Rivista Italiana di Paleontologia e Stratigrafia
(*Research in Paleontology and Stratigraphy*)
vol. 125(2): 421-431. **July 2019**

PALEOGEOGRAPHIC NORTHEASTERN LIMITS OF *APHRODINA DUTRUGEI* (COCQUAND, 1862) (HETERODONTA, BIVALVIA) FROM THE CENOMANIAN OF THE ARABIAN PLATFORM

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To cite this article: Hoşgör İ. & Yilmaz İ.Ö. (2019) - Paleogeographic northeastern limits of *Aphrodina dutrugei* (Cocquand, 1862) (Heterodonta, Bivalvia) from the Cenomanian of the Arabian Platform. *Riv. It. Paleontol. Strat.*, 125(2): 421-431.

Keywords: Cenomanian; *Aphrodina*; palaeogeography; Derdere Formation.

Abstract. The finding of *Aphrodina dutrugei* (Cocquand, 1862) in a rich collection of non-rudist bivalve fauna from the famous Cenomanian-Turonian carbonates of the Afro-Arabian Plate has permitted the reevaluation of venerid bivalves during an important period of their evolution. The genus *Aphrodina* Conrad, 1869, Family Veneridae Rafinesque, 1815, embraces several Tethyan Cretaceous species that range from Cenomanian to Santonian. During the late Albian-Maastrichtian 'Aphrodiniid' venerids, were distributed along the western margin of the Atlantic (North and South America), the Afro-Arabian Plate (Jordan, SE Turkey, Morocco, Algeria and Egypt), the eastern Tethys, and the Southern Ocean (India, Japan, western Australia and New Zealand). They are also known in the Turonian-Santonian Trans-Saharan Seaway (Gabon). Until now these fossils have been unknown in any Upper Cretaceous localities of southeastern Turkey. In this paper, we report the first record of one of the most common and widespread shallow infaunal species, *Aphrodina dutrugei*, in the Cenomanian Derdere Formation in the Mardin-Mazıdağı area, SE Turkey, which is in the extreme northeastern part of its known range.

Introduction

Previous attempts to study the palaeobiogeography of Cretaceous bivalves and their global evolutionary patterns have been provided by Kauffman (1973, 1975), Freneix (1981), Dhondt & Dieni (1988), Malchus (1990), Dhondt (1992), Lazo (2007) and Ayoub-Hanna et al. (2014). However, compared to oysters, rudists or inoceramids and other invertebrate fossil groups, venerid bivalves have been poorly studied and probably not sampled intensively enough to reliably recognize the establishment of a useful palaeogeographic architecture and the timing of its onset.

Here, we present the northernmost occurrence of a Tethyan record of venerids located close to the Turkey/Syria border in the Derdere Formation of the Mardin Group (Fig. 1). Recent field work in the Upper Cretaceous successions of the Mardin-Mazıdağı area have discovered new fossil records which were collected bed-by-bed from lower Upper Cretaceous sediments. The studied heterodont species have been collected from the Cenomanian rocks of the Mardin Group located 30 km southwestern of the Mazıdağı area, at Mardin. The studied sequence consists of fossiliferous limestones with bivalve-dominated assemblages. These pinkish-light brown limestones include a distinctive monotaxic venerid-bivalve shell beds in the Mazıdağ section. The shell bed is composed of one species, *Aphrodina dutrugei* (Cocquand, 1862). This paper aims to clarify the stratigraphic setting of the Derdere Formation in the Mardin region on the basis of the occurrence of *A. dutrugei* and to discuss the palaeogeographic implications of this occurrence.

Received: November 21, 2018; accepted: April 24, 2019

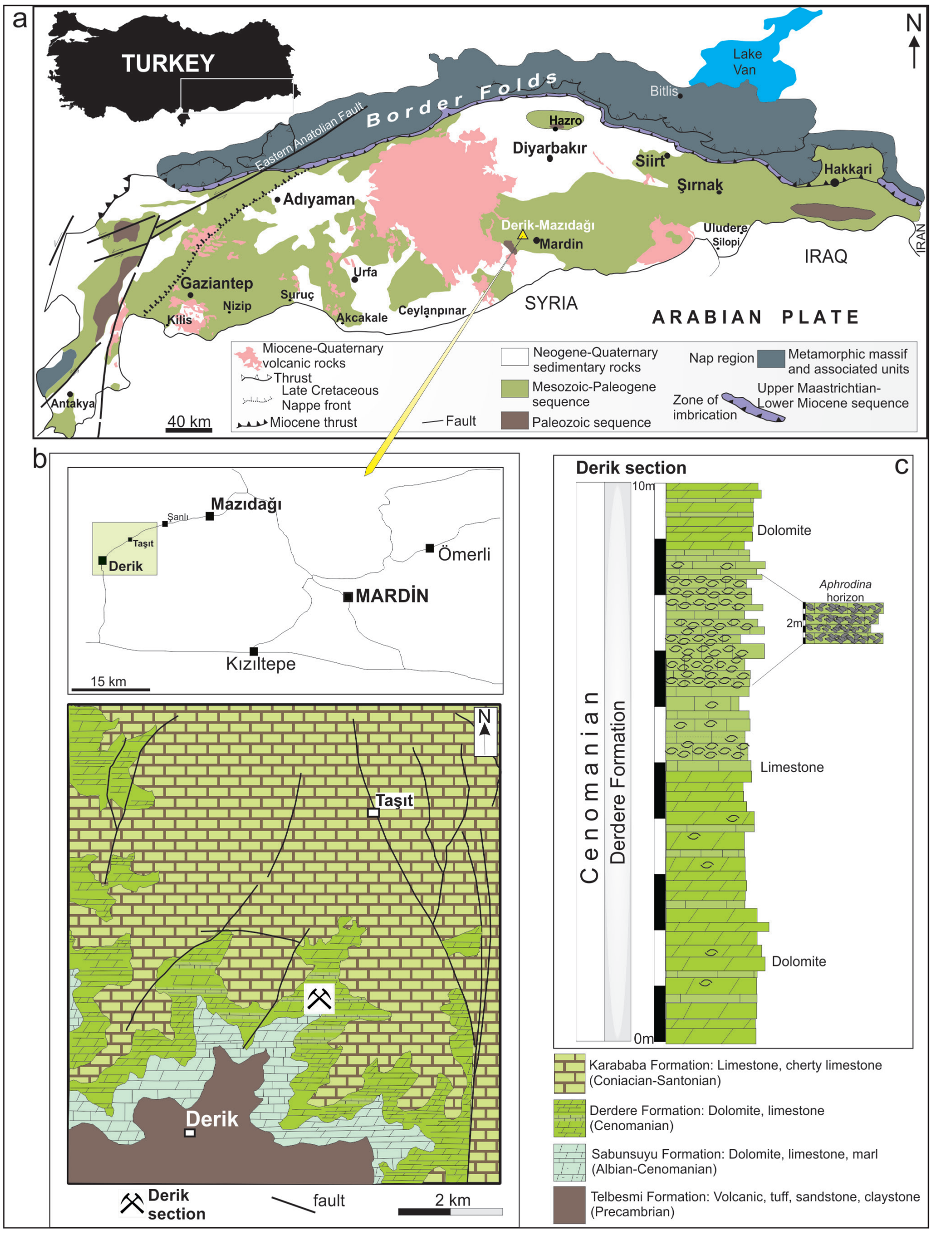

Fig. 1 - Geological map of the southeast Turkey and Derik-Taşıt area showing the locations of the study area and the stratigraphic column of the Derik section (Perinçek 1980; Yılmaz et al. 2018).

Methods

The presence of supposed species of *Aphrodina dutrugei* in the Cenomanian of SE Turkey was briefly mentioned by Hoşgör and Yılmaz (2013). This material is described and figured here for the first time (Figs 2, 3). The studied stratigraphic section was measured on a bed-by-bed scale, up to a total thickness of 10 m corresponding to the upper part of the Derdere Formation. Stratigraphic and microfacies analyses were performed at the Department of Geological Engineering, Middle East Technical University (METU), Ankara, Turkey. Microfacies determinations were carried out by point-counting/visual estimation for rock constituents, matrix and cement on thin sections by using a James Swift point-counting apparatus and an Olympus CX31 polarizing microscope, and based on the principles of microfacies analysis of Flügel (2010). The material is stored in the Department of Geological Engineering at METU under the inventory numbers M/A 20180030-42.

One hundred thirty-five specimens (90% articulated internal moulds) of *Aphrodina dutrugei* were available for study. They are preserved as internal moulds, outer casts and composite moulds. All linear measurements are given in millimeters (see pag. 424). The morphological analyses performed here are based on those of well studied members of the Veneridae, as *Mercenaria mercenaria*; we used characters already defined in several monographs (e.g., Mikkelsen et al. 2006). Abbreviations used are as follows: L = shell length; H = shell height; W = width of articulated shell (Fig. 3a).

Geological and stratigraphic setting

The Mardin Group was deposited in shelf and intrashelf basins developed along the northern margin of the Arabian Platform (Perinçek 1980; Cater & Gillcrist 1994; Yılmaz et al. 2018; Özkan & Altıner 2019). The Mardin Group is divided into four formations: the Areban, Sabunsuyu, Derdere, and Karababa formations (Yılmaz & Duran 1997). The studied interval covers the upper part of the

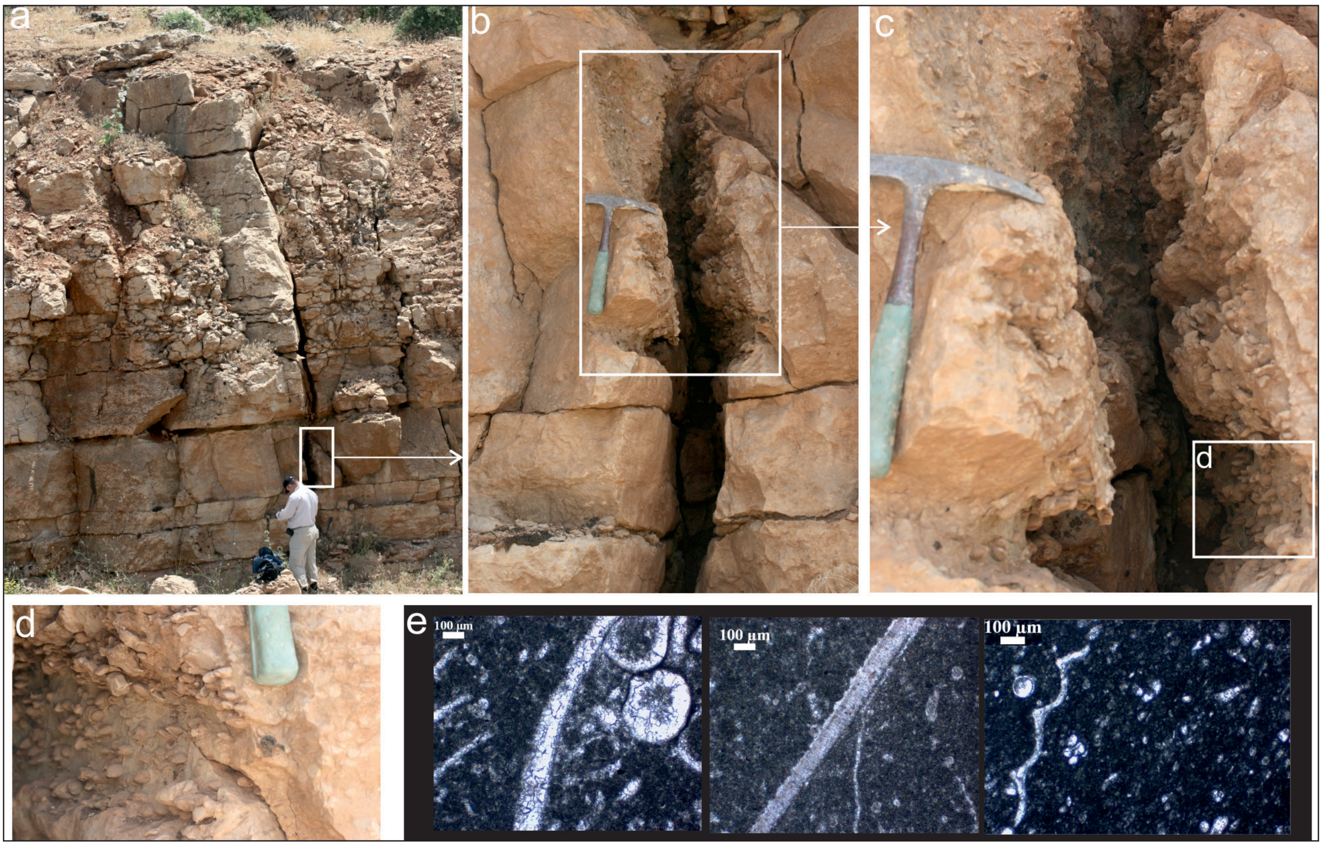

Fig. 2 - Field views of lithofacies in the Derik section, *Aphrodina dutrugei* monotaxic shell beds and photomicrographs of the microfacies (bioclastic packstones) recognized in the stratigraphic section.

Derdere Formation. The best exposures of the Mardin Group in this area are along the road from Derik to Mazıdağı and, roadside quarries south of Mardin. The base of the sequence (Areban clastics) is not exposed in the Mazıdağı area. The sequence above the Areban clastics is divisible into the Sabunsuyu Formation of Albian age, the Derdere Formation of Cenomanian to Turonian age and the Karababa Formation of late Coniacian to early Campanian age (Yılmaz et al. 2018). The Mardin Group is unconformably overlain by the middle-upper Campanian Karaboğaz and Sayındere formations; the Sayındere Formation is not exposed in the Derik area and the Karaboğaz Formation is overlain unconformably by the Maastrichtian Germav Formation (Cater & Gillcrist 1994).

Previous Palaeontological Research

Since the 1960s a number of studies have focused on the stratigraphic evolution of SE Turkey from the Mesozoic onwards based on biostratigraphy of the units (Yılmaz et al. 2018). Kellog (1961), Köylüoğlu (1988) and Özkan & Altıner (2019) mentioned the presence of benthic foraminifera and algae belonging to an association of common Cretaceous genera from the Mardin-Mazıdağ sections in southeastern Turkey, whereas Kuru (1987) mentioned Upper Cretaceous planktonic foraminiferas from the Derik-Mazıdağı area. Previous attempts to study the systematic and biostratigraphic features of Cretaceous bivalves have focused only rudists and their global evolutionary patterns (Özer 1992, 2005). The present paper deals with the systematic description of mollusca of southeastern Turkey other than the rudist fauna (Steuber et al. 2009) and some belemnites (Hoşgör & Kostak 2012).

The heterodont bivalve *Aphrodina dutrugei* occurs in monotaxic shell beds, which are the focus of this study in the Derdere Formation. This study illustrates that the monospecific articulated bivalve accumulation forms a marker bed in the Derdere Formation in the Derik section.

The Derik stratigraphic section

The Derik section is 10 m-thick and it is mainly composed of thick-bedded limestones and dolostones (Fig. 2a). Sedimentological analysis of the measured section confirms the cyclic alternation of facies throughout the succession (Yılmaz et al. 2017). Parallel and cross laminations, bioturbation and bioclast imbrications are the sedimentary structures observed throughout the measured section (Hoşgör & Yılmaz 2013). The thick-bedded carbonate-ramp facies includes packstones with convex-up monotaxic bivalves with current oriented accumulations (Fig. 2a-d). The matrix of the bivalve packstones is a micrite with planktonic foraminifera and minor dolomite. Shells are embedded in the partially dolomitized micritic matrix and partially replaced by sparry calcite (Fig. 2e). Preserved shells are observed in some samples and indicate bivalve shell lamellar microstructure.

Systematic Palaeontology

The classification of the 'aphrodiniid' venerid bivalves used herein follows Carter et al. (2011).

Class **BIVALVIA** Linnaeus, 1758
Grade **EUPROTOBRANCHIA** Nevesskaja, 2009
Megaorder **Cardiata** Férussac, 1822
Superorder **Cardiiformii** Férussac, 1822
Order **Cardiida** Férussac, 1822
Suborder **Cardiidina** Férussac, 1822
Superfamily Veneroidea Rafinesque, 1815
Family Veneridae Rafinesque, 1815
Subfamily Venerinae Rafinesque, 1815
Tribe Venerini Rafinesque, 1815
Genus *Aphrodina* Conrad, 1869
Type species: *Meretrix tippana* Conrad, 1858

Aphrodina dutrugei (Coquand, 1862)

Fig. 3b-i

1862 *Venus dutrugei* Coquand, p. 193, Pl. 7, figs. 5-6.
1917 *Venus dutrugei* Coquand, 1862 - Fourtau, p. 88.
1962 *Meretrix dutrugei* (Coquand, 1862) - Abbas, p. 147, pl. 22, fig. 22.
1963 *Venus dutrugei* Coquand, 1862 - Fawzi, p. 79.
2002 *Aphrodina (Aphrodina) dutrugei* (Coquand, 1862) - Berndt, p. 128, pl. 7, fig. 1-2.
2005 *Aphrodina dutrugei* (Coquand, 1862) - Ahmad, p. 191, pl. 1, figs. 1-9.
2013 *Aphrodina dutrugei* (Coquand, 1862) – Musavu Moussavou et al., p. 4, figs. 4-5, 6, 11, 13-15.
2015 *Aphrodina dutrugei* (Coquand, 1862) – Musavu Moussavou, p. 319, pl. 4, fig. 1.
2016 *Aphrodina dutrugei* (Coquand, 1862) - Benzaggagh, p. 24, fig. 18.

Material: A dozen measurable articulated valves represented by internal moulds are available. The majority of the valves come from a single horizon (about 2 m thick) that was recorded about 7 m above the base of the the Derdere Formation in the Derik section (Fig. 2c).

Measurements (in mm):

Specimen	Length	Height	Width	L/H
M/A 20180030	21	19	11	1.1
M/A 20180031	22	19	12	1.16
M/A 20180032	24	20	12	1.2
M/A 20180033	20	18	11	1.1
M/A 20180034	25	22	14	1.14
M/A 20180035	26	22	15	1.18
M/A 20180036	27	24	15	1.12
M/A 20180037	28	24	14	1.17
M/A 20180038	26	21	14	1.23
M/A 20180039	24	19	13	1.26
M/A 20180040	23	21	12	1.1
M/A 20180041	24	21	14	1.14

Description. Specimens small (maximum length of 28 mm and 24 mm in high), shell form variable from oval to elongated, slightly longer than high (Fig. 4) (length/height ratio from 1.1 to 1.26), equivalved, inequilateral. Escutcheon shallow and lunule present. Umbo situated at the anterior 30–35 % of valve length. Anterior margin slightly convex to straight, posterior margin rounded. The valves are almost smooth.

Remarks. Blanckenhorn (1890) reported 75 bivalves from the Cenomanian-Turonian successions in NW Syria. Among them, four belong to venerid species: *Cytherea libanotica* (Fraas, 1878), *C. syriaca* (Conrad, 1852), *C. obruta* (Conrad, 1852), and *Venus syriaca* (Conrad, 1852). *C. obruta* (Blanckenhorn, 1890, p. 92, pl. 5, figs. 9-11) is similar to *A. dutrugei* in its slightly ovate outline, but differs in having more inflated valves and smaller umbonal area. *Aphrodina angustosinuosa* Riedel, 1957 (in Collignon, 1971; p. 46, pl. 1, figs. 2-4) from the Maastrichtian of the Sahara (Algeria) differs from *A. dutrugei* by its prominent concentric sculpture and inflated umbonal ridge. Shell shape is closest to *Paraesa faba* (Sowerby, 1827) (in Ghenim et al. p. 35, pl. 14, fig. 8) from the Cenomanian of Algeria, but this species has a small lunule and it is less elongate than *A. dutrugei*. The Turkish specimens closely resemble the Jordanian specimens described by Ahmad (2005; pl. 1, figs. 1-9) from the Zarga section, on the basis of the L/H ratio range from 1.1 to 1.2. However, the majority of the specimens from Jordan have a less inflated and elongated outline than the Derik section material.

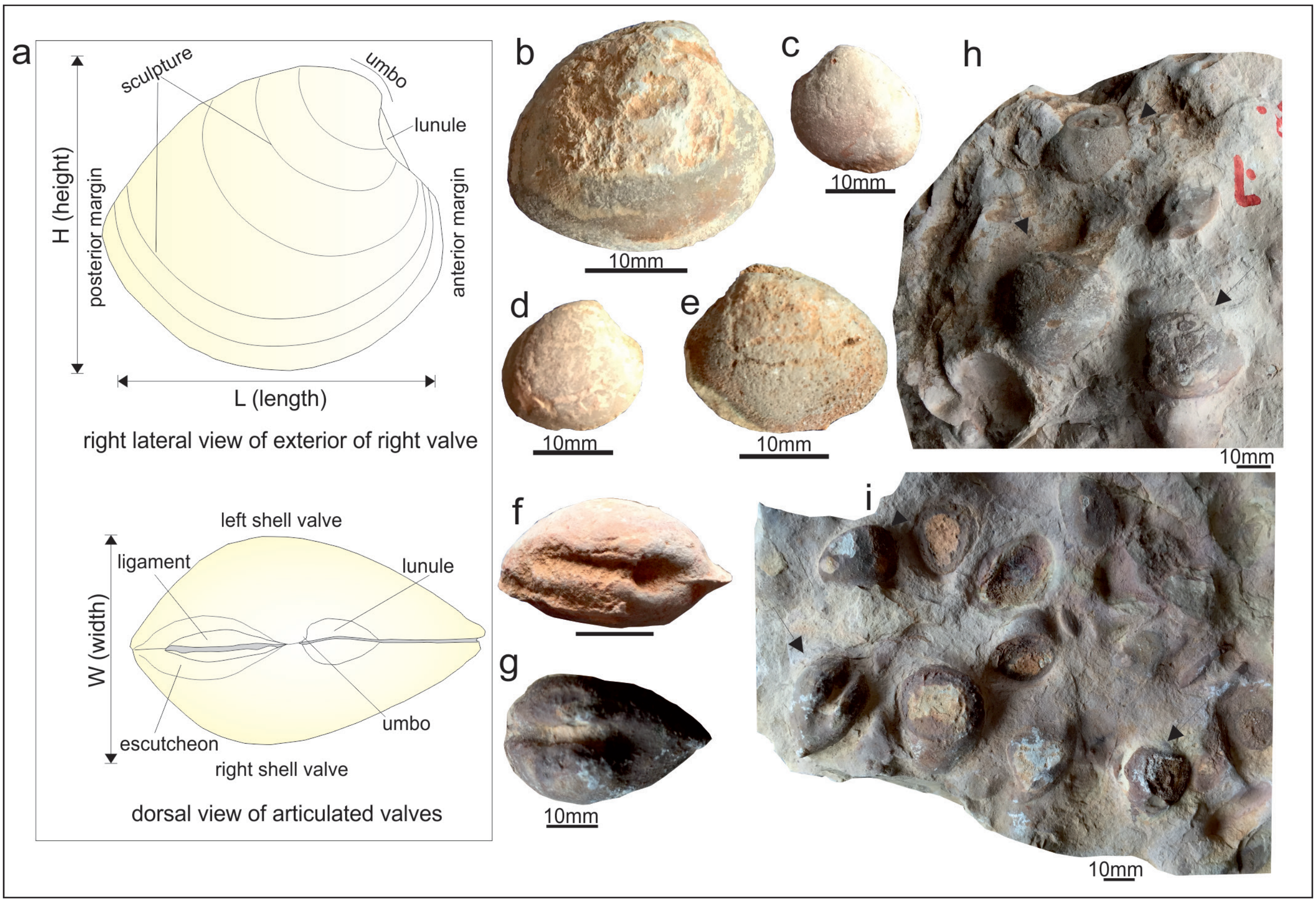

Fig. 3 - a) General venerid shell morphological terms used in this analysis (Mikkelsen et al. 2006), b) M/A 20180030 in right lateral views, c) M/A 20180039 in left lateral views, d) M/A 20180032 in right lateral views, e) M/A 20180037 in left lateral views, f-g) M/A 20180034-35 in right dorsal views, h-i) monotaxic venerid-bivalve shell slabs.

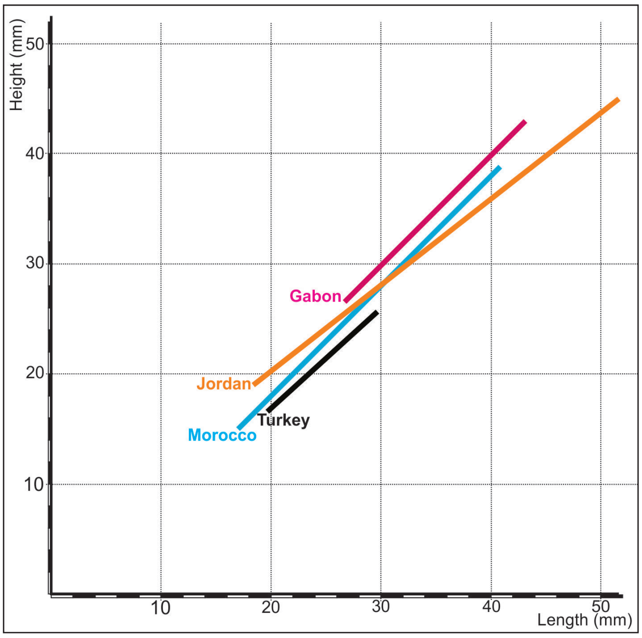

Fig. 4 - Scatter diagram of shell dimensions of *Aphrodina dutrugei* from Gabon (Moussavou et al. 2013), Jordan (Ahmad 2005), Morocco (Benzaggagh 2016) and Turkey (this study, see Measurements).

‘Aphrodiniid’ venerids in the Cretaceous

The Veneridae is the most advanced and diverse Recent bivalve family, comprising over 800 extant species in approximately 170 genera (Mikkelsen et al. 2006). Its early evolution and increasing diversity in the Cretaceous remain lesser known (Saul 1993). Since the establishment of the genus *Aphrodina* by Conrad (1869), nearly 17 species of *Aphrodina* have been listed from the Tethys (Fig. 5). The earliest candidate of ‘aphrodiniid’ venerid bivalve is in the Valanginian-Hauterivian and the latest known occurrence dates from the Danian, with the greatest diversity in the Cenomanian to Santonian. The earliest record of *Aphrodina* species (*A. quintucoensis* (Weaver 1931)) is from the Pilmatue Member of the upper Valanginian to lower Hauterivian Agrio Formation at Agua de la Mula in the Neuquen Basin, west-central Argentina (Lazo 2007). The genus then rapidly dispersed widely, with the majority of spe-

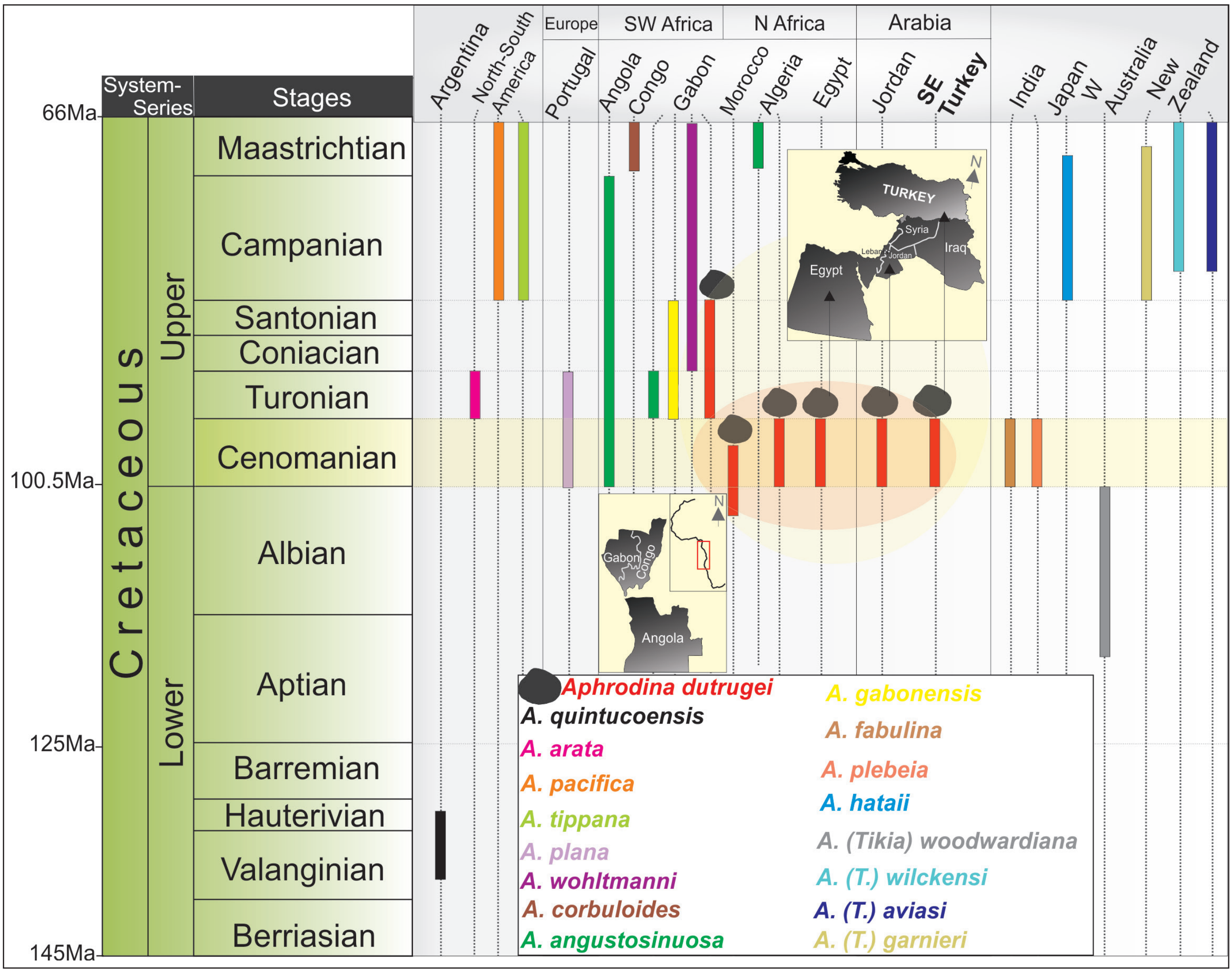

Fig. 5 - Stratigraphic range of *Aphrodina* species during the Cretaceous (primary data sources are: Dartevelle & Freneix 1957; Collignon 1971; Freneix 1981; Saul 1993; Callapez 1998; Stilwell 1998; Brendt 2002; Ahmad 2005; Kendrcik & Vartak 2007; Lazo 2007; Musavu Moussavou et al. 2013; Musavu Moussavou 2015; Benzaggagh 2016).

cies documented from the Atlantic (North-South America) (Saul 1993; Lazo 2007), Arabian and African pericratonic platforms (Jordan, SE Turkey, Morocco, Algeria and Egypt) (Collignon 1971; Brendt 2002; Ahmad 2005; Benzaggagh 2016; this study), eastern Tethys and Southern Ocean (India, Japan, western Australia and New Zealand) (Freneix 1981; Stilwell 1998; Kendrick & Vartak 2007; Nobuhara et al. 2008), as well as from the Trans-Saharan Seaway (Angola, Congo and Gabon) (Dartevelle & Freneix 1957; Musavu Moussavou 2015). The distribution and diversity of 'aphrodiniid' venerid bivalves (Fig. 5) sharply increased in the Cenomanian-Santonian interval with *A. dutrugei, A. fabulina* (Stoliczka, 1870), *A. plebeia* (Kendrick & Vartak, 2007), *A. plana* (Sowerby, 1813), and *A. arata* (Gabb, 1864) (Dartevelle & Freneix 1957; Freneix 1981; Callapez 1998; Ahmad 2005; Musavu Moussavou 2015). Some isolated occurrences of venereid species are also reported in the Cenomanian to Campanian, in localities such as Gabon (Musavu Moussavou 2015) and Angola (Dartevelle & Freneix 1957). The endemic species *A. gabonensis* (Dartevelle & Freneix, 1957) (Turonian-Santonian) and *A. angustosinuosa* (Riedel, 1932) (Cenomanian-Campanian) indicate that open marine connections were established between northern Gabon-Angola and the Mediterranean Tethys through the Cenomanian-Santonian Trans-Saharan Seaway (Musavu Moussavou et al. 2013; Musavu Moussavou 2015).

Aphrodina dutrugei seems to be a unique species in the Cenomanian 'aphrodiniid' venerid fauna of the Afro-Arabian Platform. In contrast, Cenomanian-Turonian occurrences of other *Aphrodina* species are limited to Europe, and *A. plana* is from the West Portuguese Basin (Callapez 1998). Other species are reported from Turonian-Santonian or Campanian- Maastrichtian formations of the Atlantic and Tethys Ocean. Kendrick & Vartak (2007) reported *A. fabulina* and A. *plebeia* from two localities in the marine parts of the Cenomanian Uttattur Group in the Odiyam village, southern India.

The endemic Campanian-Maastrichtian 'aphrodiniid' venerid fauna of New Zealand is of low diversity consisting of *A. (Tikia) wilckensi* (Woods, 1917), *A. (T.) aviasi* Freneix, 1958 and *A. (T). garnier* Freneix, 1958 (Freneix 1981; Stilwell 1998). In Peru, *A. pacifica* Olsson, 1944 is one of the dominant species in the shallow and warm water Maastrichtian assemblage at the La Tortuga section (Olsson 1944; Dhondt & Jaillard 2005). An exceptional occurrence is *Aphrodina hataii* (Katto & Hattori, 1965) from the Campanian–Maastrichtian "Sada Limestone" seep deposit in Japan (Nobuhara et al. 2008). These specimens may represent a separate genus known only from this seep locality.

Discussion

The Cenomanian-Santonian 'aphrodiniid' venerid bivalve assemblages are typically low diversity compared with other Upper Cretaceous marine invertebrate assemblages. The temporal changes of ammonoid species and rudist bivalves were great during the late Albian to early Turonian in Europe and on the Afro-Arabian plate (Monet 2009; Steuber et al. 2016). Rudist diversity decreased markedly at the Cenomanian/Turonian boundary (Steuber & Löser 2000). Rudists, oysters and inoceramids are widely accepted as international zonal markers for the Cenomanian to Turonian successions (Fig. 6). Gastropods (Heterobranchia) were another most diverse taxon during the Late Cretaceous, and the increase in numbers of species during that time was comparable to that of ammonoids, rudist bivalves, inoceramids, and oysters. During the Cenomanian-Campanian, however, the number of Nerineoidea and Acteonelloidea species increased very rapidly (Kollmann 2014). New faunal elements appeared in the Cenomanian, including ammonoid and oyster faunal markers in Jordan, Egypt and Morocco (Lehmann & Herbig 2009; Ayoub-Hanna & Fürsich 2012; Ahmad et al. 2015; Nagm et al. 2017). *Neolobites vibrayeanus* and *Vascoceras cauvini* ammonite biozones and the oysters zones (*Ceratostreon flabellatum* (Goldfuss, 1833)*, Ilymatogyra africana* (Lamarck, 1801)*, Costagyra olisiponensis* (Sharpe, 1850), and *Pycnodonte (Phygraea) vesicularis vesiculosa* (Sowerby, 1823)) are recorded in the upper Cenomanian carbonate Fuhels, Hummar and Shueib formations in central Jordan (Ahmad et al. 2015; Nagm et al. 2017). According to Ayoub-Hanna & Fürsich (2012), a very detailed biostratigraphic data set on ammonites from the Cenomanian-Turonian succession of the eastern Sinai of Egypt is used to correlate the upper Cenomanian to Turonian ammonite zones from North Africa, Arabian Plate to Europe.

A similar pattern of Cenomanian–Turonian bivalve species and of facies evolution prevailed across carbonate platforms in the whole of western Africa from the Trans-Saharan Seaway margin to eastern Africa and northern Arabia (Ayoub-Hanna et al. 2014; Ghenim 2019). During the Cenomanian-Turonian, bivalves, and in particular oysters, inoceramids and rudists, were highly diverse and widespread on the Atlantic margins and in the Mediterranean and eastern Tethys (Dhondt 1992; Zakhera 2011; Ayoub-Hanna et al. 2014; Benzaggagh 2016; Özer & Ahmad 2016). These faunal associations are typical of Cretaceous Tethyan carbonate platform margins and are very useful for palaeobiogeographic reconstructions.

East-to-west-directed oceanic currents during Cenomanian-Turonian facilitated or hindered the dispersal of venerids and many other invertebrate groups across the shallow carbonate shelves of Tethyan margins (Fig. 6) (Saul 1993; Ayoub-Hanna et al. 2014; Callapez et al. 2015). These currents affected the distribution of *A. dutrugei*, whose oldest known occurrence is in upper Albian-Cenomanian successions of northern Morocco (Benzaggagh 2016). The Tethys Ocean played a critical role in determining the warm climate ecosystems of the Cretaceous (Stanley 1995). Tropical climates between paleolatitudes of 30°N and 30°S are believed to have contributed to the westward-flowing Tethys Circumglobal Current (TCC) throughout the Cretaceous Period (Stanley 1995). The opening of the Trans-Saharan Seaway facilitated immigration of southern Tethys bivalves onto the Afro-Arabian margins and south Atlantic (Ayoub-Hanna et al. 2014).

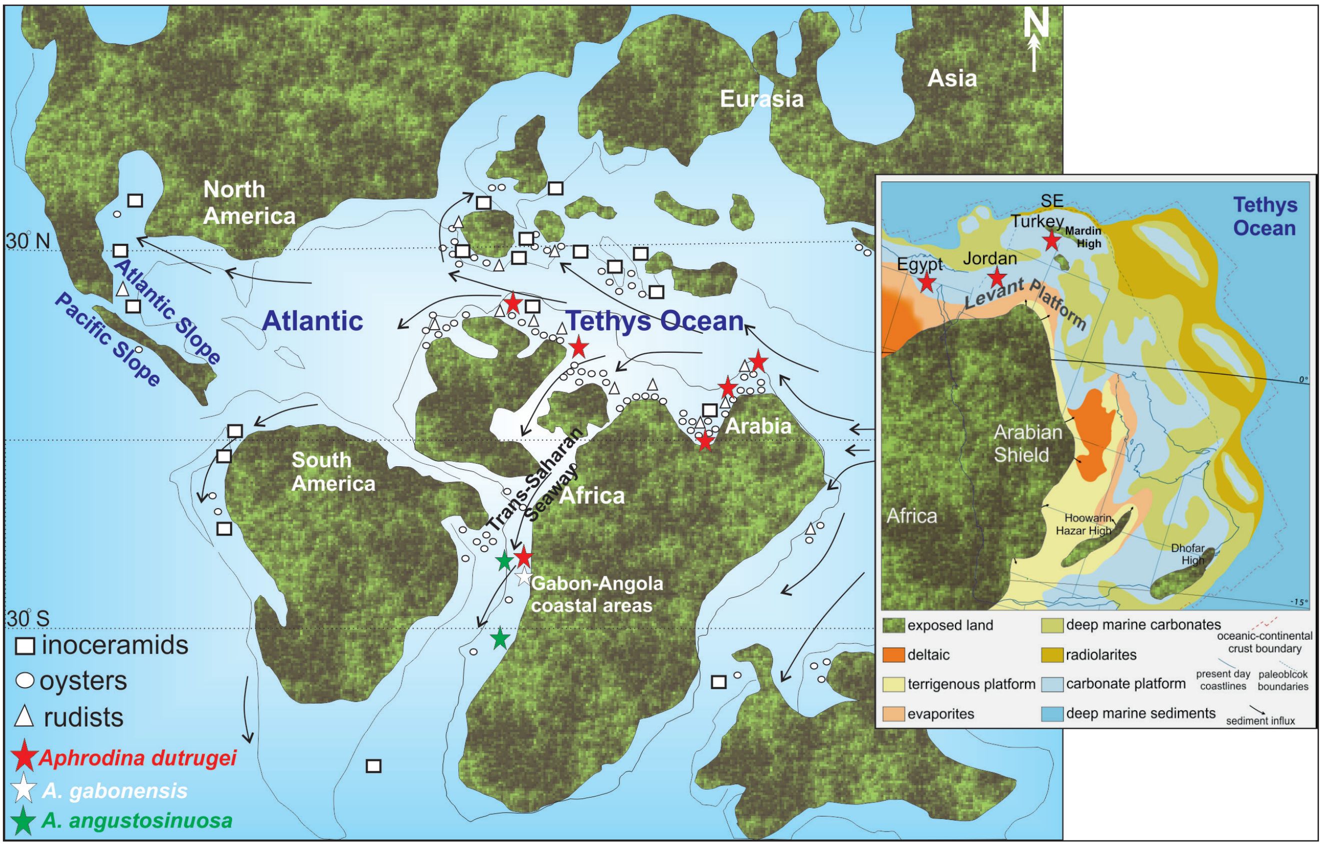

Fig. 6 - Geographic distribution of the most representative Upper Cretaceous mollusc assemblages (inoceramids, oysters and rudists) with *Aphrodina* species (including the northeastern Tethyan record of *A. dutrugei*) and reconstruction of surface water circulation based on dispersal pathways of aphrodinid venerids (Collignon 1971; Dhondt 1992; Saul 1993; Steuber & Löser 2000; Brendt 2002; Ahmad 2005; Schulze et al. 2005; Zakhera 2011; Ayoub-Hannaa & Fürsich 2012; Musavu Moussavou et al. 2013; Ayoub-Hanna et al. 2014; Ahmad et al. 2015; Callapez et al. 2015; Musavu Moussavou 2015; Benzaggagh 2016; Özer & Ahmad 2016; Steuber et al. 2016).

The sedimentary record of the late Albian, Cenomanian and Turonian in the north Arabian Platform and Levant carbonate shelf (89-98.9 Ma) includes similar facies variations along the northern passive margin of the Arabian Plate and was influenced by the southern Tethys (Schulze et al. 2005).

The huge area in between, comprising the Levant Platform and Mardin High region (SE Turkey) (Fig. 6), has remained poorly studied and milestone studies like those done in the successions of Egypt (Ayoub-Hanna et al. 2014) are completely missing. In a detailed overview of the Cenomanian-Turonian successions, *A. dutrugei* was reported from southwestern Jordan on Levant Platform (Brendt 2002; Ahmad 2005). The new record reported here of *A. dutrugei* in the Cenomanian Derdere Formation (SE Turkey) extends the distribution of 'aphrodiniid' venerid taxa along the northern Arabian plate. Larvae of *A. dutrugei* could have migrated along the northern Arabian shelf in the Tethys seaway between Egypt and SE Turkey (Fig. 6).

The Cenomanian Stage is characterized by transgressive phases (Haq 2014) that flooded continental areas and developed widespread shallow marine settings. The transgression resulted in a variety of marine facies, among which especially ramp carbonates were favorable for shallow burrowing infaunal, filter-feeding venerids. This low diversity and monotaxic *A. dutrugei* assemblage is preserved as articulated specimens and it was found only in one horizon in SE Turkey. This 'aphrodiniid' venerid bivalve species is stratigraphically useful in the Cenomanian, and this biomarker is applicable to large parts of the Tethys. The new record of *Aphrodina* in SE Turkey may help to refine the inter-regional correlations, and it provides new information to improve the level of knowledge about the effects of Cenomanian transgression. This species is not known in other parts of SE Turkey and surroundings areas. Its limited occurrence indicates that this species is not distributed farther northeastern of the Arabian platform.

Conclusions

As already stressed by Saul (1993), records of Cretaceous venerid are too sparse. So the palaeobiogeographic approaches have been limited to the northern border of the Afro-Arabian Plate. *Aphrodina* is a widespread Cretaceous genus with a continuous history ranging from the Valanginian to the Danian, and with a cosmopolitan distribution during the Cenomanian–Campanian. Records of *A. dutrugei* are mostly restricted to the Cenomanian-Santonian on the Afro-Arabia Plate suggesting that it may have potential as a Cenomanian biostratigraphic marker in SE Turkey. The more comprehensive study made here of the diversity of 'aphrodiniid' venerid taxa (*A. dutrugei*) in the Upper Cretaceous deposits of the Mazıdağı section allows us to better understand possible connections and larval distribution between this area, SE Turkey to Morocco (Afro-Arabian platform margin) and Gabon-Angola coastal areas.

Acknowledgements: We would like to thank Robert William Scott for discussion on the specimen, and for the constructive comments which have helped to improve the paper. The authors thank the anonymous reviewers for their helpful comments and suggestions. Financial support for this study was provided by a national research project of TUBITAK-111Y138.

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