Revised orbitolinid biostratigraphic zonation for the Barremian – Aptian of the eastern Arabian Plate and implications for regional stratigraphic correlations

Rolf Schroeder, Frans S.P. van Buchem, Antonietta Cherchi, Darioush Baghbani, Benoit Vincent, Adrian Immenhauser and Bruno Granier

ABSTRACT

The biostratigraphic zonation of Barremian – Aptian shallow-water carbonate systems has a low resolution due to the slow evolutionary rate of most species living in these environments. A notable exception to this are the orbitolinid foraminifers, which show relatively rapid evolutionary trends mainly in the embryonic structures, and can thus be used for high-resolution dating of these strata. Here a revised orbitolinid biostratigraphic zonation scheme is presented for the eastern Arabian Plate.

This zonation is based on published work and new research on orbitolinid-rich successions in shallow-water carbonate platform environments and intra-shelf basin margins. A subdivision into six zones and three subzones is proposed for the Barremian and Aptian, using the evolutionary lineages Montseciella (= ex-Dictyoconus) arabica – Rectodictyoconus giganteus, Eopalorbitolina – Palorbitolina and Praeorbitolina – Mesorbitolina. In this paper we also introduce a new species, Palorbitolina ultima, which represents the advanced development of Palorbitolina lenticularis.

This revised zonation was derived from a unique database covering the eastern Arabian and northeastern African plates including offshore Abu Dhabi, Ethiopia, southwest Iran, Oman, Somalia and Yemen. As a result, a revision of the age assignment of the Dariyan Formation in southwest Iran is proposed. In addition, examples of biostratigraphic zonations, which constrain regional (sequence) stratigraphic correlations are: (1) the regional appearance of the short range, Late Barremian species Montseciella arabica, that allows to correlate a third-order sequence in a low-angle, carbonate ramp system over a distance of 4,000 km; (2) the assemblage of Palorbitolina and Praeorbitolina species that characterise the late Early Aptian maximum flooding event; and (3) the subsequent appearance of different Mesorbitolina species that characterise the regressive Upper Aptian deposits.

INTRODUCTION

One of the fundamental problems with stratigraphic work on Barremian – Aptian shallow-water carbonate systems of the Arabian Plate is the low biostratigraphic resolution, which is due to the slow evolutionary rate of most species living in these environments. Exceptions to this rule are the rudists (e.g. Masse et al., 1998; Skelton and Masse, 2000) and the orbitolinid foraminifera, the latter of which are the subject of this paper.

Orbitolinid foraminifera show a relatively rapid evolutionary trend observed in the embryonic structures during the Barremian to Early Cenomanian. Orbitolinids are found – sometimes in very large quantities (locally rock forming) - throughout the carbonate platforms, and readily available in outcrops, core material and cuttings. Therefore orbitolinid micropaleontology is an ideal biostratigraphic tool for the oil industry. Currently, however, this tool is not commonly used in the Middle East, mainly because a comprehensive study of the orbitolinid phylogenetic lineages, established in the western Tethys, was never carried out for the Arabian Plate.

Henson (1948) was the first to realise the importance of the internal structure of orbitolinids in taxonomy, and published his results in a monograph that included a complete revision of the orbitolinids in the Middle East. This work, however, is not compatible anymore with the now widely accepted studies...
Schroeder et al. by Schroeder (1962, and thereafter), and the recently proposed revision of the Henson collection by Simmons et al. (2000). A few other authors have presented orbitolinid biostratigraphic zonations, which were only for particular regions of the Arabian Plate: Sampò (1969) for the Zagros Mountains area (southwest Iran), and Simmons (1994) as well as Witt and Gökdağ (1994) for northern Oman.

The purpose of this study is to propose a revised orbitolinid biozonation based on both published and newly sampled and studied sections along the eastern Arabian and northeastern African plates. Firstly, the palaeontological fundamentals of a revised orbitolinid biostratigraphy are presented, including illustrations of the morphological changes characterising the different phylogenetic lineages. Secondly, a number of reference stratigraphic sections of the study area, which provided the material to establish this biozonation, are presented. Brief mention will be made of the sequence-stratigraphic context of the sections, but for more detailed accounts the reader is referred to the provided literature references.

**MATERIALS**

The dataset used for this study includes 12 outcrop sections and one well, distributed along a transect of approximately 4,000 km, including both published and new sections (Figure 1). The new material from southwest Iran comes from outcrop locations in Fars and Khuzestan provinces, the re-examined material in Oman comes from the northern Oman Mountains and the Al Huqf area, while published material from Yemen (Cherchi et al., 1998), Somalia (Cherchi and Schroeder, 1999a) and Ethiopia (Bosellini et al., 1999) is also included. All palaeontological identifications of orbitolinids were carried out by R. Schroeder and A. Cherchi. For the study of the Iranian material use has been made of new ammonite biostratigraphic information which is presented in detail in the palaeontological appendix of Vincent et al. (2010).

**BIOSTRATIGRAPHY OF ORBITOLINID FORAMINIFERA**

The essential structural elements of an orbitolinid foraminifer are shown in Figure 2. The test is in the form of a small cone of a few millimetres in diameter and height. A vertical section through the test shows that it is made up of two structural elements: (1) the embryo, which is located either in a central position in the tip of the test or at the beginning of a small initial spiral, and (2) of a subsequent series of discoidal or annular chamber layers. Horizontal (transversal) sections reveal that the marginal zone of each chamber layer is subdivided by small vertical and transversal plates of different length into marginal chamberlets, whose outer part is lined by a layer of minute subepidermal cells. The external part of the central zone of each chamber layer is subdivided into radial chamber passages by radial partitions, the latter being morphologically the prolongations of vertical plates of the marginal zone. These partitions join together in the internal part of the central zone producing an irregular network. In other orbitolinids (Dictyoconus and allied forms) the central zone is characterised by the presence of pillars or pillar-like structures.

**Phylogenetic Lineages and Evolutionary Trends of Orbitolinid Foraminifers**

Detailed studies of orbitolinids carried out on specimens mainly from the Mediterranean area since the early 1960s, allowed not only an exact definition of different species, based upon structural criteria, but also the establishment of phylogenetic lineages (Schroeder, 1975; Schroeder et al., 2002; Cherchi and Schroeder, 2004a). The chronological succession of species composing each lineage revealed a number of evolutionary trends relating to the dimensions as well as the outer morphology and the inner structure of the test.

With regard to the outer morphology, the following trends are observed: (1) the enlargement of the test, (2) the increase of the apical angle and, in parallel, the flattening of the test, and (3) the gradual reduction of the initial spiral of megalospheric forms. The main evolutionary trends of the inner structure are: (1) a gradual enlargement of the megalospheric embryo, shifting from an eccentric to a centric position in the tip of the test, (2) a gradual subdivision of the upper part of the embryonic chamber, respectively the embryonic apparatus by plates into subepidermal chamberlets, and (3) the increase of the subdivision of the marginal zone.
During the phylogenetic evolution of orbitolinids there is a marked tendency to develop a depressed outer form of tests as size increases; this trend, however, is not continuous and can be influenced by ecological factors (Schroeder, 1962, 1975). Several authors observed that the most discoidal forms are related to deeper-water environments, whereas conical forms are related to shallower-water environmental settings (e.g. Vilas et al., 1995; Simmons et al., 2000; Hughes, 2000; for further details see Pittet et al., 2002). In contrast to the outer morphology, the internal structures of the test are very constant and therefore of great taxonomic importance. Specifically, the structures of the embryonic
apparatus of the large orbitolinid foraminifers are valuable distinctive marks that allow a definition of different species and the establishment of phylogenetic lineages.

The majority of the orbitolinid foraminifers found in the Barremian – Aptian sections of the southern Arabian and northeastern African plates belong to the following three phylogenetic lineages (Figure 3):

1. Montseciella glanensis – Rectodictyoconus giganteus lineage,
2. Eopalorbitolina pertenuis – Palorbitolinoides hedini lineage,

In Figures 4 to 6 the phylogenetic trends of the embryonic apparatus of these three lineages are documented, and illustrated with thin section photos. Additional illustrations from the study area are provided in Figure 8. The framed species in Figure 3 are present on the Arabian Plate. The three lineages show two similar evolutionary trends: (1) a gradual enlargement of the whole embryo, and (2) an increasing complication of the structures. The vertical ranges of the species of these lineages generally overlap, suggesting a gradual transition between the ancestor and the descendant of a member of a lineage and their direct relationship. This implies that there is no evolutionary break between the species.

In the following the diagnostically important characteristics of the different species are presented in combination with the main evolutionary trends of each lineage. The bibliographic data of each species refer to selected papers containing the original description, change of systematic position and good illustrations.

A. Montseciella arabica – Rectodictyoconus giganteus lineage (Figure 4)

This lineage, established by Cherchi and Schroeder (1999b), comprises the following four species in chronological order:
Barremian – Aptian biostratigraphic zonation, eastern Arabian Plate

<table>
<thead>
<tr>
<th>Age</th>
<th>Montseciella – Rectodictyoconus</th>
<th>Eopalorbitolina – Palorbitolinoides</th>
<th>Praeorbitolina – Mesorbitolina</th>
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<td>Lower</td>
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Figure 3: General stratigraphic distribution of three orbitolinid phylogenetic lineages.

(1) *Montseciella glanensis* (Foury, 1968)
1968 *Palaeodictyoconus glanensis* n.sp. – Foury, p. 146–148; pl. 18, figs. 1–12.
1999b *Montseciella glanensis* (Foury, 1968). – Cherchi and Schroeder, p. 9–10; pl. 1, figs. 1–6; pl. 2, figs. 1–7.

(2) *Montseciella alguerensis* Cherchi and Schroeder, 1999
1999b *Montseciella alguerensis* n. sp. – Cherchi and Schroeder, p. 10–12; pl. 3, figs. 1–3; pl. 4, figs. 1–5.

(3) *Montseciella arabica* (Henson, 1948)
1948 *Dictyoconus arabicus* sp. nov. – Henson, p. 35–36; pl. 1, figs. 5–8; pl. 14, figs. 1–12.
1978 *Palaeodictyoconus arabicus* (Henson). – Schroeder et al., p. 244; pl. 2, figs. 9–10.
1979 *Palaeodictyoconus arabicus* (Henson), 1948. – Schroeder and Cherchi, p. 575; pl. 1, figs. 3–7; pl. 2, figs. 1, 2, 4, 5.
1999a *Dictyoconus arabicus* (Henson), 1948. – Cherchi and Schroeder, p. 6, 8; pl. 2, figs. 1–8.

(4) *Rectodictyoconus giganteus* Schroeder 1964
1964a *Rectodictyoconus giganteus* n. gen., n. sp. – Schroeder, p. 466–468; fig. 2a-c.

The megalospheric embryo of the species belonging to this lineage is located either at the beginning of a more-or-less developed initial spire (*Montseciella*), or in a centric position in the tip of the test (*Rectodictyoconus*). The central zone of the chamber layers shows in its outer part radially directed rows of pillars merging into rudimentary, relatively thin radial partitions in the upper part of each layer. The inner part of this zone is subdivided by pillar-like or vermicular structural elements. All these structures are arranged in alternating position from one chamber layer to the next.

This lineage is characterised by the following three main evolutionary trends:

(1) Increase of the test diameter. *Montseciella glanensis*: 1.4–1.7 mm; *M. alguerensis*: 2.5–3 mm; *M. arabica*: 2.4–3.2 mm; *Rectodictyoconus giganteus*: 4–5 mm.
Figure 4: (a) Montseciella – Rectodictyoconus phylogenetic lineage. Illustrations. (1) Montseciella glanensis (Foury), tangential section (AC 5-4), Serra del Montsec, Lérida Province, North Spain, Early Barremian. (2) Montseciella alguerensis Cherchi and Schroeder, oblique tangential section (CC 27-1), Capo Caccia, Northwest Sardinia, Italy, Early Barremian. (3) Montseciella arabica (Henson), median section (AM 106-7), Ahl Medo, North Somalia, Late Barremian. (4) Rectodictyoconus giganteus Schroeder, axial section, holotype (3742-5), Villarroya de los Pinares, Teruel Province, East Spain, Early Aptian.

(b) (See facing page) Illustrations of specimens of Montseciella arabica (Henson) from the study area. (1) Transversal section through the initial stage of a transitional form to Rectodictyoconus giganteus, Abu Dhabi offshore well, United Arab Emirates (x100). (2) Tangential section (M 35), Kuh-e-Mangasht, southwest Iran (x50). (3) Axial section (M 36), Kuh-e-Mangasht, southwest Iran (x50). (4) Oblique transversal section (MSM 2/106-2), Ahl Medo, North Somalia (x50). (5) Oblique tangential section (MSM 2/106-2), Ahl Medo, North Somalia (x50). (6) Oblique transversal section, Abu Dhabi offshore well, United Arab Emirates (x30). (7) Subaxial section through a microspheric form, Abu Dhabi offshore well, United Arab Emirates (x25).

(2) Morphology and position of the embryo. The test of M. glanensis begins with a compressed initial spire showing a sharply angular carina. The axis of coiling of the spire differs up to 90 degree from that of the later conical part of the test. The small globular embryonic chamber (diameter: 0.06–0.08 mm) is followed by a series of 8–9 flat and undivided chambers showing an interiomarginal aperture. Compared to M. glanensis, the carinate initial spire of M. alguerensis is more reduced. The embryo of the holotype of this latter species is circular in outline and has a diameter of 0.07 mm. Another section through the initial spire indicates a subdivision of the embryo into a globular protoconch and a hemispherical undivided deutoconch. The initial spire of the M. arabica is reduced to 1–4 cuneiform chambers. The embryo is not exactly in the tip of the test, but somewhat eccentrically situated. It has a diameter of 0.17–0.2 mm (max. 0.25 mm) and consists of a
Figure 4a: Montseciella — Rectodictyoconus phylogenetic lineage. Illustrations.

1. Montseciella glanensis (Foury), tangential section (AC 5-4), Serra del Montsec, Lérida Province, North Spain, Early Barremian.
2. Montseciella alguerensis Cherchi and Schroeder, oblique tangential section (CC 27-1), Capo Caccia, Northwest Sardinia, Italy, Early Barremian.
3. Montseciella arabica (Henson), median section (AM 106-7), Ahl Medo, North Somalia, Late Barremian.
4. Rectodictyoconus giganteus Schroeder, axial section, holotype (3742-5), Villarroya de los Pinares, Teruel Province, East Spain, Early Aptian.

Figure 4b: (see facing page for caption).

5. Oblique tangential section (MSM 2/106-2), Ahl Medo, North Somalia (x50).
6. Oblique transversal section, Abu Dhabi of offshore well, United Arab Emirates (x30).
7. Subaxial section through a microspheric form, Abu Dhabi of offshore well, United Arab Emirates (x25).
more or less globular protoconch and an overlying deuteroconch showing a layer of chamberlets. Finally, the genus *Rectodictyoconus* differs from *Montseciella* by the centric position of its embryo. The protoconch of *R. giganteus*, only representant of this genus, has a diameter of 0.15–0.17 mm and is overlain by a hemispherical deuteroconch (0.21–0.23 mm in diameter), the latter showing a well-developed layer of tubular chamberlets in its upper part. Specimens from the type-locality Villarroya de los Pinares (Teruel Province, eastern Spain) attain a height of 3–4 mm and a breadth of 4–5 mm.

(3) Subdivision of the marginal zone. *M. glanensis* is mainly characterised by the absence of horizontal plates within this zone. However, some topotypes of this species show sporadically this structural characteristic, which subsequently is regularly present in *M. alguerensis*. A system of subepidermal plates forming a layer of chamberlets is highly developed in *M. arabica* and becomes still more complex in *R. giganteus*.

**B. Eopalorbitolina pertenuis - Palorbitolinoides hedini lineage (Figures 5 and 8)**

This lineage was established by Schroeder et al. (2002) and Cherchi and Schroeder (2004a). It comprises the following seven species in chronological order:

(1) *Eopalorbitolina pertenuis* (Foury, 1968)
- 1968 Eopalorbitolina pertenuis n. sp.- Foury, p. 148–151; pl. 18, fig. 17.

(2) *Eopalorbitolina charollaisi* Schroeder and Conrad, 1968
- 1968 Eopalorbitolina charollaisi n. gen. et n. sp.- Schroeder and Conrad, p. 149–155; pl. 1, figs. 1–5; pl. 2, figs. 1–7; pl. 3, figs. 1–3; pl. 4, figs. 1–6.
- 2002 Eopalorbitolina charollaisi Schroeder & Conrad.- Schroeder et al., p. 862; pl. 2, figs. 3–4, II.

(3) *Eopalorbitolina transiens* (Cherchi and Schroeder, 1999)
- 1999a Valserina transiens n. sp.- Cherchi and Schroeder, p. 5–6; pl. 1, figs. 1–13.
- 2002 Eopalorbitolina transiens (Cherchi & Schroeder, 1999).- Schroeder et al., p. 860–862; pl. 6, 8.

(4) *Palorbitolina lenticularis* (Blumenbach, 1805)
- 1805 Madreporites lenticularis.- Blumenbach, pl. 80, figs. 1–6.
- 1816 Orbuites lenticulata.- Lamarck, p. 197.
- 1850 Orbitolina lenticulata Lamarck.- d’Orbigny, p. 184.
- 1963 Orbitolina (Palorbitolina) lenticularis (Blumenbach 1805).- Schroeder, p. 348–354; pl. 23, figs. 2, 7, 9.
- 1964a Palorbitolina lenticularis (Blumenbach 1805).- Schroeder, p. 465.
- 1994 Palorbitolina lenticularis (Blumenbach, 1805).- Witt and Gökdag, pl. 10.1, fig. 2.
- 1999 Palorbitolina lenticularis (Blumenbach).- Bosellini et al., figs. 5b, i–l.

(5) *Palorbitolina ultima* Cherchi and Schroeder n. sp.
- 1978 Palorbitolina lenticularis (Blumenbach) 1805.- Cherchi et al., pl. 3, fig. 3.
- 1993a Palorbitolina lenticularis (Blumenbach).- Luperto Sinni and Masse, pl. 27, figs. 1, 5.
- 1998 Palorbitolina lenticularis (Blumenbach 1805).- Cherchi et al., pl. 3; fig. 3.
- 2001 Palorbitolina lenticularis (Blumenbach).- Husinec, pl. 1, fig. 1.

(6) *Palorbitolinoides cf. orbiculata* Zhang, 1986
- 1978 Palorbitolina lenticularis (Blumenbach) 1805.- Cherchi et al., pl. 2, fig. 8.

(7) *Palorbitolinoides hedini* Cherchi and Schroeder, 1980
Figure 5: (a) Eopalorbitolina - Palorbitolinoides phylogenetic lineage. The embryo of Eopalorbitolina is in eccentric position, and of Palorbitolina/Palorbitolinoides in centric position. The periembyronic zone (screened area) of Eopalorbitolina is wedge-shaped, becoming annular in Palorbitolina and covering also completely the base of the globular chamber in Palorbitolinoides.

(b) Illustrations of specimens: (1) Eomalorbitolina pertenuis (Foury), median section (RN 12-6), Roca de Narieda, Organyà, Lérida Province, Northeast Spain, Early Barremian. (2) Eomalorbitolina charollaisi Schroeder and Conrad, median section, holotype (42-2), Rocher des Hirondelles, Ain department, Southeast France, Early Barremian. (3) Eomalorbitolina transiens (Cherchi and Schroeder), median section (4111), Wadi Mu’aydin, Oman, Late Barremian. (4) Palorbitolina lenticularis (Blumenbach), axial section of a primitive form (GR 5-2), Graua, Southeast Ethiopia, Early Aptian. (5) Palorbitolina lenticularis (Blumenbach), axial section of an advanced form (GR 5-4), Graua, Southeast Ethiopia, Early Aptian. (6) Palorbitolina ultima Cherchi and Schroeder, axial section, holotype (102-5), Road house “Dolmen de Bisceglie” of the motorway Napoli-Bari, Apulia, South Italy, Early Aptian. (7) Palorbitolinoides cf. orbiculata, axial section (A.5710.1), locality and age as in (6). (8) Palorbitolinoides hedini Cherchi and Schroeder, axial section, holotype (106-9), Shigatse, South Tibet, Early Albian.
Figure 6: (a) Praeorbitolina-Mesorbitolina phylogenetic lineage. The embryo of Praeorbitolina is in eccentric position and of Mesorbitolina in a centric position.

(b) Illustrations of specimens. (1) Praeorbitolina cormyi Schroeder, median section (QM 26-7), Al Mukalla, Hadhramaut, South Yemen, Early Aptian. (2) Praeorbitolina wienandsii Schroeder, median section (QM 20-3), Al Mukalla, Hadhramaut, South Yemen, Early Aptian. (3) Mesorbitolina parva (Douglass), axial section (SO-1), Sopexano 4 well, Valle de Mena, Burgos Province, North Spain, Late Aptian. (4) Mesorbitolina texana (Roemer), axial section (VI 3806-15), Villarroya de los Pinares, Teruel Province, East Spain, Late Aptian. (5) Mesorbitolina gr. subconcava (Leymerie), axial section (E 1-30), Eguierreta, Navarra Province, North Spain, Late Albian. (6) Mesorbitolina aperta (Eiman), axial section (SA 7-5), Sierra de Aule, Huesca Province, North Spain, Late Albian.
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1982 *Orbitolina (Orbitolina) bangoinica* Zhang sp. nov.- Zhang, p. 73; pl. 12, figs. 4–5.
1986 *Palorbitolinoides tenuis* sp. nov.- Zhang, p. 107; pl. 6, figs. 11–12.
1986 *Palorbitolinoides hedini* Cherchi et Schroeder.- Zhang, p. 105; pl. 2, figs. 8–10.

Figure 7: Transversal sections (a-e) through the embryonic apparatus of *Mesorbitolina* made up of three elements: 1 – protoconch, 2 – deuteroconch, 3 – subembryonic zone. Diagnostic criteria for *Mesorbitolina parva* (1) and *Mesorbitolina texana* (2) in transversal sections through the subembryonic zone are shown on the right.

The megalospheric embryonic apparatus of the before mentioned species (Figure 5) is located either in a somewhat eccentric position (*Eopalorbitolina*) or in a central position (*Palorbitolina, Palorbitolinoides*). It consists of a more or less globular embryonic chamber (in white) and a periembyonic zone (in grey). The external part of the central zone of the chamber layers is subdivided by radial partitions, which join together in the internal part of this zone producing an irregular network. All these structures are arranged in alternating position from one chamber layer to the next. Transversal and vertical plates subdivide the marginal zone into chamberlets, whose external part is lined by a layer of subepidermal cells.

The main evolutionary trends of this lineage refer to the position, morphology, increase and subdivision of the whole embryonic apparatus, as well as the extension of its periembyonic zone. *Eopalorbitolina pertenuis*, the first representative of this lineage, exhibits a bichambered embryo in a clear eccentric position (*Eopalorbitolina*) or in a central position (*Palorbitolina, Palorbitolinoides*). It appears in *E. charollaisi* as a wedge-shaped chamber laterally of the embryonic chamber and can be interpreted as the inflated original first postembryonic chamber. During the evolution of this lineage, the periembyonic zone embraces more and more the embryonic chamber. In *E. transiens* it laterally surrounds the upper half of the nearly centric embryonic chamber, the latter exhibiting for the first time a thin layer of chamberlets in its uppermost part.

The periembyonic zone of *Palorbitolina lenticularis* is annular (“periembryonic ring”), now completely surrounding the upper part of the centric embryonic chamber. This species grades into *P. ultima* Cherchi and Schroeder n. sp., characterised by its inflated annular periembryonic zone extending downwards to the base of the embryonic chamber, but without covering completely its basal surface. A detailed description of this new species (holotype: Cherchi et al., 1978: pl. 3, fig. 3), based upon a rich and well-preserved material from the Bari region (Apulia Carbonate Platform, southern Italy), is in preparation. In the Bari region and in the Zagros Ranges (sections Asaluyeh and Gach, Fars Province) *Palorbitolina ultima* is sometimes associated with an advanced form, whose periembryonic zone covers the embryonic chamber not only laterally but also underneath. We regard this latter form as the direct descendant of *P. ultima* and, at the same time, as the most primitive representative of the genus *Palorbitolinoides* Cherchi and Schroeder, 1980, characterised by this feature. Transitional specimens between these two taxa confirm our earlier assumption (1980) that *Palorbitolinoides* descends from *Palorbitolina*. This primitive *Palorbitolinoides* shows some similarities to *Palorbitolinoides orbiculata*, described by Zhang (1986) from
the Lower Cretaceous of the Lhasa Block (Tibet). Further studies are, however, necessary to confirm the identity between our specimens and this species and we therefore designate it at present as P. cf. orbiculata.

The final member of the Eopalorbitolina – Palorbitolinoides lineage is Palorbitolinoides hedini, described by Cherchi and Schroeder (1980) from Shigatse (Tsangpo valley, southern Tibet), which shows a well developed inflated periembyronic zone surrounding the large and flattened embryonic chamber. Parts of the first postembryonic chamber layer are also inflated, compared to the subsequent layers.

During the evolution of this lineage the dimensions of the embryonic apparatus gradually increased. The deuteroconch of Eopalorbitolina pertenuis has a diameter of only 0.1 mm, whereas the embryonic chamber of Palorbitolinoides hedini is 0.45–0.7 mm (diameter of the whole embryonic apparatus: 0.95–1.15 mm). Parallel to this evolutionary trend, the layer of chamberlets in the upper part of the embryonic chamber becomes increasingly complex and is finally developed in Palorbitolinoides hedini as a system of small alveoli of different length.

C. Praeorbitolina cormyi - Mesorbitolina aperta lineage (Figures 6, 7 and 8)

This lineage, established by Schroeder (1964b, 1975, 1979), comprises the following seven species in chronological order:

1. Praeorbitolina cormyi Schroeder, 1964
   - 1964b Praeorbitolina cormyi n. sp.- Schroeder, p. 412; text-fig. 1A.

2. Praeorbitolina wienandsi Schroeder, 1964
   - 1964b Praeorbitolina wienandsi n. sp.- Schroeder, p. 412; text-fig. 1B.
   - 1979 Praeorbitolina wienandsi Schroeder, 1964.- Schroeder, p. 291; pl. 1, fig. 2.
   - 1996 Praeorbitolina wienandsi Schroeder.- Claps et al., pl. 5, figs. 1, 5, 9–10, 12.

3. Mesorbitolina lotzei Schroeder, 1964
   - 1964a Orbitolina (Mesorbitolina) lotzei n. sp.- Schroeder, p. 469–470; text-fig. 3.
   - 1975 Orbitolina (Mesorbitolina) lotzei Schroeder.- Schroeder, p. 120–121; text-fig. 4.
   - 1979 Orbitolina (Mesorbitolina) lotzei Schroeder, 1964.- Schroeder, p. 291; pl. 1, fig. 3.

   - 1960 Orbitolina parva Douglass, n. sp.- Douglass, p. 39; pl. 9, figs. 4, 5.
   - 1964a Orbitolina (Mes.) texana parva Douglass 1960.- Schroeder, p. 470–471; text-fig. 4a.
   - 1979 Orbitolina (Mesorbitolina) parva Douglass, 1960.- Schroeder, p. 291; pl. 1, figs. 4, 5.
   - 1994 Orbitolina (Mesorbitolina) parva Douglass, 1960.- Witt and Gökdağ, pl. 10.1, figs. 8, 10.

5. Mesorbitolina texana (Roemer, 1849)
   - 1849 Orbitulites Texanus n. sp.- Roemer, p. 392.
   - 1852 Orbitulites Texanus.- Roemer, p. 86; pl. 10, fig. 7a–d.
   - 1964a Orbitolina (Mesorbitolina) texana texana (Roemer 1849).- Schroeder, p. 471; text-fig. 4b.
   - 1994 Orbitolina (Mesorbitolina) texana (Roemer, 1852).- Witt and Gökdağ, pl. 10.1, figs. 7, 9.

6. Mesorbitolina subconcava (Leymerie, 1881)
   - 1878 Orbitolina sub-concava, Leym.- Leymerie, pl. E, fig. 7.
   - 1881 Orbitolina sub-concava, Leym.- Leymerie, p. 754.
   - 1960 Orbitolina texana (Roemer).- Douglass, p. 34–36; pl. 6, figs. 1–7.
   - 1972 Orbitolina (Mes.) subconcava Leym.- Jaffrézo and Schroeder, p. 804.
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1973 Orbitolina (Mesorbitolina) sp. A.- Fourcade and Raoult, p. 239–240; pl. 1, figs. 8–9.
1979 Orbitolina (Mesorbitolina) subconcava Leymerie 1878.- Schroeder, p. 294; pl. 1, fig. 8.
1985 Orbitolina (Mesorbitolina) subconcava Leymerie, 1878.- Schroeder in Schroeder and Neumann, p. 80–82; pl. 37, figs. 1–8.

(7) Mesorbitolina aperta (Erman, 1854)
1854 Orbitolites apertus mihi.- Erman, p. 603–606; pl. 23, figs. 1-3.
1962 Orbitolina (Mesorbitolina) texana aperta (Erman 1854).- Schroeder, p. 182–184; text-fig. 5.
1985 Orbitolina (Mesorbitolina) aperta (Erman, 1854).- Schroeder in Schroeder and Neumann, p. 82–85; pl. 38, figs. 1–6.
1999c Mesorbitolina aperta (Erman).- Cherchi and Schroeder, p. 320; pl. 1, figs. 3, 7, 9.

As in the species of the Eopalorbitolina pertenuis - Palorbitolinoides hedini lineage, the external part of the central zone of the chamber layers is subdivided by radial partitions joining together in the internal part of this zone and producing a reticulate pattern. The structural elements of this zone alternate in position from one chamber layer to the next. The marginal zone is subdivided by transversal and vertical plates into chamberlets, whose external part is lined by a layer of subepidermal cells. The most important character allowing a reconstruction of this lineage is the megalospheric embryonic apparatus (Figure 6). It is located either in a somewhat eccentric position (Praeorbitolina) or is centrically situated (Mesorbitolina) and consists of the protoconch, the deuteroconch (both in white), and the subembryonic zone (in red).

Figure 7 exhibits some schematic sections through the embryonic apparatus (from Schroeder, 1975, text-figure 3). The axial section in the centre shows: (1) the globular protoconch with a crumpled pseudochitinous wall, (2) the deuteroconch above the protoconch, and (3) the subembryonic zone below the protoconch. The transversal sections (a–e) run: (a) through the lower part of the deuteroconch, subdivided by radially directed plates, (b) and (d) through the alveolar layers of the deuteroconch and the subembryonic zone, and (c) through the middle and (e) the uppermost part of the subembryonic zone with radially directed plates.

Praeorbitolina cornyi Schroeder, 1964, the oldest representative of this lineage, shows a clearly developed initial spiral and a bilateral symmetrical embryonic apparatus, whose deuteroconch is still undivided. In median sections, the subembryonic zone seems also to be undivided; however, sections directed perpendicularly to the median plane exhibit some plates running parallel to this plane. This species is followed by Praeorbitolina wienandsi Schroeder, 1964, whose initial spiral is reduced to the embryo and only 2–3 cuneiform postembryonic chamber layers. The deuteroconch shows sometimes in its uppermost part one or two rudimentary plates, whereas the subembryonic zone exhibits a basal layer of chamberlets.

Mesorbitolina lotzei Schroeder, 1964, the direct descendant of P. wienandsi, is characterised by the centric position of the embryo, which is laterally surrounded by an annular first postembryonic chamber. The deuteroconch of this species is still undivided or shows rare rudimentary plates in its uppermost part; however, the subembryonic zone presents a small but well-developed alveolar layer. The deuteroconch of Mesorbitolina parva (Douglass, 1960) shows for the first time a complete system of alveoli. Transversal sections through the upper part of the subembryonic zone exhibit the diagnostic character of this species: the distance between two neighbouring radially directed plates is generally greater than the distance between the protoconch and the first postembryonic chamber (Figure 7, no. 1). In contrast, in Mesorbitolina texana (Roemer, 1849) the distance between two neighbouring radially directed plates is generally the same as or smaller than the distance between the protoconch and the first postembryonic chamber (Figure 7, no. 2).

Due to the general enlargement and especially the widening of the whole embryonic apparatus, the originally subglobular protoconch (M. parva, M. texana) flattens and becomes irregularly lenticular. At the same time the alveolar layer of the deuteroconch and the subembryonic zone becomes more complex. The alveoli of the deuteroconch of Mesorbitolina subconcava (Leymerie, 1878), generally subdivided by a set of shorter plates, lead not only to the protoconch, but also to the lower part of the deuteroconch (Figure 6). The upper part of the deuteroconch of Mesorbitolina aperta (Erman, 1854) is subdivided by several sets of alveoli of different length and breath, whereas the basal part exhibits a more or less
Figure 8 (facing page): Orbitolinid foraminifera of the eastern Arabian Plate.

(1 and 7) Dictyoconus tunesianus (Peybernès) [1: subaxial section; 7: tangential section (FT 882)], Meymand, southwest Iran, Late Aptian (x50).

(2, 12 and 13) Mesorbitolina parva (Douglass) [2, 12: axial sections (2: FC 4; 12: FC 5)], Kuh-e-Fahliyan, southwest Iran; 13: transversal section cutting the protoconch and the subembryonic zone (M A 31), Kuh-e-Mangasht, southwest Iran, Late Aptian (x100).

(3, 4 and 9) Eopalorbitolina transiens (Cherchi and Schroeder), axial sections [3: W adi Nakhr/Oman (Ga 1 1); 4, 9: W adi Mu’aydin, Oman (M 11 1)], Late Barremian (x100).

(5) Mesorbitolina texana (Roemer), axial section (FT 883), Meymand, southwest Iran, Late Aptian (x100).

(6) Mesorbitolina gr. subconcava (Leymerie), axial section (FT 894), Meymand, southwest Iran, Early Albian (x50).

(8) Palorbitolina lenticularis (Blumenbach), axial section (BHM 47), Asaluyeh, southwest Iran, Early Aptian (x100).

(11) Praeorbitolina cormyi Schroeder, oblique section showing the embryonic chamber (proto- and deuteroconch) and the drop-like subembryonic zone (arrow) (M 159), W adi Mu’aydin, Oman, Early Aptian (x100).

(14) Palorbitolina ultima Cherchi and Schroeder, axial section (QR 2-3), Al Mukalla, Hadhramaut, Yemen, Early Aptian (x100).

(15 to 17) Palorbitolinoides cf. orbiculata Zhang, axial sections [15 and 17: Asaluyeh, southwest Iran (15: BHM 51; 17: BHM 53); 16: Gach, southwest Iran (MZY 402)], Early Aptian (x100).
developed irregular network of plates, which in highly evolved specimens are frequently joined with the longest set of alveoli.

During the evolution of this lineage the diameter of the embryonic apparatus gradually increases: from 0.08–0.09 mm in *Praorbitolina cornyi* up to 1.4 (max. 1.9) mm in *Mesorbitolina aperta*. Microspheric specimens of this latter species attain a diameter of maximally 58 mm.

**Revised Orbitolinid Biostratigraphic Zonation for the Barremian – Aptian of the Eastern Arabian and Northeastern African Plates**

In the past, a few authors have presented orbitolinid biostratigraphic zonations for this region, which were, however, restricted only to partial areas of the Arabian Plate: Sampò (1969) for the Zagros area (southwest Iran) and Simmons (1994) as well as Witt and Gökdag (1994) for northern Oman. In the Zagros area, Sampò (1969) established within the Early Cretaceous four orbitolinid biozones: (1) the “Dictyoconus arabicus Zone” (Barremian), containing also “Orbitolina discoidea delicata”, (2) the lituolid “Choffatella decipiens Zone” (Aptian) with “Orbitolina discoidea conoidea” and “Orbitolina lenticularis”, (3) the “Orbitolina discoidea-conoidea Zone” (Albian), showing also “Orbitolina kurdica” and “Orbitolina concava”, and (4) a “large Orbitolina Zone” (Albian) with “Orbitolina concava subsp.”. All these orbitolinid determinations refer to the monograph of Henson (1948), and are now obsolete (except *Dictyoconus arabicus*) and therefore not applicable.

Simmons (1994) presented a biozonation scheme of the central Oman Mountains, based upon larger foraminifers and algae (Figure 9a) for the Late Barremian and Early Aptian (Kharaib and Shu’aiba formations). Within this time interval he established a *Palorbitolina lenticularis* Zone, including the *Eopalorbitolina charollaisi*, *Paleodictyoconus arabicus* and *Palorbitolina lenticularis* Subzones. Witt and Gökdag (1994) published a chart showing the total range of orbitolinids and some other microfossils, recorded in Late Barremian to Albian cores (Kharaib, Shu’aiba and Nahr Umr formations) of northern Oman (Figure 9b). Although these authors did not establish formal biozones, their studies allow differentiating some intervals, each of them characterised by one or more orbitolinid species. A *Palorbitolina lenticularis* interval of Late Barremian – Early Aptian age (corresponding to the zone of the same name of Simmons) contains in its lower part *Paleodictyoconus arabicus* and in its upper half...
**Praeorbitolina cormyi** and **Mesorbitolina lotzei**. The successions of the Late Aptian – Albian are characterised by species of the **Mesorbitolina** lineage: **M. parva** and **M. texana**.

The recent study of a number of orbitolinid-bearing outcrop sections in shallow-water carbonate platform environments and intra-shelf basin margins from different regions of the eastern Arabian and northeastern African plates (Ethiopia, Somalia, Yemen, Oman, United Arab Emirates and southwest Iran) has provided sufficient material to propose a revised orbitolinid biostratigraphic zonation for this area. The ranges of orbitolinids found in these sections, completed by additional information of other localities from the literature, were combined in a composite range chart (Figure 10). On the basis of this chart, a biozonation scheme is proposed (Figure 10) with a subdivision of the Barremian – Aptian successions into six zones and three subzones (numbered in chronological order):

(6) **Mesorbitolina gr. subconcava** Zone
(5) **Mesorbitolina texana** Zone
(4) **Mesorbitolina parva** Zone
   - 3b. **Palorbitolinoides cf. orbiculata** Subzone
   - 3a. **Palorbitolina ultima** Subzone
(3) **Praeorbitolina cormyi** Zone
   - 2a. **Montseciella arabica** Subzone
(2) **Palorbitolina lenticularis** Zone
(1) **Eopalorbitolina transiens** Zone
The base of each biostratigraphic unit is defined by the inception of its nominate taxon, whereas the top is marked by the lowest occurrence of the index taxon of the following unit or in some cases (Zone 6, Subzones 2a, 3b) by the disappearance of the nominate taxon. In the following, the biozonation scheme is described in detail in ascending stratigraphic order.

1. Eopalorbitolina transiens Zone

Definition: Interval from first occurrence of Eopalorbitolina transiens Cherchi and Schroeder to first occurrence of Palorbitolina lenticularis (Blumenbach).

Distribution:
North Somalia
- Bosaso region: Ahl Medo Range (Cherchi and Schroeder, 1999a).
Oman
- Al Huqf area (South Oman) (this paper).
- Al Jabal al-Akhdar (North Oman): Wadi Mu’aydin section; Wadi Nakhr section; Wadi Madar section (all this paper).

Abu Dhabi (UAE)
- Offshore well in Field “A” (Granier et al., 2003; this paper).

Southwest Iran
- The oldest determinable orbitolinid association of the Asaluyeh section (Fars) comprises *Eopalorbitolina transiens*, *Palorbitolina lenticularis* and *Montseciella arabica*, belonging to the *P. lenticularis* Zone. The underlying 15 m thick interval with indeterminable orbitolinids could belong to the *Eopalorbitolina transiens* Zone in the above-mentioned sense.

**Age:** This species ranges from the end of the Early Barremian to the earliest Late Barremian (Schroeder et al., 2002). In this study, the *Eopalorbitolina transiens* Zone comprises probably the early Late Barremian.

**Comments:** This interval corresponds to the “*Eopalorbitolina charollaisi* Subzone” of Simmons (1994). The nominate taxon was figured under this name by that author (1994: Plate 9.3, figure 4) and by Simmons and Hart (1987: Plate 10.2, figure 6) from the Wadi Mu’aydin section (Central Oman Mountains) and dated as Late Barremian referring to papers of Schroeder and Conrad (1968: middle to upper Barremian), Arnaud-Vanneau (1980: Late Barremian) and Moullade et al. (1985, not dated). However, the figured specimen belongs to *Eopalorbitolina transiens*, whereas the age of the true *E. charollaisi* is Early Barremian (Clavel et al., 2007).

2. *Palorbitolina lenticularis* Zone

**Definition:** Interval from the first occurrence of *Palorbitolina lenticularis* (Blumenbach) to first occurrence of *Praeorbitolina cormyi* Schroeder.

**Distribution:**
Oman
- Al Huqf area (Immenhauser et al., 2004; this paper).
- Al Jabal al-Akhdar: Jabal Madar, Wadi Mu’aydin and Wadi Nakhr sections (this paper), containing *Eopalorbitolina transiens* and *Montseciella arabica*.
- Rakha-1 well (Witt and Gökdağ, 1994: Figure 10.2).

Southwest Iran
- Fars: Asaluyeh section (this paper), containing *Eopalorbitolina transiens* and *Montseciella arabica*; Gach section (this paper).

**Age:** *Palorbitolina lenticularis* ranges from the Late Barremian to the Early/Late Aptian boundary (Schroeder, 1963). The *P. lenticularis* Zone comprises the Late Barremian (excluding its lowermost part) and the early Early Aptian (*Deshayesites oglanlensis* and *D. weissi* ammonite Zones).

2a. *Montseciella arabica* Subzone

**Definition:** Interval of total range of *Montseciella arabica* (Henson).

**Distribution:**
South Yemen
- Wadi Masila section (Mahra Province) (Beydoun, 1968).

North Oman
- Al Jabal al-Akhdar: Wadi Mu’aydin and Wadi Nakhr sections (this paper), containing *Palorbitolina lenticularis*; Jabal Madar section (this paper), containing *Eopalorbitolina transiens* and *Palorbitolina lenticularis*.

Abu Dhabi (UAE)
- Offshore well in Field “A” (Granier et al., 2003; this paper), containing *Eopalorbitolina transiens* and *Palorbitolina lenticularis*.

Southwest Iran
- Fars: Asaluyeh section (this paper), containing *Eopalorbitolina transiens* and *Palorbitolina lenticularis*. 66
Barremian – Aptian biostratigraphic zonation, eastern Arabian Plate

- Khuzestan: Kuh-e-Fahliyan section (this paper).
- High Zagros: Kuh-e-Mangasht section (this paper).

North Somalia
- Bosaso region: Ahl Medo section (Cherchi and Schroeder, 1999a).

**Age:** *Montseciella arabica* (= *Dictyoconus arabicus* Henson) was described by that author (1948) from “Barremian?” limestones with *Orbitolina discoidea* var. *delicata* var. nov.” (= *Palorbitolina lenticularis*; cf. Schroeder, 1963) of Qatar. The presence of this latter species excludes an Early Barremian age. At present, *Montseciella arabica* is mostly regarded as a zonal marker of the Late Barremian. This age is confirmed by the co-occurrence in some localities with Late Barremian ammonites (e.g. Constantine region, northeastern Algeria: Gramont and Lombard, 1967; Schroeder et al., 1978: biozone IV, associated with *Palorbitolina lenticularis*). In Lebanon, however, *M. arabica* was reported by Saint-Marc (1970, Plate 1, figures 12, 13, 15; non figure 14 [= *Palorbitolina*]) from the lower half of the so-called “Falaise de Blanche.” This formation contains in its uppermost part *Praeorbitolina wienandsi* (erroneously determined as “Mesorbitolina lotzei” by Saint-Marc), a characteristic species of the late Early Aptian. Probably, *M. arabica* ranges therefore in this region into the Early Aptian. In eastern Spain, *M. arabica* occurs together with its direct phyletic descendant *Rectodictyoconus giganteus* in the early Early Aptian (Cherchi and Schroeder, unpublished). They were also reported by Luperto Sinni and Masse (1987) from the early Aptian of the Gargano Promontory (Apulia Carbonate Platform, southern Italy). In the uppermost part of the *Montseciella arabica* interval in Field “A” from Abu Dhabi, this species is associated with transitional forms to *Rectodictyoconus giganteus*, showing a nearly centric embryonic apparatus.

On the basis of the available data, the stratigraphic range of *Montseciella arabica* is Late Barremian to early Early Aptian, with its maximum development in the Late Barremian (Baud et al., 1994). The *Montseciella arabica* Subzone of the eastern Arabian and northeastern African plates has to be placed approximately from the middle to end of the Late Barremian.

### 3. Praeorbitolina cormyi Zone

**Definition:** Interval of total range of *Praeorbitolina cormyi* Schroeder.

**Distribution:**
- Southeast Ethiopia
  - Graua (Bosellini et al., 1999), containing *Palorbitolina lenticularis*.

- South Yemen
  - Al Mukalla (Hadhramaut) (Cherchi et al., 1998), containing *Palorbitolina ultima* and *Praeorbitolina wienandsi*.

- North Oman
  - Al Jabal al-Akhdar: Wadi Mu’aydin and ?Wadi Nakhr sections (this paper), containing *Palorbitolina lenticularis* and *P. ultima*.
  - Rakha-1 well (Witt and Gökdağ, 1994: Plate 10.1, figure 6), containing “*Palorbitolina lenticularis*”.

- Southwest Iran
  - Fars: Gach section (this paper), containing *Palorbitolina lenticularis*, *P. ultima*, *Praeorbitolina wienandsi* and *Palorbitolinoides* cf. *orbiculata*; ?Asaluyeh section (this paper), containing *Palorbitolina lenticularis*.

**Age:** late Early Aptian (*Deshayesites deshayesi* and *D. furcata* ammonite Zones).

**Comments:** According to Schroeder (1975), *Praeorbitolina* characterises “approximately the upper part of the Lower Aptian.” Masse (2003) called the attention to the absence of this genus in well-dated platform carbonates of early Early Aptian age in Spain. We believe that the appearance of *Praeorbitolina* is in connection with one of the most widespread drowning events of the geological record (T13; Jacquin et al., 1998; Bosellini et al., 1999), beginning in the *Deshayesites weissi* ammonite Zone. In this zone, *Praeorbitolina cormyi* seems to develop from an unknown, probably endemic ancestor, spreading in the subsequent *Deshayesites deshayesi* Zone over vast areas of the Neo-Tethyan realm (e.g. Mediterranean region, Tanzania, Ethiopia, Oman, Iran, Afghanistan, Tibet, Japan) (Cherchi and Schroeder, 2009).
In the uppermost part of the *Praeorbitolina cormyi* interval (Al Mukalla, Yemen: Cherchi et al., 1998; Gach section, southwest Iran: this paper) this species is associated with *P. wienandsi*. In southern France (Corbieres, La Clape) the two species occur within a series dated by *Deshayesites deshayesi* and *D. furcata* as belonging to the late Early Aptian ammonite Zones of the same names (Jaffrézo and Schroeder, 1972; Peybernès, 1976). In eastern Spain (Teruel Province), *P. wienandsi* was found in the type-level of *Mesorbitolina lotzei* (Schroeder, 1964 and new data), located above a horizon with *Deshayesites deshayesi*. Therefore, *Praeorbitolina wienandsi* could be restricted to the *D. furcata* ammonite Zone.

*Mesorbitolina lotzei* as the connecting link between *Praeorbitolina wienandsi* and *Mesorbitolina parva* was not proved in the studied sections, probably because the vertical range of this species is very small. It is therefore surprising that Witt and Gökdağ (1994, figure 10.2; Figure 9 of our paper) give for *Mesorbitolina lotzei* nearly the same range as for *Praeorbitolina cormyi*. We suppose that a considerable part of the former species is based upon sections of *P. cormyi* and/or *P. wienandsi*, which are perpendicularly directed to the median plane of the initial spiral, thus simulating the centrically located embryo of *Mesorbitolina lotzei*.

### 3a. *Palorbitolina ultima* Subzone

**Definition:** Interval from first occurrence of *Palorbitolina ultima* Cherchi and Schroeder to first occurrence of *Palorbitolinoides cf. orbiculata* Zhang.

**Distribution:**

- **South Yemen:** Al Mukalla (Hadhramaut) (Cherchi et al., 1998), containing *Palorbitolina lenticularis* and *Praeorbitolina cormyi*.
- **North Oman:** Al Jabal al-Akhdar: Jabal Madar section, containing *Palorbitolina lenticularis*; Wadi Mu’aydin section, containing *Palorbitolina lenticularis* and *Praeorbitolina cormyi*; Wadi Nakhr section, containing *Praeorbitolina cormyi* (all this paper).
- **Southwest Iran:** Asaluyeh section, containing *Palorbitolina lenticularis*; Gach section, containing *Palorbitolina lenticularis*, *Palorbitolinoides cf. orbiculata* and *Praeorbitolina cormyi* (all this paper).

**Age:** Late Early Aptian.

### 3b. *Palorbitolinoides cf. orbiculata* Subzone

**Definition:** Interval of total range of *Palorbitolinoides cf. orbiculata* Zhang.

**Distribution:**

- **Southwest Iran:** Fars: Asaluyeh section, containing *Palorbitolina lenticularis*; Gach section, containing *Palorbitolina lenticularis*, *Palorbitolinoides cf. orbiculata* and *Praeorbitolina cormyi* (all this paper).

**Age:** Latest Early Aptian.

**Comments:** *Palorbitolinoides cf. orbiculata*, associated with *Palorbitolina ultima*, rare *P. lenticularis*, as well as *Praeorbitolina cormyi* and *P. wienandsi* were found in the environs of Bari (Apulia Carbonate Platform, southern Italy; Cherchi and Schroeder, unpublished). This level was dated by Cherchi et al. (1978) as Late Early Aptian.

### 4. *Mesorbitolina parva* Zone

**Definition:** Interval from first occurrence of *Mesorbitolina parva* (Douglass) to first occurrence of *Mesorbitolina texana* (Roemer).

**Distribution:**

- **Southwest Iran:** High Zagros: Kuh–e–Mangasht section (this paper).
- Khuzestan: Kuh-e–Fahliyan section (this paper), at the base of this interval ammonites *Epicheloniceras* *gr.* *buxtorfi*, and *Epicheloniceras* *gr.* *martinoides* were found, and a loose specimen of *Nolaniceras nolani* (Vincent et al., 2010).

**Age:** early Late Aptian.

**Comments:** In southwest Europe, *Mesorbitolina parva* appears as direct descendant of *M. lotzei* at the start of the Late Aptian (Schroeder, 1975) and ranges up in the Pyrenees to the late Late Aptian (Clansayesian, *Nolaniceras nolani* ammonite Zone; Peybernès, 1976). In the southeastern European Karst Dinarides, the “*Mesorbitolina parva* lineage Zone” ranges from the “transitional level Early – Late Aptian to the Late Aptian (Gargasian)” (Velić, 2007). It can, however, not be excluded that this species already appeared in the latest Early Aptian.

5. *Mesorbitolina texana Zone*

**Definition:** Interval from first occurrence of *Mesorbitolina texana* (Roemer) to first occurrence of *Mesorbitolina gr.* *subconcava* (Leymerie).

**Distribution:**
North Oman
- Al Jabal al-Akhdar: Wadi El Assy section (Masse et al., 1997).

Southwest Iran
- Khuzestan: Kuh-e–Fahliyan section (this paper), containing *Mesorbitolina parva* (upper Dariyan Formation).
- High Zagros: Kuh-e–Mangasht section (this paper).

**Age:** late Late Aptian.

**Comments:** In southwest Europe, *Mesorbitolina texana* appears in the middle of the Late Aptian (Schroeder, 1975), ranging up in the Pyrenees to the end of the Middle Albian (Peybernès, 1976, recorded by that author under the name *M. minuta*). In the southeastern European Karst Dinarides, the “*Mesorbitolina texana* lineage Zone” has a late Late Aptian age (Velić, 2007).

6. *Mesorbitolina gr.* *subconcava* Zone

**Definition:** Interval of total range of *Mesorbitolina gr.* *subconcava* (Leymerie).

**Distribution:**
North Oman
- Al Jabal al-Akhdar; Wadi El Assy section (Masse et al., 1997).

Southwest Iran
- Khuzestan: Kuh-e–Fahliyan section, Kazhdumi Formation (this paper), containing *Mesorbitolina texana* and *M. aperta* (primitive forms), as well as the ammonite *Knemiceras aff. kazhdumiense* and *Mirapelia* spp., just above an assemblage with *K. persicum* (Vincent et al., 2010).
- High Zagros: Kuh-e–Mangasht section, top Dariyan Formation (this paper), containing *Mesorbitolina cf. texana*. Meymand section (this paper), containing *Mesorbitolina cf. texana* as well as *Dictyoconus tunesianus* and *Hemicyclammina sigali* in its middle part (upper Dariyan Formation).

**Age:** latest Late Aptian to early Middle Albian (*Hoplites dentatus* ammonite Zone).

**Comments:** In southwest Europe, *Mesorbitolina gr.* *subconcava* appears in the latest Late Aptian (Schroeder, 1975), ranging up in the Pyrenees to the Late Albian (Peybernès, 1976, recorded by that author under the name *M. texana*). In the southern European Karst Dinarides, the “*Mesorbitolina subconcava* taxon–range Zone” comprises the “transitional level between the Aptian and Albian and/or the Early Albian” (Velić, 2007).
Figure 11 (facing page): Early Aptian and Early Albian benthic foraminifera of the eastern Arabian Plate.

1. Chof fatella decipiens Schlumberger, equatorial section (N 107), Wadi Nakhr, Oman, Early Aptian (x50).

2 to 4. Voloshinoides murgensis Luperto Sinni and Masse, 2: tangential section (Ga 30), Wadi Nakhr, Oman (x50); 3: transversal section (ASL 2564), Asaluyeh, southwest Iran (x100); 4: subaxial section (ASL 2564), Asaluyeh, southwest Iran (x100), Early Aptian.

5, 11 to 13. Praechrysalidina infracretacea Luperto Sinni, 5: transversal section showing the triserial stage (Ma 15), Kuh-e-Mangasht, southwest Iran (x50); 11: tangential section (Ga 29), Wadi Nakhr, Oman (x50); 12: axial section (N 124), Wadi Nakhr, Oman (x50); 13: subaxial section (MZ 358), Gach, southwest Iran (x50), Early Aptian.

6. Hemicyclammina sigali Maync, equatorial section (FT 887), Meymand, southwest Iran, Early Albian (x50).

7, 10 and 14. Archaealveolina sp., 7: nearly axial section (FT 850) (x50); 10: tangential section (FT 850) (x100); 14: subequatorial section (FT 852) (x40), Meymand, southwest Iran, Early Aptian.

8. Charientia cuvillieri Neumann, axial section (BHM 48), Asaluyeh, southwest Iran, Early Aptian (x50).

9. Tr ocholina sagittaria Arnaud-Vanneau et al., axial section (M 136), Wadi Mu’aydin, Oman, Early Aptian (x50).

10. Tr oglotella incrustans Wernli and Fookes, a boring cryptobiotic foraminifer, longitudinal section (ASL 2564), Asaluyeh, southwest Iran, Early Aptian (x40).
Of special stratigraphic interest is the occurrence of the orbitolinid foraminifer *Dictyoconus tunesianus* (Peybernès et al., 1981) (synonym: *Dictyoconus algerianus*; see Cherchi and Schroeder, 1982) illustrated in Figure 8. This species was recorded before in the Mediterranean region (e.g. Algeria, Tunisia, Sicilia) from different carbonate platforms, located at the southern Tethyan margin. In Algeria (Constantine region), the beds containing *D. tunesianus* can be dated by means of ammonites as uppermost Late Aptian (Clansayesian) (Vila, 1980), but it cannot be excluded that the species appears on both sides of the border between Algeria and Tunisia already in somewhat older Late Aptian horizons (Gargasan) (Cherchi and Schroeder, 1982).

**STRATIGRAPHIC REFERENCE SECTIONS**

The material that was used for the revision of the orbitolinid biozonation comes from a large number of sections in the Middle East and northeast Africa. Here a selection of these stratigraphic sections is presented, in order to demonstrate the consistency of the assemblages, and how their stratigraphic distribution is related to well-established Barremian and Aptian depositional sequences. In addition to the orbitolinids, a number of other typical benthic foraminifera are also recorded and illustrated in Figure 11. The studied sections are located in regional palaeogeographic maps of the Late Barremian maximum flooding (Figure 12a), and of the late Early Aptian maximum flooding (Figure 12b). They are presented starting with the northeastern African Plate, then moving along the southern and eastern parts of the Arabian Plate from Yemen to southwest Iran.

**Northeast Ethiopia and Somalia**

In northeast Ethiopia, along the eastern margin of the African Plate, a thin band (10 m thick) of shallow-water limestones of the Graua Formation occurs embedded in a thick succession of terrestrial deposits of the Amba Aradam Formation (Figure 13). This limestone contains abundant specimens of *Palorbitolina lenticularis* and *Praeorbitolina cormyi* (Bosellini et al., 1999), and was dated as late Early Aptian.

The Graua Limestone was deposited in an overall transgressive-regressive trend along the eastern African Plate starting in the Late Barremian. This overall trend is also illustrated in the more seaward position of the Ahl Medo II section in Somalia (Cherchi and Schroeder, 1999a; Figure 12a), where Late Barremian shallow-water carbonates, containing *Montseciella arabica*, are overlain by a sharp flooding
Figure 12: Schematic palaeogeographical maps of the eastern African and Arabian plates and study locations showing (a) the regional flat shelf which existed during the Late Barremian (maximum flooding surface of AP Barremian 2 Sequence; from van Buchem et al., 2010a), and (b) the platform and intra-shelf basin topography that existed during the late Early Aptian (maximum flooding surface of the AP Aptian Supersequence). Palaeogeography of Somalia and Ethiopia is after Bosellini et al. (1999). (1a) Ahl Medo section (Bosaso, North Somalia; Cherchi and Schroeder, 1999a); (2a) Wadi Masila section (Yemen; Beydoun, 1968). See Figure 1 caption for description of other study locations.
surface and marls with an Aptian age ammonite fauna (*Cheloniceras* spp., *Parahoplites* sp.; Luger et al., 1990).

**Yemen**

In Yemen, just across from the African sections, a very similar stratigraphic organisation has been found. The Hadhramaut sections (QR and QM; Figure 14) are characterised by the presence of a 15-m-thick marine carbonate bed of the Qishn Formation (Unit 3), intercalated between the continental deposits of the Harshiyat Formation (Cherchi et al., 1998). The carbonates are rich in orbitolinids and contain several species indicative of the late Early Aptian: *Praeorbitolina cormyi*, *Praeorbitolina wienandsi*, *Palorbitolina lenticularis* and *Palorbitolina ultima*. In the QM section *Mesorbitolina lotzei* has also been recorded.

The Qishn limestones were also deposited in an overall transgressive-regressive trend. In a more seaward position, in the Wadi Masila section (Figure 12a), the overall transgression is also clearly recognised with Late Barremian shallow-water carbonates containing *Montseciella arabica*, which are overlain by marls with an Aptian ammonite fauna (Beydoun, 1968).

**Oman**

In Oman five published sections have been re-examined for their orbitolinid content, four in northern Oman (Al Jabal al-Akhdar and Jabal Madar; Pittet et al., 2002; van Buchem et al., 2002) and one in eastern Oman (Al Huqf area; Immenhauser et al., 2004). In the northern Oman sections (Figure 15) the Late Barremian index species *Eopalorbitolina transiens* and *Montseciella arabica* are systematically present in the upper part of the Kharai Formation. *Palorbitolina lenticularis* has a longer range, and occurs in the Kharai Formation, the Hawar Member, and the lower part of Shu’aiba Formation. In the lower part of the Shu’aiba Formation the late Early Aptian species *Palorbitolina ultima* and *Praeorbitolina cormyi* are systematically found (Figure 15). In the upper part of the Shu’aiba Formation no datable orbitolinids were observed.

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**Figure 13:** Graua outcrop section in eastern Ethiopia, illustrating the late Early Aptian transgressive limestones of the Graua Formation intercalated between the terrestrial and transitional deposits of the Amba Aradam Formation (after Bosellini et al., 1999). The Aptian Supersequence is indicated.
In an earlier study Simmons and Hart (1987) and Simmons (1994) reported *Eopalorbitolina charollaisi* from the Kharaib Formation, which can safely be interpreted as corresponding to *E. transiens* (M. Simmons, personal communication, 2007). In the Nahr Umr Formation, directly overlying the Shu’āiba Formation in Wadi Mu‘aydin, Simmons and Hart (1987) and Simmons (1994) reported the presence of *M. texana*, *M. subconcava* and *Hemicyclammina sigali* Mayng. The presence of *H. sigali*, and the primitive forms of *M. texana*, are considered indicative of an Early – Middle Albian age by these authors. In the Oman Foothills, in Jabal Madar, a late Early Albian ammonite fauna, containing *Knemiceras persicum*, was found 10 metres above the Shu’āiba – Nahr Umr contact (L. Bulot, personal communication, 2009).

In the Al Huqf area of southern Oman, *Eopalorbitolina transiens* and *Palorbitolina lenticularis* were found (Figure 16). The former indicates a Late Barremian age. The sole presence of the latter in the upper part of the section, in combination with the absence of *Palorbitolinoides* and *Pracrobitolina*, may suggest that only the lower part of the Lower Aptian succession is present.

**Offshore United Arab Emirates (UAE)**

An offshore well in the UAE, studied by Granier et al. (2003), has been included to represent the succession in the Bab Basin (Figure 16). Datable orbitolinids have only been found in the Kharaib
Barremian – Aptian biostratigraphic zonation, eastern Arabian Plate

Formation (Thamama B), and comprise the species *Eopalarbitolina transiens*, *Montseciella arabica*, *Palorbitolina lenticularis* and transitional forms between the latter species and *Rectodictyoconus giganteus*. This assemblage is interpreted as indicative for the Late Barremian. No orbitolinids were dated in the Lower Shu’aiba Formation.

Southwest Iran

In southwest Iran, Barremian and Aptian strata of the eastern margin of the Arabian Plate crop out in many anticlinal structures along the Zagros Mountains (James and Wynd, 1965). The five sections reported here represent three palaeogeographical domains: (1) the shallow-water platforms in Fars Province (Asaluyeh and Gach sections), (2) the margins and centre of the Kazhdumi intra-shelf basin in Khuzestan (Kuh-e-Fahliyan, Kuh-e-Mangasht, Kuh-e-Bangestan), and (3) shallow-water platforms in the High Zagros (Kuh-e-Mangasht, Meymand) (Figures 12b and 17). The studied interval comprises the limestones and marly intervals of the Gadvan Formation, the shallow-water limestones of the Dariyan Formation, and the intra-shelf basinal deposits of the Kazhdumi Formation. Up to now the biozonation scheme of James and Wynd (1965) has been followed in Iran, which does not formally distinguish between the Early and Late Aptian. Here the first detailed revision of the orbitolinid group is presented for five Barremian – Aptian outcrop sections.

In the Barremian Gadvan Formation orbitolinids commonly occur in a characteristic limestone marker bed, the Khalij Member (James and Wynd, 1965). This bed is prominent by thickness, lateral continuity and faunal content, and can be followed in all the studied outcrop sections (Figure 17), and in the subsurface throughout the entire Zagros Mountains. It is characterised by the occurrence of *Montseciella arabica*, *ex-Dictyoconus arabis* used by earlier workers (James and Wynd, 1965), and in the Asaluyeh section it also contains *Eopalarbitolina transiens* and *Palorbitolina lenticularis*. This assemblage confirms a Late Barremian age for this stratigraphically important regional marker bed.

The shallow-water carbonates of the Dariyan Formation have up to now been dated as “Aptian” based on the presence of *Orbitolina discoidea - conoidea* (Henson, 1948; James and Wynd, 1965). The present revision of the orbitolinid group shows a significant regional variation in age of the top of this formation, varying from Early Aptian to Early Albian. This is illustrated in five sections (Figure 17), and is supported in several of these locations by ammonite material (Vincent et al., 2010).

1. Asaluyeh Section, Southwest Iran

The orbitolinid assemblage in this section consists of *Palorbitolina lenticularis* (224–250 m), followed by *Palorbitolina ultima*, *Praeorbitolina cormyi* (?), and *Palorbitolinoides cf. orbiculata* (250–275 m; Figure 17). This suggests an age range from early Early Aptian in the lower part, to late Early Aptian age in the upper part. In the top part of the succession (275–320 m) no datable orbitolinids have been found. Just above the Dariyan Formation, the typical form of *Mesorbitolina aperta* has been found, which is a Late Albian orbitolinid. In addition, at the same level a typical Late Albian ammonite fauna (*Knemiceras aff. iraniense* Collignon) was found (Vincent et al., 2010). This suggests the presence of a significant stratigraphic hiatus that may cover most of the Late Aptian and the Early and Middle Albian.

2. Gach Section, Southwest Iran

In the Gach section, the lower part of the Dariyan Formation (62–120 m) contains exclusively specimens of *Palorbitolina lenticularis*. The upper part (120–165 m) contains a latest Early to Late Aptian assemblage including *Palorbitolina ultima*, *Praeorbitolina cormyi*, *Praeorbitolina wienandsi*, and *Palorbitolinoides cf. orbiculata*. In the overlying marls of the Kazhdumi Formation a late Early/Middle Albian age ammonite fauna (*Knemiceras persicum*) was found (Vincent et al., 2010). This suggests the presence of a significant stratigraphic hiatus that may cover most of the Late Aptian and the Early and Middle Albian.

3. Fahliyan Section, Southwest Iran

In this section, *Mesorbitolina purva* and a questionable *Mesorbitolina lotzei* (?) were found in the upper part of the Kazhdumi Tongue (170 m; Figure 17), together with ammonites *Epicheloniceras gr. buxtorfi* and *E. gr. martinioides* (Vincent et al., 2010) suggesting an early Late Aptian age. The Upper Dariyan Formation contains *Mesorbitolina purva* and *Mesorbitolina texana*, indicating an early Late Aptian age. *Mesorbitolina texana* extends in the upper part of the Upper Dariyan, where it occurs with the ammonite *Epicheloniceras gr. clansayense*, suggesting a Late Aptian age (lower *H. jacobi* Zone, at the youngest;
### Lithostratigraphy

- **Barremian Supersquence**
  - **16**
  - **15**
  - **14**
  - **13**
  - **12**
  - **11**
  - **10**
  - **9**
  - **Apt 1**
  - **Apt 2**
  - **Apt 3**

- **Aptian Supersquence**
  - **16**
  - **15**
  - **14**
  - **13**
  - **12**
  - **11**
  - **10**
  - **9**
  - **8**
  - **7**

### Chronostratigraphy

- **EARLY BARREMIAN**
  - **Y**
  - **EARLY APTIAN**
  - **Y**

### Fauna

- **P. lenticularis**
- **E. transiens**
- **M. arabica**
- **P. ultima**
- **C. decipiens**
- **V. murgensis**
- **D. hahounerensis**
- **P. infracretacea**
- **P. cormyi**
- **P. infracretacea**

### Texture

- Marl (m)
- Mudstone (M)
- Wackestone (W)
- Packstone (P)
- Boundstone (B)
- Grainstone (G)
- Floatstone (F)
- Ruditextured (R)
- Phosphatized (P)

### Outcrop Sections

- **Northwest**
  - **Wadi Bani Kharus**
  - **Wadi Nakhr**
  - **Wadi Bani Kharus**

- **Southeast**
  - **Wa di Nakhr**

- **Jabal Madar (Oman)**

- **AL JABAL**

- **Al Jabal al-Akhdar Transect**

- **100 km**
- **50 km**
- **38 km**

### Figure 15

Outcrop sections of Al Jabal al-Akhdar in the northern Oman Mountains and Jabal Madar in the Adam Foothills displaying the Barremian and Early Aptian Kharaib and Lower Shu’aiba formations after van Buchem et al. (2002) and revised depositional sequences (following van Buchem et al., 2010a). The orbitolinid distribution and associated fauna are from this paper.

### Maps

- **Northwest**
  - **38 km**
  - **50 km**
Figure 15: Outcrop sections of Al Jabal al-Akhdar in the northern Oman Mountains and Jabal Madar in the Adam Foothills displaying the Barremian and Early Aptian Kharaiib and Lower Shu’aiba formations after van Buchem et al. (2002) and revised depositional sequences (following van Buchem et al., 2010a). The orbitolinid distribution and associated fauna are from this paper.
OMAN-UAE CORRELATION

<table>
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<th>Stage</th>
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<tr>
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</tr>
<tr>
<td></td>
<td>Late</td>
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</tr>
<tr>
<td></td>
<td>Late</td>
<td>200 m</td>
<td>M. arabica</td>
</tr>
<tr>
<td></td>
<td>Late</td>
<td>250 m</td>
<td>E. transiens</td>
</tr>
<tr>
<td></td>
<td>Late</td>
<td>300 m</td>
<td>M. tardefurcata</td>
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<tr>
<td></td>
<td>Late</td>
<td>350 m</td>
<td>H. jacobi</td>
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<td></td>
<td>Late</td>
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<td>L. tardefurcata</td>
</tr>
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<td>D. mammilatum</td>
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<td></td>
<td>Late</td>
<td>500 m</td>
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</tr>
<tr>
<td></td>
<td>Late</td>
<td>550 m</td>
<td>M. texana</td>
</tr>
</tbody>
</table>

Figure 16: Regional correlation between the Al Huqf outcrop sections in southern Oman (from Immenhauser et al., 2004), the Wadi Mu’aydin outcrop section in the northern Oman Mountains (from van Buchem et al., 2002), and an offshore well in the UAE (from Granier et al., 2003). Note lateral continuity of the Barremian sequences and the significant erosion/non-deposition of the Aptian succession in the Al Huqf area. For legend see Figure 15.

Vincent et al., 2010). *Mesorbitolina texana* extends further in the overlying marls and limestone beds of the Kazhdumi Formation, where it is found at 350 m in association with *Mesorbitolina subconcava* and *Mesorbitolina aperta* (primitive form), indicating a Middle Albian age. In a level 50 cm above the Upper Dariyan, in the Kazhdumi marls, ammonites *Knemiceras gr. persicum* and a juvenile *Douvilleiceras* were found, suggesting a late Early Albian age (Vincent et al., 2010). This demonstrates that there is a hiatus at the base of Kazhdumi Formation, and that most of the *H. jacobi*, the *L. tardefurcata* and the greatest part of the *D. mammilatum* zones are missing here.
4. Meymand Section, Southwest Iran
The Dariyan Formation in this section contains in the lower part (0–165 m) a Lower Aptian fauna, including *Palorbitolina lenticularis* and *Palorbitolina ultima*. The middle part (165–222 m) contains *Mesorbitolina cf. texana*, *Mesorbitolina gr. subconcava*, and *Dictyoconus tunesianus*. In particular, the presence of the latter species suggests this interval may be of latest Late Aptian age. Based on regional sequence-stratigraphic considerations, an Early Albian age should not be excluded (van Buchem et al., 2010b). The upper part of the section contains *M. cf. texana*, *M. gr. subconcava*, and *Hemicyclammina sigali*, and has been interpreted as (Early) Albian age.

5. Kuh-e-Mangasht, Southwest Iran
The Dariyan Formation in this section can be subdivided in three units, which are separated by sequence boundaries (see below). The lower unit, from 160–370 m, contains an Early to early Late Aptian orbitolinid assemblage comprising *Palorbitolina lenticularis*, *Palorbitolina ultima*, and *Praeorbitolina sp. (?)*, followed by *Mesorbitolina cf. parva* at the top. The next two units, from 370–460 m, contain an orbitolinid assemblage including, in order of appearance: *Mesorbitolina cf. texana*, and *Mesorbitolina gr. subconcava*. The co-occurrence of these species indicates a late Late Aptian to Middle Albian age. By comparison with the rich assemblages in the Meymand section, and using sequence-stratigraphic considerations (van Buchem et al., 2010b), a late Late Aptian age for the second unit (370–420 m) and an (Early?) Albian age for the third unit (420–460 m) are proposed.

To summarise, this revision shows that: (1) the Dariyan Formation in Fars Province is of Early Aptian age, (2) the Upper Dariyan in the Dezful Embayment is of early Late Aptian age, and (3) the Dariyan Formation in the High Zagros (Kuh-e-Mangasht and Meymand) covers the Early and Late Aptian, and probably passes into the (Early?) Albian.

**REGIONAL CORRELATIONS AND DEPOSITIONAL SEQUENCES**

In order to better understand the Barremian – Aptian depositional conditions, in which the orbitolinids evolved in the study area, a brief summary is given of the regional sequence-stratigraphic framework. To facilitate the regional comparison of the orbitolinid assemblages and their evolution, they are presented together with the general sedimentary facies evolution and the depositional sequences in a chronostratigraphic chart (Figure 18). The outcrops in Wadi Mu’aydin, in the northern Oman Mountains, provide a clear overview of the Barremian to Early Aptian stratigraphy in the carbonate platform succession and the distribution of the orbitolinids therein (Figure 19). In the following the Arabian Plate sequence terminology as defined in van Buchem et al. (2010a) is used.

**Barremian Sequences**

During the Barremian, the eastern Arabian Plate was covered by a homogenous, low-angle, carbonate ramp system with very little relief (Murris, 1980; Davies et al., 2002). In this system, two clearly expressed depositional sequences have been recognised consisting of a clay-rich lower part, and a carbonate dominated upper part, that have been correlated over most of the Arabian Plate and are well documented in the literature (e.g. Hughes Clarke, 1988; Sharland et al., 2001; Pittet et al., 2002; van Buchem et al., 2002; Strohmenger et al., 2006; van Buchem et al., 2010a). They are named AP Bar 1 and AP Bar 2 sequence (see van Buchem et al., 2010a, for more details). Orbitolinids appear on the Arabian Plate in the late Early Barremian, and become common to abundant in the Late Barremian (Simmons and Hart, 1987; Pittet et al., 2002; Figure 19). Here we focus on the AP Bar 2 Sequence, which falls within the Late Barremian, and is characterised by the occurrence of *Eopalorbitolina transiens* in the lower part, and *Montseciella arabica* in the upper part (Figure 18). These short-range index species allow correlating this sequence with confidence along the margins of the northeastern African and eastern Arabian plates.

In Oman and the UAE, orbitolinids are abundant in the marly lower part of the AP Bar 2 Sequence, where they preferably occur in thin, slightly more argillaceous interbeds (Figure 19). Both *Eopalorbitolina transiens* and *Montseciella arabica* are observed in these sections. In Yemen and Ethiopia, Late Barremian shallow-water carbonates containing *Montseciella arabica* were reported along the margin of the plates (see above; Figure 18). In Qatar, in the Late Barremian Kharai B Member, *Montseciella arabica* has been...
<table>
<thead>
<tr>
<th>Sedimentological facies</th>
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<tr>
<td>Restricted platform top facies, miliolids, green algae</td>
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<tr>
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</tr>
<tr>
<td>Platform top facies, rudist dominated wackestone to</td>
</tr>
<tr>
<td>floatstone</td>
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<tr>
<td>Platform top and slope facies, orbitolinid dominated</td>
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<td>wackestone to packstone</td>
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<tr>
<td>Platform slope and margin facies, oyster and bivalve</td>
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<td>dominated wackestone to packstone</td>
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<table>
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<th>Lithological facies</th>
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<td>Shallow-water, platform top marls, and marly limestone</td>
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<td>Intra-shelf basin marls and limestones</td>
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observed (Raven et al., 2010). In the Iranian sections, the regional marker bed named ‘Khalij Member’ systematically contains *Montseciella arabica*, and is correlated with the AP Bar 2 Sequence (Figure 18). The Khalij Member is a carbonate bed occurring within a shaly succession (Gadvan Formation), and is interpreted as the highest sea level (late transgression to early highstand) part of this sequence (van Buchem et al., 2010a).
It appears from our observations that *E. transiens* is more restricted to the lower, early transgressive part of the AP Bar 2 Sequence, whereas *M. arabica* seems to have had its maximum abundance (and extension) during the maximum flooding and early highstand of this sequence.

### APTIAN Supersequence

During the APTIAN Supersequence a fundamental palaeogeographical change occurred on the Arabian Plate with the creation of at least two distinct intra-shelf basins: the Bab Basin, located in Oman and the UAE, and the Kazhdumi Basin, located in Khuzestan Province in southwestern Iran (e.g. Murriss, 1980; Sharland et al., 2001; van Buchem et al., 2002, 2010b; Figure 12b). This change occurred during a second-order depositional sequence, which comprises a step-wise evolution from: (1) a flat-bedded,
ramp system in the early TST, to (2) the development of an intra-shelf basin to carbonate platform topography during late TST, followed by (3) progradation in the early HST, and finally (d) exposure and forced regression in the late HST, due to a eustatic sea-level drop (e.g. Witt and Gökdağ, 1994; Sharland et al., 2001; van Buchem et al., 2002, 2010a, b; Yose et al., 2006; 2010; Raven et al., 2010). These steps are used to evaluate the orbitolinid distribution in the different locations.
In Oman and the UAE, the Aptian sequence-stratigraphic model is well documented in outcrop (Pittet et al., 2002; van Buchem et al., 2002; Hillgärtner et al., 2003), and in the subsurface (Sharland et al., 2001; Yose et al., 2006; GeoArabia Special Publication 4). The early transgressive part of the sequence, approximately corresponding to the Hawar Member, is characterised by the abundant presence of a single species, *Palorbitolina lenticularis*. The late transgressive deposits are characterised by the occurrence of *Palorbitolina ultima* and *Praeorbitolina cornyi*, which are indicative of a late Early Aptian age (Figure 15). In the highstand part of the section no datable orbitolinids were found.

A correlation of the Al Huqf area with the Wadi Mu‘aydin section in northern Oman and the offshore UAE well, shows that the basal Aptian Supersequence boundary has a similar expression in all three sections: it is marked by a sharp facies change from a rudist-rich grainy facies, to a muddy, orbitolinid-dominated facies (Figure 16). The Hawar facies, characterising the early transgressive part of the sequence, has a homogenous thickness in these three sections. The late TST, has a different expression in each one of them: (1) in the offshore well it is represented by the backstepping and deepening of the environment as a result of the intra-shelf basin creation, (2) in Wadi Mu‘aydin the platform aggrades, while (3) in the Al Huqf area only a very thin interval is preserved (a few metres). Based on the sole occurrence of *Palorbitolina lenticularis*, the absence of the *Praeorbitolinids* and *Palorbitolinoides*, and the thin preserved succession, it is assumed that the later part of the Early Aptian is not present in the Al Huqf area. This can be due to either erosion, or to synsedimentary uplift.

The sections in Ethiopia and Yemen show a gradual deepening-up trend from terrigenous siliciclastics to marginal marine mixed siliciclastic/carbonate deposits, to open-marine limestones (Figures 13 and 14). This is followed in both locations by an abrupt return to terrestrial conditions. The orbitolinid assemblage contained in the carbonate beds includes *Palorbitolina ultima*, *Praeorbitolina cornyi*, *Praeorbitolina wienandsi*, an assemblage indicative of the late Early Aptian. The relevance of these sections is that the interfingering of the late Early Aptian open-marine carbonates with marginal marine siliciclastics provides unambiguous evidence for the timing of maximum coastal encroachment caused by the transgression of the Aptian Supersequence (Bosellini et al., 1999).

In southwest Iran, the early TST facies of the Aptian Supersequence change laterally from the oyster and bivalve-dominated wackestones (Lower Dariyan) in the area of the future Kazhdumi Basin (Kuh-e-Fahliyan, Kuh-e-Bangestan) to orbitolinid-dominated wackestone and packstone in the areas that remained shallow-water carbonate environments (lower part of the Dariyan Formation in Kuh-e-Mangasht, Kuh-e-Asaluyeh, and Kuh-e-Gach) (Figure 17). The orbitolinids in the latter facies are monospecific (*Palorbitolina lenticularis*), and occur at a stratigraphically similar position as the Hawar Member in Oman and the UAE (Figure 18). During late TST, an intra-shelf basin (Kazhdumi Formation) was created surrounded by shallow-water platforms (Dariyan Formation), which were locally rich in orbitolinids (*Palorbitolina lenticularis*, *Palorbitolina ultima* in the coastal Fars and the High Zagros sections; Figure 17).

During the early HST, the facies of the platforms shallow-up with the common presence of miliolids and rudists (Figure 17). The orbitolinid assemblage observed in Kuh-e-Gach includes *Palorbitolina ultima*, *Praeorbitolina cornyi* and *Praeorbitolina wienandsi*, which suggests a latest Early Aptian age for the top of the platforms in Fars Province. In Kuh-e-Mangasht, in the High Zagros, *Mesorbitolina parva* has been found at the top of this sequence suggesting an earliest Late Aptian age. In the Meymand section, no datable orbitolinids were found in the upper part of this sequence, but a possible correlation with Kuh-e-Mangasht can be proposed based on the range of the *Archaealveolina* sp. (Figure 17), also suggesting a late Early Aptian age.

During late HST, shelf-margin wedges prograded into the intra-shelf basin, while the surrounding platforms became exposed. An example of such a wedge is the Kuh-e-Fahliyan section (Figure 17), which consists of a 100-m-thick succession of orbitolinid wackestones and packstones (Upper Dariyan Formation) containing exclusively *Mesorbitolina parva* and *Mesorbitolina texana*, suggesting an early Late Aptian age.

**Upper Aptian – Lower Albian Supersequence**

Deposits belonging to the Upper Aptian – Lower Albian Supersequence were recorded in Kuh-e-Mangasht and in Meymand, where a succession of orbitolinid wackestones and packstones was dated
of late Late Aptian age in the lower part, based on the presence of *Dictyoconus tunesianus* (Meymand section, 223 m; Figure 17), and of (Early?) Albian age in the upper part, based on the sole presence of *Mesorbitolina texana* and *Mesorbitolina* gr. *subconcava* (Meymand, 225–280 m; Figure 17).

**PALAEOGEOGRAPHICAL CONSIDERATIONS**

A comparison between the Barremian – Aptian orbitolinid spectres of the eastern Arabian Plate, located at the southern Neo-Tethys margin, and those of southwest Europe (e.g. Iberian Peninsula, South France, Sardinia) situated at the northern margin of the Neo-Tethys, shows that part of the species are restricted to only one of these margins, whereas others have a large intercontinental distribution. Consequently, a difference can be made between endemic and cosmopolitan forms.

Endemic forms generally comprise mostly conical species of relatively small size, presenting a simple, predominantly bilocular and eccentrically situated megalospheric embryo (for example *Dictyoconus*). They are mostly found in fine-grained carbonate sands and muddy sands in very shallow environments (Masse, 1992) and are generally restricted to the infra-littoral zone of the carbonate platforms, occurring only exceptionally in the outer-shelf facies.

Cosmopolitan forms mostly comprise large, flat and frequently discoidal tests (up to 5 cm in diameter), presenting a relatively voluminous and complex embryonic apparatus (e.g. *Praeorbitolina*, *Mesorbitolina*, *Palorbitolina*, highly developed Montseciellas). They occur in the infra-littoral and circa-littoral zone with carbonate or mixed fine-grained terrigenous sediments (Masse, 1992). In a dedicated palaeo-ecological study of the Early Aptian *Palorbitolina lenticularis* from southwest Spain, Vilas et al. (1995) have shown that this species spreads over the whole platform system (from the littoral zone to the outer shelf).

Ecological and biological factors are responsible for the fact that the cosmopolitan orbitolinids of the Barremian – Aptian time interval were able to cross the oceanic barriers between the different plates (Cherchi, 1989; Cherchi and Schroeder, 2004b). The relatively extensive niche of these species and their capacity to adapt to different platform environments are in our opinion one of the main reasons for their cosmopolitan nature. The meroplanktic embryonic stage of the cosmopolitan orbitolinids facilitated the spreading of these species throughout the Tethyan realm. Furthermore, the flattened basis of the protoconch and sometimes also of the deuteroconch of highly developed mesorbitolinids indicate a fixation to the surface of algae and other floating objects, which would have allowed them to be transported by transoceanic currents far away from their original environment (Cherchi and Schroeder, 2004b). According to Pélissié et al. (1982), the complex megalospheric embryonic apparatus of the cosmopolitan forms, whose protoconch is surrounded by large peri-embryonic chambers (*Palorbitolina*) or by the deuteroconch and the subembryonic zone (*Mesorbitolina*), probably facilitated their flotation during the meroplanktic initial stage, thus favouring their dispersal by marine currents.

Nearly all the orbitolinids found in the studied sections of the eastern Arabian Plate belong to the cosmopolitan genera *Palorbitolina*, *Praeorbitolina*, *Mesorbitolina* and the highly developed Montseciellas, which are widely distributed on the carbonate platforms along the northern and southern Neo-Tethys margins. From the sequence-stratigraphic context it is clear that there is a natural connection between the migration of cosmopolitan orbitolinids and the Early Aptian transgression of the *deshayesi* Zone (e.g. spreading of *Praeorbitolina cormyi*).

The endemic orbitolinid species of this time interval are only represented by *Dictyoconus tunesianus* Peybernès, a species abundant on the southern Neo-Tethys margin and reported from the Late Aptian of Algeria, Tunisia and the Appenine platform (Fournace and Raoult, 1973; Schroeder et al., 1978; Peybernès et al., 1981; Cherchi and Schroeder, 1982; Chiocchini et al., 2004). However, it is noteworthy that *Dictyoconus tunesianus*, also occurs very rarely in the southern part of Iberia (Algarve region, south Portugal; Peybernès et al., 1981), belonging to the northern Neo-Tethys margin. It is supposed that this taxon invaded the southern areas of Iberia via the westernmost part of the Alkapec microplate (Alboran-Kabylian-Peloritan-Calabrian domain), intercalated between the Iberian sub-Plate and the African Plate (Bouillin et al., 1986; Durand-Delga, 2006).

Also a number of other benthic foraminifers found on the eastern Arabian Plate are restricted to the southern margin of the Tethys. For example, *Prachrysalidina infracretacea* Luperto Sinni as well as *Voloshinoides murgensis* Luperto Sinni and Masse, the latter figured from Saudi Arabia by Hughes (2004).
under the name “cf. Cribellopsis spp.”, are characteristic species of the carbonate platforms of the Italo-Dinaric domain and northwest Africa (Luperto Sinni, 1979; Luperto Sinni and Masse, 1993b; Velić, 2007; Pélissié et al., 1982).

Of great systematic interest is the occurrence of alveolinid foraminifers in several horizons of the Meymand and Kuh-e-Mangasht sections (southwest Iran) (Figure 11), named at present *Archaealveolina* sp. In the lower *Archaealveolina* horizons of the Meymand section this form is associated with *Palorbitolina ultima* and *Choffatella decipiens*, both indicating an Early Aptian age (Figure 17). At present, two species belonging to the genus *Archaealveolina* are known: *A. reicheli* (de Castro) from the Late Aptian of the southern Tethyan margin (Italo-Dinaric domain and northwest Africa; Bassoullet et al., 1985) and *A. decastroi* Fourcade from the Late Aptian of Ibiza (Balearic Islands, Spain; Fourcade, 1980). Early Aptian
alveolinids, associated with *Palorbitolina lenticularis*, were hitherto only reported from central Croatia (Adriatic Carbonate Platform) by Velić and Sokač (1978) under the name *Ovalveolina reicheli* and later on (Velić, 2007) as *Archaalveolina* sp. These specimens and our Early Aptian material from southwest Iran represent the earliest alveolinids known at present. A detailed study of the Iranian specimens is planned.

**DISCUSSION**

**Orbitolinid Distribution and Depositional Sequences**

The integrated palaeontological and sequence-stratigraphic work allows evaluating the orbitolinid distribution in the context of well-established Barremian and Aptian depositional sequences, both in terms of the consistency of their use as age diagnostic microfossils, and their abundance as rock-forming components. The following observations, illustrated in Figures 19 and 20, are made:

(A) **early Late Barremian:** The first significant appearance of orbitolinids (in terms of abundance) is observed in the studied sections in the early transgressive and marly part of the AP Bar 2 Sequence with *E. transiens*, *P. lenticularis*, and locally *M. arabica*.

(B) **Late Barremian:** The maximum flooding of the AP Bar 2 Sequence is characterised by the regional distribution and high abundance of the short range index fossil *Montseciella arabica* (*ex-Dictyoconus arabicus*) in this carbonate-dominated interval. This rock unit has a member status in southwest Iran: Khalij Member.

(C) **early Early Aptian:** The early TST of the Aptian Supersequence is locally characterised by the abundant presence of a single orbitolinid species, *Palorbitolina lenticularis*, which can be rock-forming. This unit has member status in Oman and the UAE (Hawar Member), and formation status in Qatar (Hawar Formation). It should be pointed out that this is only an abundance criterium, since the range of *Palorbitolina lenticularis* covers the Late Barremian and Early Aptian, and that circumstantial evidence of strata below and above is needed to identify this interval.

(D) **late Early Aptian:** The late TST and MFS of the Aptian Supersequence is characterised by the occurrence of *Palorbitolina ultima* and *Praeorbitolina cormyi*.

(E) **latest Early Aptian:** The early HST of the Aptian Supersequence is characterised by a specific orbitolinid assemblage consisting of *Praeorbitolina wienandsi*, *Mesorbitolina lotzei* and *Palorbitolinaoides cf. orbiculata*. These are present wherever the Aptian carbonate platform was well-developed at the Arabian Plate.

(F) **Late Aptian:** The basin margin wedges of the late HST of the Aptian Supersequence and the LST of the Upper Aptian – Lower Albian Supersequence are characterised by the subsequent appearance of the Mesorbitolinas: *M. parva*, *M. texana*, and *M. subconcava* which become locally rock-forming.

The orbitolinid biozonation proposed for the eastern Arabian Plate has been calibrated with substantial ammonite findings and carbon-isotope analyses made on the sections presented in this paper (e.g. Vahrenkamp, 1996; Masse et al., 1998; van Buchem et al., 2002, 2010a, b; Immenhauser et al., 2004; Yose et al., 2006, 2010; Vincent et al., 2010; and GeoArabia Special Publication 4), and with age constraints obtained in other locations (from the literature see above), which allows to present them against the ammonite time scale (Figure 10).

The detailed, well documented and very consistent dataset upon which this orbitolinid zonation is based, makes it a reference for the southern margin of the Neo-Tethys, but it can potentially also be of use for the re-evaluation of sections along the northern margin, which are often much less complete for the Aptian – Albian interval, and thus more ambiguous to interpret (e.g. Arnaud-Vanneau and Arnaud, 1990; Föllmi et al., 2007; Föllmi and Gainon, 2008).
(a) Orbitolinid Biostratigraphy (This study)

<table>
<thead>
<tr>
<th>Stage</th>
<th>Orbitolinid Distribution and Zonation</th>
<th>Sequence Stratigraphy</th>
<th>Orbitolinid Abundance</th>
<th>Sedimentary System</th>
<th>Nutrient Level</th>
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<tr>
<td>MIDDLE ALBIAN</td>
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<td>EARY ALBIAN</td>
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<td>LATE APTIAN</td>
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Note: Maximum of orbitolinid speciation during the Early Aptian regional carbonate platform development, followed by extinction of the Palorbitolinids and Praeorbitolinids around the Early−Late Aptian boundary when sea level started to fall, and platforms gradually became exposed. The Mesorbitolinids are typical for the Late Aptian late HST prograding clinoforms (in yellow) of the Aptian Supersequence, and are a dominant component of the LST of the Upper Aptian−Lower Albian Supersequence (in light brown). See text for further explanation of stages A to F.

(b) Kazhdumi Basin Margin Early/Late Aptian Boundary Bab Basin Margin Early/Late Aptian Boundary

Figure 20 (see facing page for caption):
Palaeoecology and Evolution

The relative abundance of orbitolinids in the bulk rock shows an overall increase from the Late Barremian to the Albian. The stratigraphic units in which they are the dominant bioclastic component change over this period (Figure 20a):

**early transgressive systems tracts:** during the Late Barremian and Early Aptian sequences, orbitolinids occurred throughout the limestone beds, but are rock-forming in the slightly more muddy interbeds (see in Wadi Mu’aydin; Figure 19). In Jabal Madar (North Oman), orbitolinids are interbedded with layers containing mudcracks and numerous miliolids, suggesting a very shallow-water, intertidal environment (van Buchem et al., 2002).

**muddy shelf margin wedges:** during the Late Aptian orbitolinids are abundant and locally rock-forming in prograding shelf-margin wedges as observed for instance in the outcrops in southwest Iran (Kuh-e-Fahlíyan; van Buchem et al., 2010b) and in the UAE (Field A; Yose et al., 2006, 2010). The depositional environment is here shallow to open marine.

**muddy carbonate ramp systems:** the Albian is the period when the orbitolinids were most abundant on the Arabian Plate. They dominated the muddy carbonate ramps around the Kazhdumi Basin in Iran (Orbitolina Limestones; James and Wynd, 1965; van Buchem et al., 2010b), and formed the main component of the marls of the Nahr Umr Formation in Oman and the UAE (e.g. Immenhauser et al., 2000). The depositional environment is shallow to open marine.

The gradual colonisation of the Arabian Plate by orbitolinids (Figure 20a) suggests that they either took over an ecological niche of pre-existing organisms, or that favourable environmental conditions developed. Granier et al. (2003) suggested that an ecological change occurred in the Barremian, when orbitolinids took over the shallow-water habitat of the benthic foraminifer *Choffatella decipiens*, which is only found in deeper-water environments thereafter. Rudists, another main rock-forming constituent of the Barremian and Early Aptian platforms, decreased dramatically in numbers in the interior of the Arabian Plate from the beginning of the Late Aptian onwards, and returned in large numbers again in the Late Albian (e.g. Murris, 1980; Alsharhan and Nairn, 1993; James and Wynd, 1965). Only along the plate margins, facing the open ocean, rudists were still found in large quantities (e.g. the Al Hassanat Formation in Oman; Masse et al., 1997; Immenhauser et al., 2001; Hillgärtner et al., 2003). This pattern is partly explained by the early Late Aptian biological extinction event that heavily affected the rudists around the Neo-Tethys (e.g. Masse et al., 1998; Skelton and Masse, 2000). One of the main causes for this faunal turnover was probably the Late Aptian cooling, which caused a lowering in seawater temperature, and a eustatic sea-level fall, which destroyed many of the platform habitats formerly inhabited by rudists.

These ecological changes coincided with the gradual increasing influx of siliciclastics on the Arabian Plate from the exposed craton. Initially this influx resulted in thin shaly interbeds that spread out over the plate during the TST of the Barremian sequences and of the Aptian Supersequence (Davies et al., 2002). This influx accelerated during the Late Aptian, when sea level fell below the carbonate platform tops and created incised valleys transporting significant amounts of fine-grained siliciclastics into the intra-shelf basins (Droste, 2010; Pierson et al., 2010; Raven et al., 2010). During the Albian, high amounts of siliciclastics were still brought onto the shelf (Davies et al., 2002). Considering that orbitolinids thrive in more mesotrophic conditions (e.g. Pittet et al., 2002), where they are capable of rapidly colonising opening biotopes (r-type strategy), these environmental changes created favourable living conditions. It was thus probably the combination of the extinction of numerous rudist species, and the creation

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Figure 20 (continued): Orbitolinid distribution in the study area in (a) time and (b) space. Note maximum of orbitolinid speciation during the Early Aptian regional carbonate platform development, followed by extinction of the *Palorbitolinids* and *Praeorbitolinids* around the Early–Late Aptian boundary when sea level started to fall, and platforms gradually became exposed. The *Mesorbitolinids* are typical for the Late Aptian late HST prograding clinoforms (in yellow) of the Aptian Supersequence, and are a dominant component of the LST of the Upper Aptian – Lower Albian Supersequence (in light brown). See text for further explanation of stages A to F.
of favourable living conditions that led to their dominant presence in the Late Aptian and Alban of the interior of the Arabian Plate. In other Aptian shallow-water carbonate systems along the Neo-Tethys shorelines, ‘Orbitolina Beds’ are also a well-known feature, and they are often associated with a siliciclastic influx in the system (e.g. Arnaud-Vanneau, 1980; Föllmi et al., 2007; Embry et al., 2010).

The evolutionary trend of the Eo-/Palorbitolina and Prae-/Mesorbitolina lineages show an interesting relationship to the Aptian sea-level fluctuations. During early transgression in the Early Aptian, when the formerly exposed platform was slowly flooded, and conditions were mesotrophic, the sediment composition was dominated by the abundant presence of a single orbitolinid species, Palorbitolina lenticularis (Hawar Member; Figure 20). This was followed, during the late Early Aptian maximum transgression and highstand by a phase of maximum speciation, when in a period of about 2 My six new orbitolinid species developed (Figure 20). The environment was at that time oligotrophic, and orbitolinids were but one element of the varied benthic faunal assemblage (Pittet et al., 2002). At the end of the Early Aptian the extinction of all the Palorbitolinids and Praeorbitolinids occurred. Only the Mesorbitolinas continued during the Late Aptian, when they dominated the muddy, mesotrophic shelf margin wedges fringing the intra-shelf basins. In this favourable environment they evolved at a more gradual and slower pace. This pattern is a good example of the link between evolutionary trend and nutrient flux, as earlier discussed by e.g. Brasier (1995), where high nutrient flux leads to dominance of only a limited number of species, but with a very high abundance, whereas periods of oligotrophic conditions lead to speciation, and a lower total abundance. In the present case a close link between nutrient level, evolutionary trends and sea-level fluctuations is demonstrated.

CONCLUSIONS

The following conclusions are drawn from this study:

(1) Based on an extensive regional dataset, derived from well-exposed shallow-water carbonate successions, a revision is proposed of the orbitolinid biozonation of the Late Barremian and Aptian for the southern Arabian and eastern African plates. This biozonation includes the proposition of a new species, Palorbitolina ultima, and the proposition of six biozones and three subzones.

(2) The biozonation scheme is based on the identification of three phylogenetic lineages: (a) Montseciella glanensis – Rectodictyoconus giganteus lineage, (b) Eopalorbitolina pertenuis – Palorbitolinoides hedini lineage, and (c) Praeorbitolina cormyi – Mesorbitolina aperta lineage. The detailed documentation of the orbitolinid distribution in the 12 studied sections shows that there are no stratigraphic breaks between these species, but systematic overlap suggesting a continuous evolution. Significant speciation occurred in the Praeorbitolina group during the late Early Aptian (six new species in a period of 2 My), at the time of maximum development of the Early Aptian carbonate platforms. Before and after, speciation occurred at a slower pace.

(3) The revised biozonation has been used to date the following sequence-stratigraphic events:
(a) The MFS of the AP Bar 2 Sequence is characterised in all the studied locations by the abundant occurrence of the short range index species Montseciella arabica indicative of a Late Barremian age (e.g. in the Khali Member in southwest Iran, Upper Khaib in Oman/UAE, and Khaib B in Qatar).
(b) The early TST of the Aptian Supersequence is characterised by the abundant (rock-forming) occurrence of one species: Palorbitolina lenticularis (e.g. Hawar Member in Oman, UAE and Qatar; base Dariyan Formation in southwest Iran).
(c) The MFS and early HST of the Aptian Supersequence are characterised by a typical late Early Aptian orbitolinid assemblage consisting of Palorbitolina ultima, Praeorbitolina cormyi, P. viennandsi, P. lotzei and Palorbitolinoides cf. orbiculata. These are present wherever the Early Aptian carbonate platform was well developed at the Arabian Plate.
(d) The late HST of the Aptian Supersequence, expressed in shelf margin wedges, is characterised by the Late Aptian Mesorbitolina species M. parva, M. texana, and M. subconcava.

(4) The biostratigraphic revision has improved our stratigraphic understanding:
- In southwest Iran, where the strong diachronous nature of the Dariyan Formation has been demonstrated: (a) in Fars Province the Dariyan Formation is of Early Aptian age, (b) in the
High Zagros, the Dariyan Formation may reach up into the Early Albian, with a likely hiatus covering part of the Late Aptian, and (c) the Upper Dariyan in the Dezful Embayment is of early Late Aptian age. This insight is of fundamental importance for the understanding of the stratigraphic architecture of the Aptian in this region.

- In Oman, where the Barremian and Aptian correlation between the Al Huqf and the northern Oman Mountains has been revised.
- Through the dating and calibration of the maximum coastal encroachment of the Aptian Supersequence in the stratigraphic sections in Yemen and Ethiopia.

(5) Since the orbitolinid species used in this zonation scheme are largely cosmopolitan, the proposed zonation scheme should be applicable over large parts of the Neo-Tethys.

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Barremian – Aptian biostratigraphic zonation, eastern Arabian Plate


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