER & BOSELLINI 1981, p. 404) which may have led to a relative decrease in relief between basins and swells. Also a decrease in current activity on the swells, as a consequence of a general slowing down of circulation would both allow for the accumulation of radiolarites on swells and for a better preservation of carbonate in the whole area.

### Diagenetic considerations

Facies differentiation due to selective winnowing of radiolarians and syndimentary dissolution at depth was certainly enhanced by diagenetic processes. Many nodular limestones on swells contain calcite-filled molds of radiolarians. Their silica became either absorbed by clays or, in view of the low sedimentation rates, could have diffused into the water. In the basins chert has completely replaced original sedimentary textures and particles including radiolarians. If there was a minor amount of carbonate particles that became incorporated in the sediment, it must have undergone severe diagenetic alteration (see discussions in KÄLIN et al. 1979; MCBRIDE & FOLK 1979).

### 3.3.3. Conclusions

It is unfortunate that the CCD model was introduced for the Tethyan Jurassic in conjunction with the radiolarite problem. While the CCD model is consistent with the observed carbonate distribution, it does not explain the occurrence and distribution of radiolarites. The absence of silica on the swells can obviously not be explained by the dissolution of carbonate at depth. Moreover, basinal late Middle Jurassic radiolarites can clearly not be considered as a solution residue of coeval nodular limestones on swells. Greater accumulation rates in the basins and the generally low abundance of radiolarians in swell facies exclude this interpretation.

The absence of late Middle Jurassic radiolarites on the swells (and the distribution of siliceous sediment in general) is not a function of the depth of the CCD.

Persistent bottom currents that prevented radiolarians from accumulation on the swells and carried them into the basins, together with a general scarcity of calcareous plankton led to the observed facies contrasts which, furthermore, were enhanced by diagenesis. Low concentration of calcareous plankton together with a vigorous circulation also explains shallow, irregular and sharply defined ACD and CCD.

During the late Oxfordian, calcareous plankton production slowly increased and/or current activity decreased leading to an overall better carbonate preservation (= beginning of fall of ACD and CCD). Because of diminished current activity, radiolarites started to accumulate also on the swells. This tendency continued through the Kimmeridgian and early Tithonian with a successive increase in carbonate, gradually displacing radiolarites first on the swells and then in the basins.

Consequently, the stratigraphic passage from limestone to radiolarites on the swells is not a function of the position of the CCD relative to these areas. Paradoxically, it is the record of a deepening CCD.

## 4. Synthesis

### Radiolarian faunal provinces and paleoceanography

There are clear indications of Jurassic faunal provincialism which may in part be responsible for some of the correlation problems between zonations established in Europe and North America. PESSAGNO & BLOME (1986) defined simple criteria to differentiate radiolarian assemblages of the "Tethyan" from those of the "Boreal" realm and to subdivide these realms into provinces. In view of the paleoceanographic characteristics of the Jurassic Atlantic, Western and Eastern Tethys, discussed in the previous chapter, it seems likely that the radiolarian faunal realms proposed by PESSAGNO & BLOME (1986) are primarily controlled by paleoceanography, rather than paleolatitude. "Tethyan" could imply "high fertility-stirred ocean" and "Boreal" could imply "lower fertility-stratified ocean". Well oxygenated, lime-poor to lime-free ribbon radiolarites typically yield "Tethyan" assemblages, whereas organic-rich, concretionary lime-mudstones are described from localities cited by PESSAGNO et al. (1986), PESSAGNO & BLOME (1986) as "Boreal". So far, there is no report that would establish the occurrence of ribbon radiolarites yielding "Boreal" radiolarian assemblages. This correlation, although not exclusive, is a reason to suspect paleoceanography as the link between faunal composition and lithology.

High diversity and abundance of pantanelliids is interpreted as characteristic for the "Tethyan" realm by PESSAGNO & BLOME (1986). The Jurassic Atlantic, Western and

Eastern Tethys, are certainly considered by everyone as of equatorial Jurassic paleolatitude and of "Tethyan" faunal affinity. However, pantanelliid abundance and diversity is relatively low in samples from the Atlantic, it is moderate to high in Western Tethys and greatly increases in Eastern Tethys (e.g. Oman). Although these data are preliminary, they suggest that pantanelliids were perhaps a group of radiolarians preferring high fertility upwelling areas, and therefore they were rare in the Jurassic Atlantic, interpreted in this paper as a low-fertility area.

While we think radiolarian assemblages may become excellent indicators for paleoceanographic conditions, they will only be indirect indicators of paleolatitude, inasmuch paleoceanography is controlled by paleolatitudinal gradients.

### Radiolarites as the normal pelagic sediment in the pre-Late Cretaceous Mesozoic

As more and more radiolarite occurrences are studied and well dated, it becomes clear that this facies, although restricted to certain ages in Tethys, is the dominant pre-Late Cretaceous pelagic facies of the Circumpacific realm. As we have exposed in the previous chapter, it is likely that any high fertility zone in the Jurassic ocean may have produced sufficient radiolarians to result in radiolarite deposits. In view of these conclusions it seems logical to consider radiolarites as the normal pelagic sediment and to define the conditions under which this facies is absent, rather than to continue considering radiolarites as a result of special paleoceanographic conditions.

The factors that may have inhibited the formation of radiolarites are summarized in Table 1. They are discussed in the following:

1. Terrigenous input to basins results in a dilution of the planktonic input and hence results in hemipelagic mudstones or claystones. A good example is the Mesozoic of the Vocontian Trough in southeastern France.

2. Platforms shed an important amount of mainly aragonitic dilute periplatform-ooze (SCHLAGER & JAMES 1978) to adjacent basins. This and dilute lime-turbidites probably from an important fraction of many deeper water limestones deposited during the Early and Middle Jurassic along foundered Tethyan margins (BERNOULLI & KÄLIN 1984). Because of the total diagenetic alteration of unstable carbonate minerals, the proportion of this shallow-water input is difficult to estimate. It dilutes planktonic input to the basin and effectively prevents the formation of radiolarites. As soon as basins get cut off (by drowning) from any shallow-water source, radiolarites may start to form.

3. High input of calcareous plankton rivals with the siliceous planktonic input to basins during the Early Cretaceous in Atlantic and Western Tethys and results in the formation of pelagic cherty limestones. This effect is less conspicuous in Eastern Tethys and totally unknown from Western North American terranes. By the Late Cretaceous, it seems as if planktonic foraminifers start to dominate over radiolarians resulting in a (possibly world-wide) decline of radiolarite formation.

4. Low surface fertility in parts of the Mesozoic ocean may have caused extensive hiatuses, which are obviously difficult to put in evidence. MURCHEY (1984) suggested low fertility conditions for the Late Jurassic of the Marin Headland Terrane in order to explain the absence of Late Jurassic radiolarian assemblages in a conformable stratigraphic sequence.

FACTORS CAUSING ABSENCE OF RADIOLARITES IN MESOZOIC BASINS

Factor	Process	Resulting sediment
1. terrigenous input	-> dilutes planktonic input	-> claystone -> mudstone
2. platform carbonate input	-> dilutes planktonic input	-> deep water "periplatform" limestone
3. high productivity of calcareous plankton	-> dilutes siliceous planktonic input	-> pelagic limestone
4. low surface fertility	-> low biogenic input	-> pelagic clays
5. persistent bottom currents	-> prevent radiolarians from accumulation	-> hardgrounds, condensed pelagic limestone

If none of these factors is effective, RADIOLARITES are the normal pelagic sediment

Table 1. Radiolarites can be considered as the normal pelagic sediment if the factors listed in Table 1 are not effective. Examples: *Factor 1.* – Terrigenous input displaces radiolarites in the Vocontian trough during the Middle and early Late Jurassic, resulting in a claystone-mudstone sequence. *Factor 2.* – Ultimately platform-derived carbonate particles constitute many Tethyan Liassic synrift deepwater limestones (Lombardian Siliceous Limestone, Corniola, etc.), areas far away or sheltered from this input show radiolarites (e.g. Lagonegro basin). *Factor 3.* – During Early Cretaceous, increasing productivity of calcareous nannoplankton displaces the radiolarite facies in the Western Tethys, while radiolarites occur in Eastern Tethys. *Factor 4.* – Low surface fertility may be the cause of a Late Jurassic hiatus within the radiolarites of the Marin Headland section (MURCHEY 1984 and Fig. 7). *Factor 5.* – Persistent bottom currents on swells and seamounts of Western Tethys prevented the accumulation of radiolarites during the late Middle Jurassic.

5. Persistent bottom currents, especially on topographic highs of the seafloor, may have prevented radiolarians from settling and determined the local occurrence and limited age span of radiolarites in Tethys and elsewhere. The resulting sediments are condensed pelagic limestones (above the ACD and CCD) and ferromanganese hardgrounds.

If none of these factors was effective, radiolarites were the normal pelagic sediment during most of the Mesozoic time.

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