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Durania cornupastoris rudist from the Turonian of El-Hassana Dome (Abu Roash area), Egypt: Systematic palaeontology and palaeoecology

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ABSTRACT

Based on newly-collected exhaustive rudist materials from the Turonian Abu Roash Formation at El-Hassana dome, *Durania cornupastoris* (Des Moulins) was clearly-identified. In many literatures, the *Durania arnaudi* (Choffat) is considered a synonym of *Durania cornupastoris* (Des Moulins). Our investigation is based on several characteristics that include dimensions, ornamentation, radial bands, interbands and shell microstructures of the right valves. These characters and comparison with specimens described in the literature were used to identify the collected specimens as *Durania cornupastoris* and differentiate it from *Durania arnaudi*. The external shape of the shell, widths of the radial bands and number of the longitudinal ribs in the interband were the main characteristics of *Durania cornupastoris*. In the described right valves, the interband (Ib) is bulge and has four to six ribs that excluded an attribution to *Durania arnaudi*. Moreover, the ventral radial band (Vb) of *Durania cornupastoris* is wider than the posterior one (Pb). The ecological and taphonomic characteristics of *D. cornupastoris* were highlighted. The elevator *D. cornupastoris* rudists of El-Hassana Dome form significant biostrome in shallow marine environments. The *D. cornupastoris* individuals are in growth position and they are densely packed. The borings are distributed on the *D. cornupastoris* shells. Moreover, these shells exhibit compaction features that appeared as fractures, deformation and/or destruction of the cellular structures in the right valves. The borings and the fractures in the shells are filled with silica materials during the silicification process. The carbon isotopic data ($\delta^{13}C$) of the *Durania cornupastoris* from Abu Roash area are similar to those from Sinai. However, the oxygen isotopic values ($\delta^{18}O$) measured from this species are high when compared with those from the Turonian rudist shells of Sinai.

1. Introduction

The progressive studies show that the Arabo-African plate platform has rich rudist fauna in the Upper Cretaceous formations of Algeria, Morroc, Libya, Tunisia, Somalia, Oman, UAE, Jordan, Saudi Arabia, Lebanon, Iraq, Iran, SE Anatolian region of Turkey and Egypt (Steuber, 2002; Kuss et al., 2003; Schulze et al., 2004; Sadooni, 2005; Negra et al., 2009; Saber et al., 2009; Steuber et al., 2009; Özer, 2010a,b; Chikhi-Aouimeur, 2010; Abdel-Gawad et al., 2011; El-Sabbagh et al., 2011; Zakhera, 2010, 2011; Özer and Ahmad, 2015, 2016; Özer et al., 2018; Salama et al., 2016, 2018). The Turonian Abu Roash Formation is marked by the occurence of *Durania* genus in north Western Desert of Egypt (Dacqué, 1903; Douvillé, 1910; De Castro and Sirna, 1996; El-Sabbagh and El-Hedeny, 2003; Mansour, 2004). In Abu Roash area, this formation contains three rudist biostromes (Abdel-Gawad et al., 2011). The rudist assemblage consists of the species of *Durania* Douvillé, *Bournonia* Fischer and *Praeradiolites* Douvillé (El-Hedeny, 2007; El-Sabbagh et al., 2011). The *D. gaensis* (Dacqué) and *D. arnaudi* (Choffat) were firstly described from the Abu Roash area by Douvillé (1910). However, according to De Castro and Sirna (1996), the rudist biostrome is only constructed by *D. arnaudi* in this area. Moreover, this biostrome was demonstrated as a bouquet of *Durania cornupastoris* by Steuber (2002). The *Durania cornupastoris* was first described from the Abu Roash area by El-Sabbagh and El-Hedeny (2003). Although they have many right valve specimens, their description was very limited and the radial bands were presented only on two specimens. Recently, the rudist specimens had been described as *Durania arnaudi* as documented by Abdel-Gawad et al. (2011) indicating a controversy on the presence of *Durania cornupastoris* at El-Hassana Dome. Although, the first author of this work studied the rudist of El-Hassana Dome through his PhD work, he did not refer to *Durania cornupastoris*. However, the extensive investigations as well as the collection of new *Durania* materials from Abu

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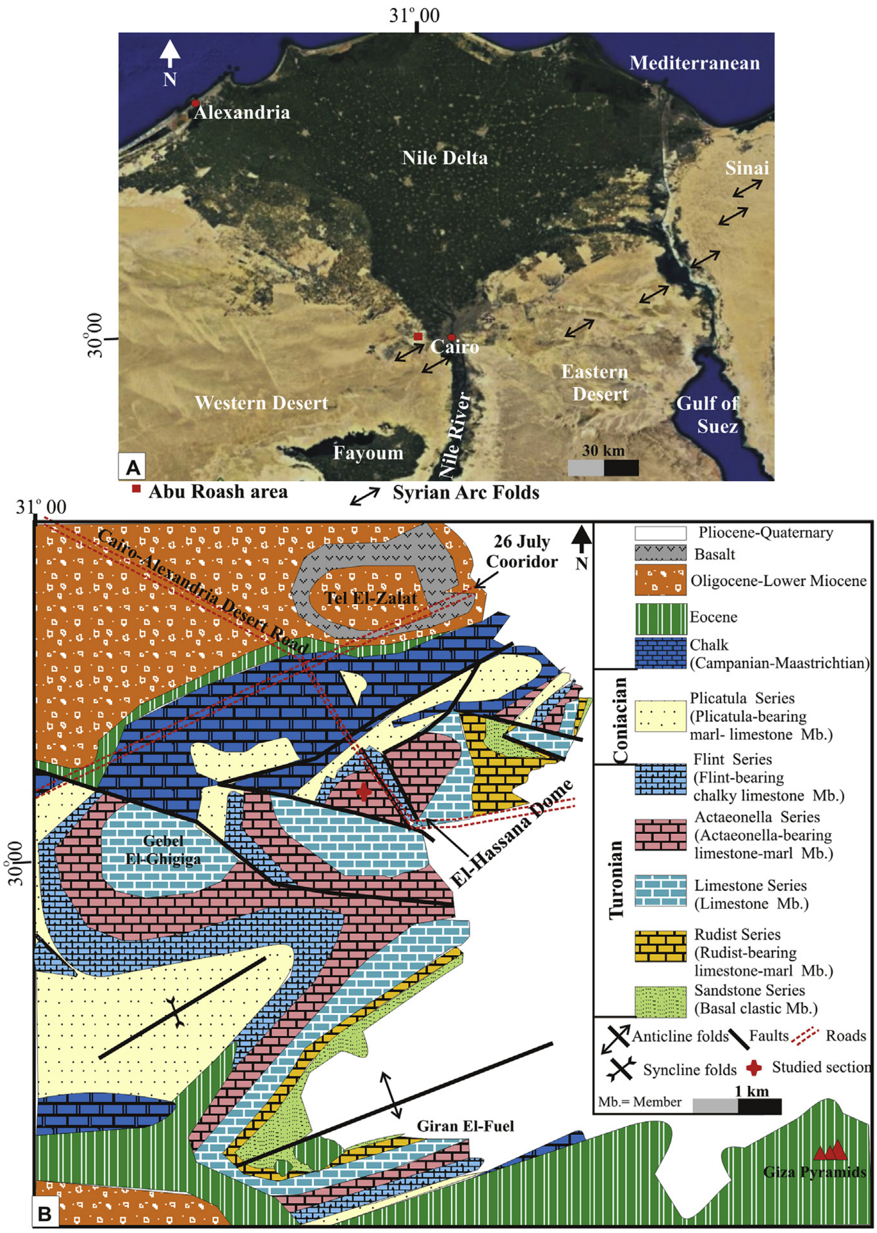

Fig. 1. A, Location of Abu Roash area (Red square) in north Western Desert. B, Geologic map of Abu Roash area from Abu Khadrah et al. (2005). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Roash area were useful to re-define the *Durania* species.

This study is focused mainly on the description of *Durania cornupastoris* from the Abu Roash area and the comparison with *D. arnaudi* reported or described from the Mediterranean Tethys and Egypt. The palaeoecological characteristics of *D. cornupastoris* and taphonomic features are also discussed. The carbon and oxygen isotope data obtained from the studied species were evaluated.

2. Geological setting and stratigraphy

The study site for the *Durania*-bearing limestone was El-Hassana Dome. It is located near Abu Roash area and to northwest of Giza Pyramids on Alexandria desert road at north Western Desert of Egypt (Fig. 1). The exposed Upper Cretaceous rocks at Abu Roash area comprised two formations named Abu Roash and Khoman chalk. The Abu Roash Formation is of Turonian age (Abdel-Gawad et al., 2011; Badawy, 2015; Abdelhady and Mohamed, 2017; Hewaidy et al., 2018). The Khoman chalk is of Campanian-Maastrichtian age (Abdel Khalek et al., 1989). The upper Turonian strata at El-Hassana Dome are composed mainly of limestone and marl intercalations that termed *Actaeonella-Nerinea* Limestone (Osman, 1954), *Actaeonella* Series (Said, 1962; Hataba and Ammar, 1990), Abu Roash C (Abdel Khalek et al., 1989), *Actaeonella*-bearing limestone-marl member (Badawy, 2015), *Actaeonella* Member (Abdelhady and Mohamed, 2017). Based on the lithologic variations, this member can be subdivided into three lithologic units: lower limestone-shale unit, middle limestone unit and upper limestone-shale unit (Badawy, 2015); the *Durania cornupastoris* rudists are widespread in the middle unit (Fig. 2). This member is comparable in age to the topmost portion of the Turonian Wata Formation in north Sinai and north Eastern Desert (Salama, 2012). The Upper Turonian index gastropoda fossils *Nerinea requieniana* d'Orbigny and *Trochacteon salomonis* Fraas indicated the Turonian age for *Actaeonella* series of Abu Roash Formation (Salama, 2012). The Turonian age for these gastropods is also supported by the presence of *Coilopoceras requienianum* (d'Orbigny) at north Eastern Desert (Salama, 2012). *T. salomonis* Fraas was also reported in the Turonian Wata Formation of Wadi El-Dier,

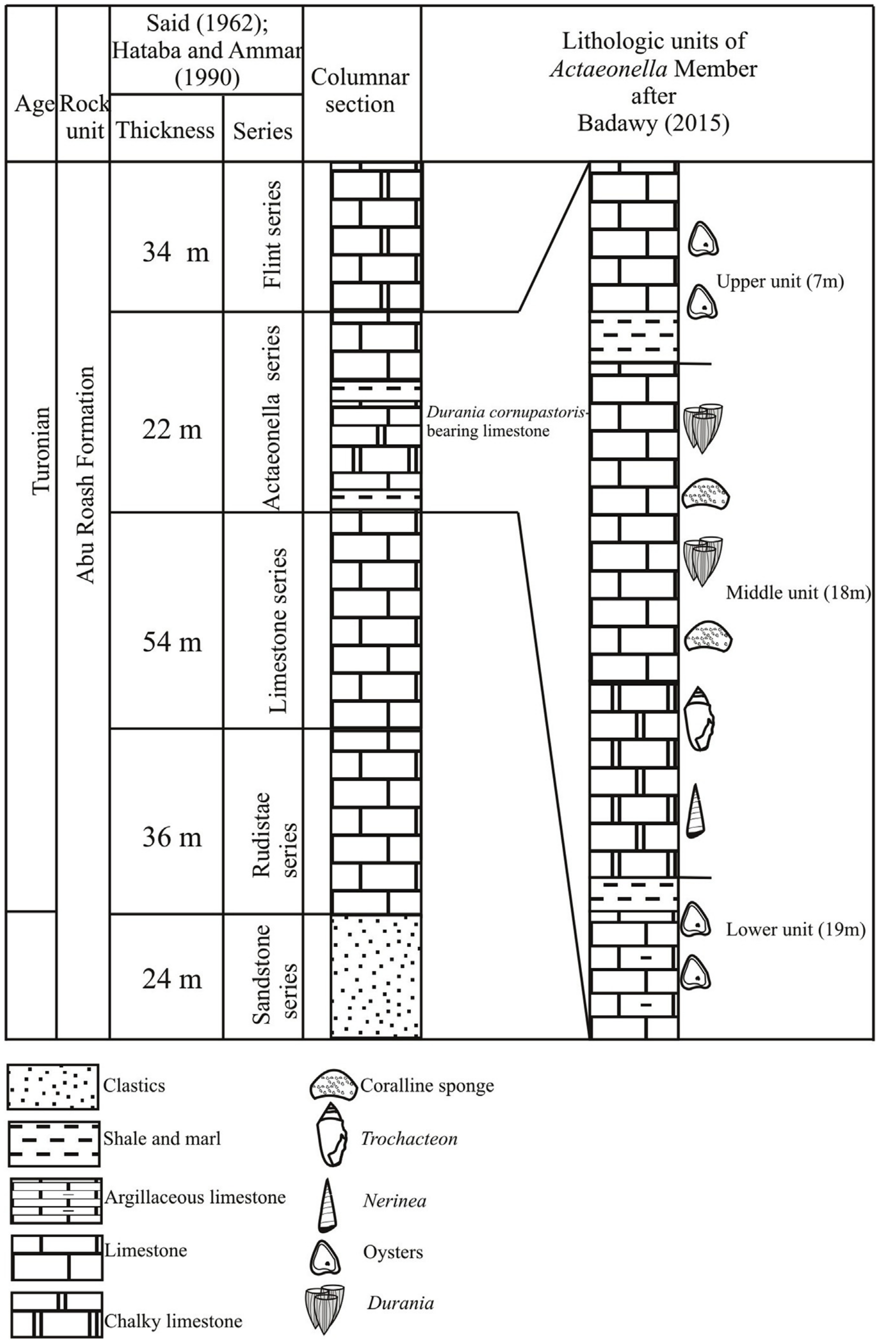

Fig. 2. Turonian succession at El-Hassana Dome of Abu Roash area.

Saint Paul area in north Eastern Desert (Abdel-Gawad et al., 2007) and Sinai (EL Qot, 2006).

3. Material and methods

New *Durania* materials collected from the Turonian outcrop at Abu Roash area of north Western Desert comprise 62 specimens of *Durania cornupastoris* shells. Three specimens are fully articulated and the other specimens are only right valves. Ten right valves are complete, well-preserved and have well-marked radial bands. Thin sections in the selected specimens and the host rocks were used to assess the shell microstructures and the taphonomic features. The palaeoecological and taphonomic observations were also recorded in the field. The materials are kept in Geology Department, Beni-Suef University (Ab-BSU).

The oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotope analyses have been made in the powder samples extracted from the outer shell layers of *Durania cornupastoris* specimens. The analyses were carried out in the Stable Isotope Laboratory of the University of Miami at USA. The standard methods as detailed in Swart and Melim (2000), Swart et al. (2005) and Swart and Eberli (2005) were used. The samples reacted with 100% phosphoric acid at 90 °C using a common acid bath. The resultant CO2 was analyzed for $\delta^{18}O$ and $\delta^{13}C$ using a Finnigan MAT 251 mass spectrometer.

4. Systematic palaeontology

The classification and morphological terminology used here follow Skelton (2013a, b). The following abbreviations have been used: LV, left valve; RV, right valve; Pb, posterior radial band; Vb, ventral radial band; Ib, interband; il, inner (aragonitic) shell layer; ol, outer (calcitic)

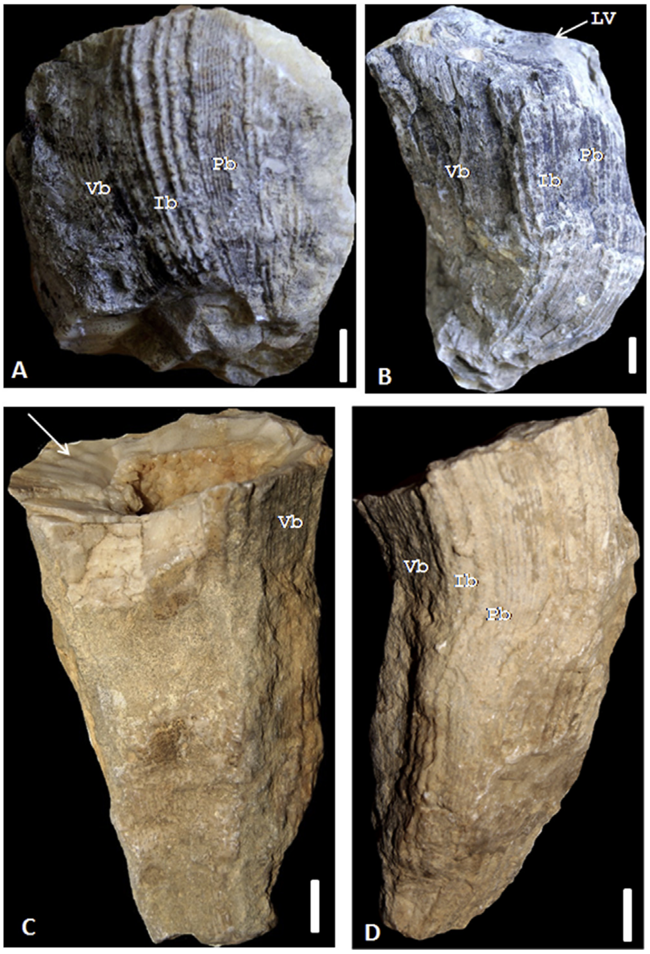

Fig. 3. *Durania cornupastoris* (Des Moulins), Abu Roash, Egypt, scale bar is 15 mm. A, RV showing the many finely ribbed, flat Pb, Vb and bulge Ib with salient ribs, sample no Ab-BSU 6. B, both valves, but LV is partially preserved (arrow), bulge Ib with salient ribs separets the radial bands, sample no: Ab-BSU 8. C, the dorso-ventral part of RV showing the finely ribbed Vb, the radiating vascular impressions (arrow) can be observed, sample no: Ab-BSU 9. D, same specimen showing the structure of the radial bands, the Vb is flat, but Pb is slowly concave.

shell layer; L, ligament.

Class Bivalvia Linnaeus, 1758

Order Hippuritida Newell, 1965

Suborder Radiolitidina Skelton, 2013a.

Superfamily Radiolitoidea d'Orbigny (1847).

Family Radiolitidae d'Orbigny (1847).

Genus ***Durania*** Douvillé, 1908

Durania cornupastoris (Des Moulins, 1826).

1826. *Hippurites cornupastoris* Des Moulins - p. 141, pl. X, Figs. 1 and 2.

1850. *Biradiolites cornupastoris* (Des Moulins) - d'Orbigny, p. 231, pl. 573, Figs. 1–6.

1903. *Radiolites cornupastoris* (Desm.) - Dacquè, p. 373.

1910. *Durania arnaudi* (Choffat), Douvillé, p. 50, pl. 3, Fig. 1.

1991. *Durania cornupastoris* (Des Moulins) - Cobban et al. D3-8, pl.1–3, text-Fig. 1.

1996. *Durania arnaudi* (Choffat) - De Castro and Sirna, p. 78, text-Figs. 5–9.

2005. *Durania arnaudi* (Choffat) - Aly et al. p. 273, pl. 10, Figs. 3–9, pl. 11, Figs. 2 and 3.

2006. *Durania arnaudi* (Choffat) - El Qot, p. 70,pl. 14, Figs. 4 and 5.

2011. *Durania arnaudi* (Choffat) - Abdel-Gawad et al., p. 365–366, Fig. 4 G, H.

2012. *Durania arnaudi* (Choffat) - Salama, p. 96, pl.3–13, Fig. 1.

2017. *Durania cornupastoris* (Des Moulins) - Özer and El-Sorogy, Figs. 4–6. (with synonymy list).

2017. *Durania arnaudi* (Choffat) - Abdelhady and Mohamed, p. 131, Fig. 8 A, C.

Material and occurrence. Ten well-preserved specimens selected from the many right valves (nos Ab-BSU 4, 6, 9, 10, 13, 15, 18, 20, 22, 24) and three articulated shells having partially preserved left valves (nos Ab-BSU 8, 11 and 14). The described specimens were collected from the *D. cornupastoris*-bearing limestone in the Turonian *Actaeonella* Member.

Description: The RV is elongate, conical in shape, slightly curved towards the ventral part, up to 170 mm in length and a diameter of up to 80 mm (Figs. 3 and 4). The large cylindro-conical specimen shows a 85 mm length and is up to 60 mm in diameter (Table 1). The RV is ornamented with salient, regular longitudinal ribs (3–6 mm width) that separated by 2–4 mm wide furrows. The Vb and Pb are generally flat, but some specimens are slightly concave in shape. The thickness of the radial bands is variable, but the Vb is always wider than Pb. The radial bands are ornamented with many radial ribs that represent the typical characteristic of the species. The Pb contains 6–12 ribs, and the Vb includes 8–18 ribs. The Ib is a bulge with four to six salient ribs, which resemble the rest of the valve. The width of Ib is variable (6–15 mm), and is narrower than radial bands. In some specimens, Ib is the same width as Pb (Tables 1 and 2).

The transverse section of the RV is subcircular and/or circular with the commissural diameter ranging from 40 to 90 mm (Fig. 5A and B). The ol of the right valve is very thick, reaching 30 mm in the dorsal part. The ol is entirely compact fibrous prismatic microstructure that consists of thin-walled, small polygonal cell network. The cells are up to 0.5 mm in height and they are hexagonal and pentagonal with subordinate rectangular cells (Fig. 5C–F). The radiating vascular impressions can be observed. The aragonitic il of the RV is thin and replaced with sparry calcite (Fig. 5F). The L is not developed, and the cardinal apparatus can not be preserved. The LV is partially preserved and covered the inner rim of RV, it seems to very smooth and its ol consists of thin and compact calcite.

5. Discussion and remarks

Specimens described here can be confidentaly attributed to the well-known radiolitid genus *Durania* Douvillé due to their regular ribbing of RV, finely ribbed radial bands, the polygonal cell structure of the ol and the absence of L. The diagnostic feature of *Durania cornupastoris* is the large number of ribs in the broad Ib. This feature is seen in our specimens. Therefore, the studied RVs are attributed to be *Durania cornupastoris* rather than *Durania arnaudi* or other species of *Durania*. The detailed comparison between *D. cornupastoris* and *D. arnaudi* is given below.

The shape of the Vb, Pb and the broad Ib of our specimens is similar to the Istrian specimens of Polšak (1967) and to the neotype of Macé-Bordy (2007), however, the RV of the Abu Roash specimens is much longer than the latter. In some specimens the structure of the radial bands is completely similar to those described by De Castro and Sirna (1996).

The Abu Roash samples are also similar in shape and radial bands to Algerian species described by Chikhi-Aouimeur (2010) and to species in Riyadh-Saudi Arabia described by Özer and El-Sorogy (2017). The ornamentation of the RV and the Pb are somewhat similar to those of *D. gaensis*, however the Vb is deeply depressed and the number of ribs is fewer than in *D. cornupastoris.*

The Abu Roash specimens show the flattish to slightly pronounced concave finely ribbed radial bands. The Vb, Pb and convex Ib of these specimens are ornamented with many salient ribs, which are similar to those of the rest of the valve that show the external characters of

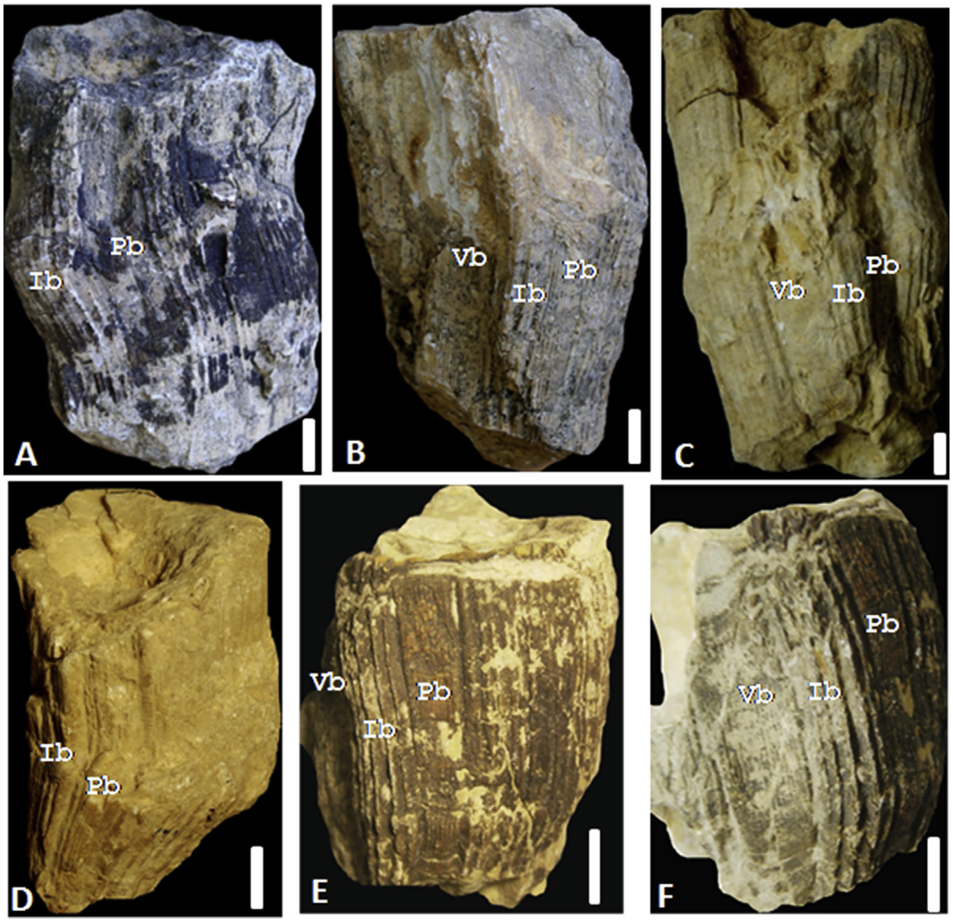

Fig. 4. *Durania cornupastoris* (Des Moulins), Abu Roash, Egypt, the RVs showing the radial bands structures and the ornamentation of valve, note the variations of shape of the Vb and the Pb, the wide of the Ib, and the bulge Ib with salient ribs similar to those of the valve, scale bar is 15 mm. A, sample no: Ab-BSU 4. B, sample no: Ab-BSU 10. C, sample no: Ab-BSU 13. D, sample no: Ab-BSU 15. E-F, sample no: Ab-BSU 18.

Durania cornupastoris. But, *Durania* specimens of Abu Roash were first described as *Radiolites cornupastoris* by Dacqué (1903) or *Durania arnaudi* by Douvillé (1910, 1913). Subsquently, the Abu Roash rudist biostrome was presented as a construction of *Durania arnaudi* (De Castro and Sirna, 1996). This name continued to be used by Abdel-Gawad et al. (2004, 2011), Aly et al. (2005), EL Qot (2006), Hamama (2010), Hannaa (2011) and Salama (2012). However, Steuber (2002) adopted *Durania cornupastoris* for this rudist. The latter species was also described based on the specimens collected from Abu Roash area by El-Sabbagh and El-Hedeny (2003). The description of the radial bands of Egyptian *Durania* in Egyptian literature is mainly inadequate and at best inconsistent (Table 3). Douvillé (1910, 1913) accurately described and illustrated the features of the Vb, Ib and Pb of the Abu Roash *Durania* specimens. However, he indicated that the Ib was formed of two ribs in the young phase and four ribs in the adult phase. This same feature was mentioned in the description of *Durania arnaudi* from the Abu Roash area by De Castro and Sirna (1996). Abdel-Gawad et al. (2011) and Salama (2012) also described the Abu Roash *Durania* specimens as *Durania arnaudi*. They showed the shape of the radial bands (Table 3) but did not present the width of the radial bands and the number of ribs in the Ib. However, the presence of three or four ribs in the Ib is clearly observed in their specimens. Although all *Durania* specimens from Sinai were reported as *Durania arnaudi* by Aly et al. (2005), EL Qot (2006), Hamama (2010), Hannaa (2011) and Salama (2012), they provided no data about the width of the radial bands and the ribs of the Ib (Table 3). The radial band structure is not evident in the figures of these authors. The specimens of Aly et al. (2005, pl. 10, Fig. 8) and Salama (2012, pl. 3–12, Fig. 6) seem to have three or four ribs. However, they present no data on the diameter and the height of the RV.

5.1. *Comparison between D. cornupastoris and D. arnaudi*

The taxonomic status of the many species of *Durania* described from the Upper Cretaceous formations of the Mediterranean Tethys is uncertain. Many probably are synonymous as indicated by Skelton in Cobban et al. (1991) and Steuber (1999). Parona (1911, 1926) indicated that the Turonian form *D. arnaudi* is closely related to *D. cornupastoris.*

The two current species differ by the comparison of the width of the radial bands and of Ib (Tables 1–2, 4). Skelton in Cobban et al. (1991) synonymized the two species because this character varies among a large set of specimens. In *Durania arnaudi* described in the literatures, the width and the shape of the Pb and the Vb are nearly similar, for example the Vb is wider than the Pb and the Ib is narrower than the Pb, the Vb and the Pb are concave and the Ib is bulge (Table 4). However, the Ib can contain four ribs like *D. cornupastoris* (Toucas, 1909; Parona, 1926; De Castro and Sirna, 1996; Chikhi-Aouimeur, 2010; Özer and Ahmad, 2015). According to Hamama (2010), the Ib consists of 2–3 ribs that distinguished *D. arnaudi.*

Durania cornupastoris formely described from the Mediterranean Tethys, shows that the Vb is wider than the Pb, the Vb and Pb are flat or slightly concave and the Ib is bulge (Table 1). But, the width of the Ib is variable, either narrower or wider than the Pb (Tables 1–2). The Ib may contain three ribs like *D. arnaudi* (Toucas, 1909; Polšak, 1967; Skelton in Cobban et al., 1991; El-Sabbagh and El-Hedeny, 2003; Chikhi-Aouimeur, 2010; Özer and El-Sorogy, 2017). The width of the Ib is very close between *D. arnaudi* and *D. cornupastoris* (Table 2). According to Chikhi-Aouimeur (2010), Özer and El-Sorogy (2017), the Ib is wider in *D. cornupastoris* than *D. arnaudi*.

This data supports the analogy between these two species as indicated by Douvillé (1910, 1913), Parona (1911, 1926) and Skelton (in

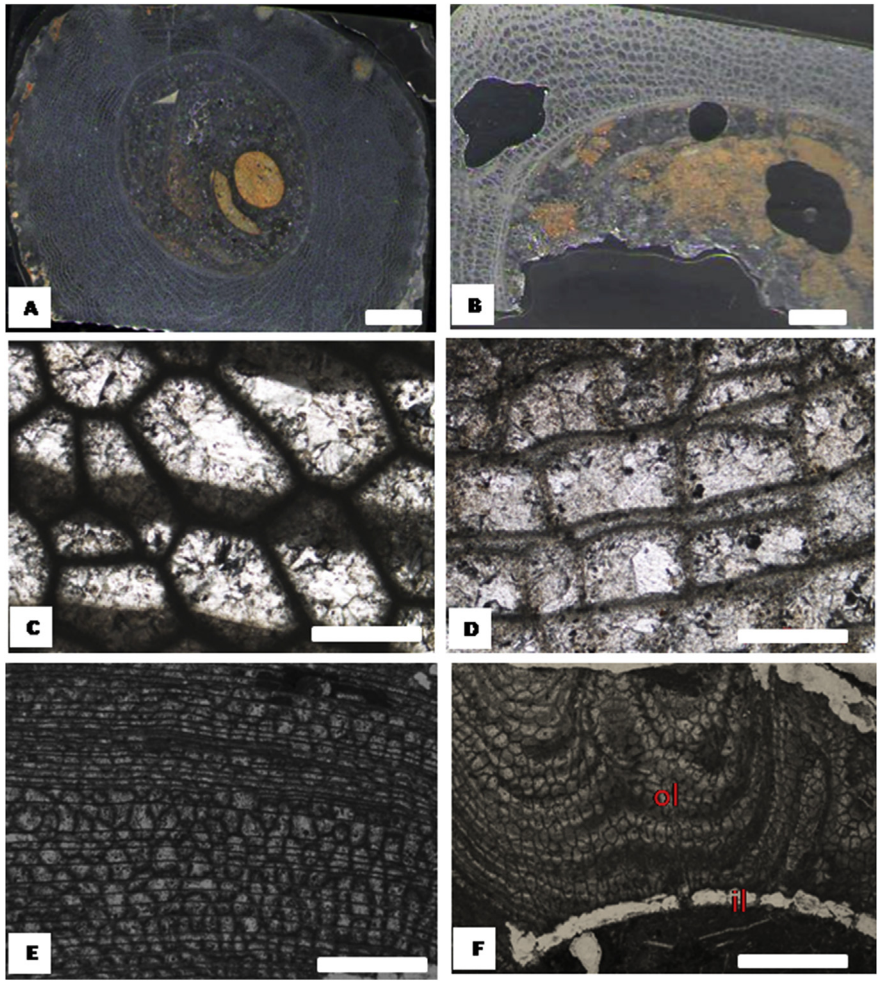

Fig. 5. *Durania cornupastoris* microstructures. A-B, shell transverse sections, note the cavity of uncompacted shell filled with sediments, scale bar is 15 mm. C, polygonal cell network of the outer layer in transverse section of RV, scale bar is 0.5 mm. D, oblique section of the RV shows rectangular cellulare microstructure, scale bar is 0.5 mm. E, Cross section in the RV shows hexagonal and pentagonal cells in the outer layer, scale bar is 3 mm. F, transverse cross section in the RV, thin inner layer (il) replaced with sparry calcite and thick outer layer (ol) with polygonal cells, scale bar is 4 mm.

Cobban et al., 1991). The variation in the width and the number of the ribs of Ib do not appear to be a valid characteristics to differentiate the two species, which are intraspecific and ontogenetic variabilities. As already emphasized above, this has created confusion in the definition of the two species in previous studies. So, it will be better to describe all *D. arnaudi* specimens under *D. cornupastoris.*

6. Palaeogeographic distribution

Durania cornupastoris is widespread on the northern Mediterranean Tethys, particularly in Turonian formations. This species was described from many localities in France (Toucas, 1907, 1908; 1909; Fabre, 1940; Bilotte, 1985). It was also documented from Italy (Parona, 1911, 1926; Carannante et al., 2000), Croatia (Toucas, 1909; Polšak, 1967; Polšak and Mamuzic, 1969), Serbia (Pejović, 1957), Bosnia-Herzegovina (Slišković, 1968, 1975) and Bulgaria (Pamouktchiev, 1966). In contrast, this species is very rare and is scattered in the southern Mediterranean Tethys. It was described from the upper Turonian of Algeria and at various other localities (Toucas, 1909; Chikhi-Aouimeur, 2010) and from Egypt (El-Sabbagh and El-Hedeny, 2003; this study). Although, it is well known from the middle-upper Turonian in the Mediterranean Tethys, it has recently been described from the Campanian of Saudi Arabia (Özer and El-Sorogy, 2017), which extends its stratigraphic range and the geographic distribution into the eastern part of the Arabo-African plate. It has been described from the New World from the middle Turonian of Colorado (USA) by Schumacher (2012) and Skelton (in Cobban et al., 1991) and from Mexico by Oviedo (2005).

7. Palaeoecology and taphonomy

Rudists formed congregations in the inner and outer parts of the Cretaceous shallow platforms. They were sessile epifaunal suspension feeding bivalves. Rudists occupied three paleoecological morphotypes: elevators, clingers and recumbents (Skelton and Gili, 1991; Ross and Skelton, 1993; Gili et al., 1995; Skelton et al., 1995). The palaeocology of the rudist bivalves (autoecologic characters, depositional fabrics, associated fauna) was recently reviewed by Gili and Götz (2018). Rudists are considered to be stenohaline bivalves, which live in salinities between 32‰ and 36‰ (Steuber, 1999). Previous studies of the palaeoecology of the Turonian *Durania* (De Castro and Sirna, 1996; Özer and El-Sorogy, 2017) identified environmental parameters that influenced the rudist community (Cestari, 2005). For example, the sizes of *Durania* in the Abu Roash area are different than those from other areas in Egypt. The large size of the *Durania* indicates that individuals grew freely until reaching their maximum size in available space. The cellular structure of the *Durania* shells allowed for rapid growth without significant exhaustion of calcium carbonate, which led to the construction of huge valves on short time (Kauffman and Sohl, 1979). Growth rates were about 54 mm per year (Steuber, 1996). *Durania* shells began to grow on a substrate of bioclastic grainstone in shallow marine

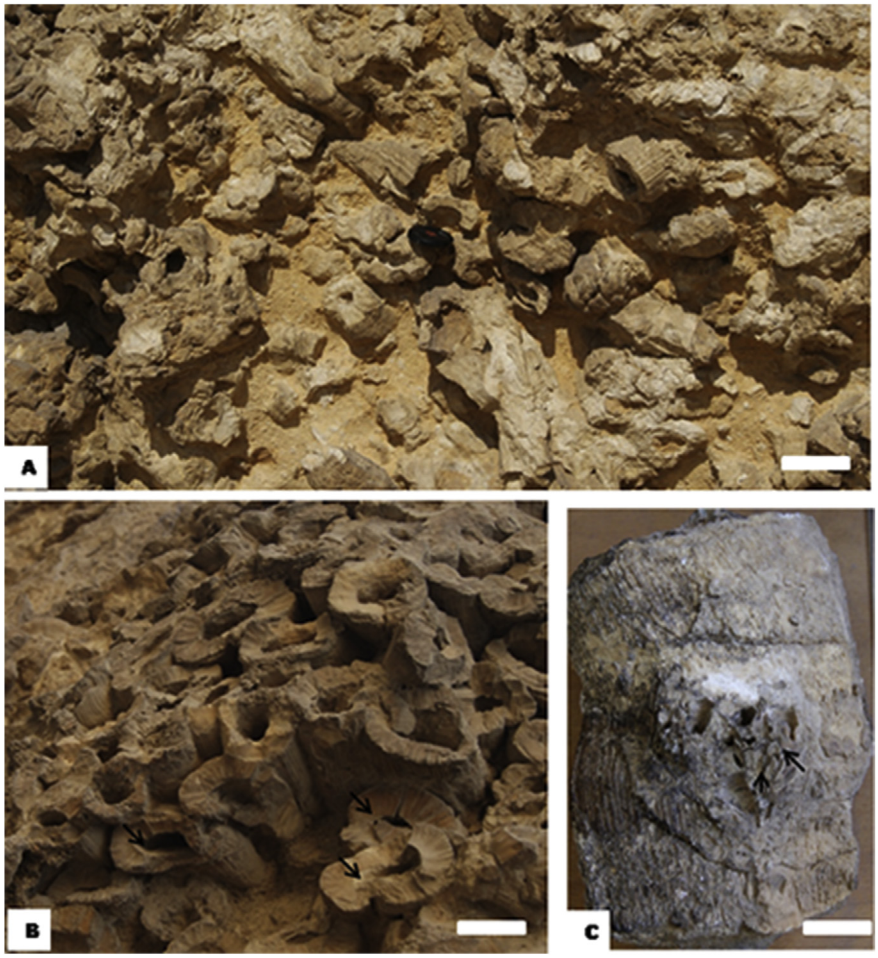

Fig. 6. A-B, Field photos for *Durania cornupastoris* biostrome. A, Open fabrics, disoriented shells with some coralline sponge, some rudist shells show less fragmentation (scale is 10 cm). B, *Durania shells* are highly packed and compacted rudist shells (black arrows), scale bar is 5 cm. C, Juvenile rudist shells (black arrows) settled on large *Durania* rudist shells (scale bar is 2 cm.

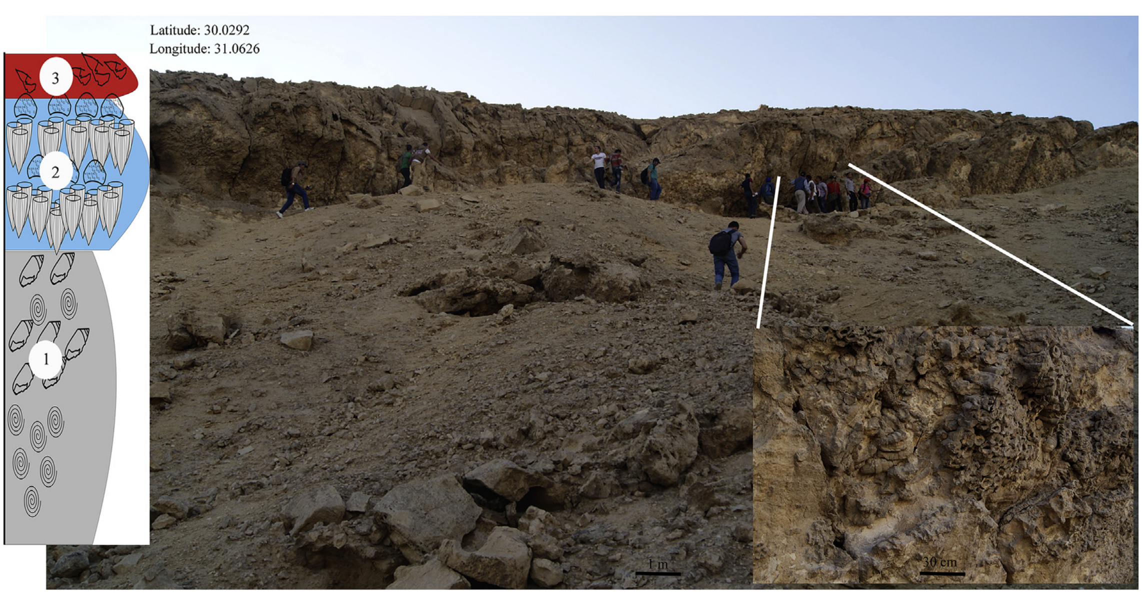

Fig. 7. Field photos for *Durania cornupastoris* biostrome in the Turonian Actaeonella Series at El-Hassana Dome, Abu Roash area. Note the vertical succession at the left with coarsening upward bioclastics; 1 is echinoid and gastropoda wackestone, 2 is *Durania* and coralline sponges rudstone/bafflestone, 3 is bioclastic grainstone facies.

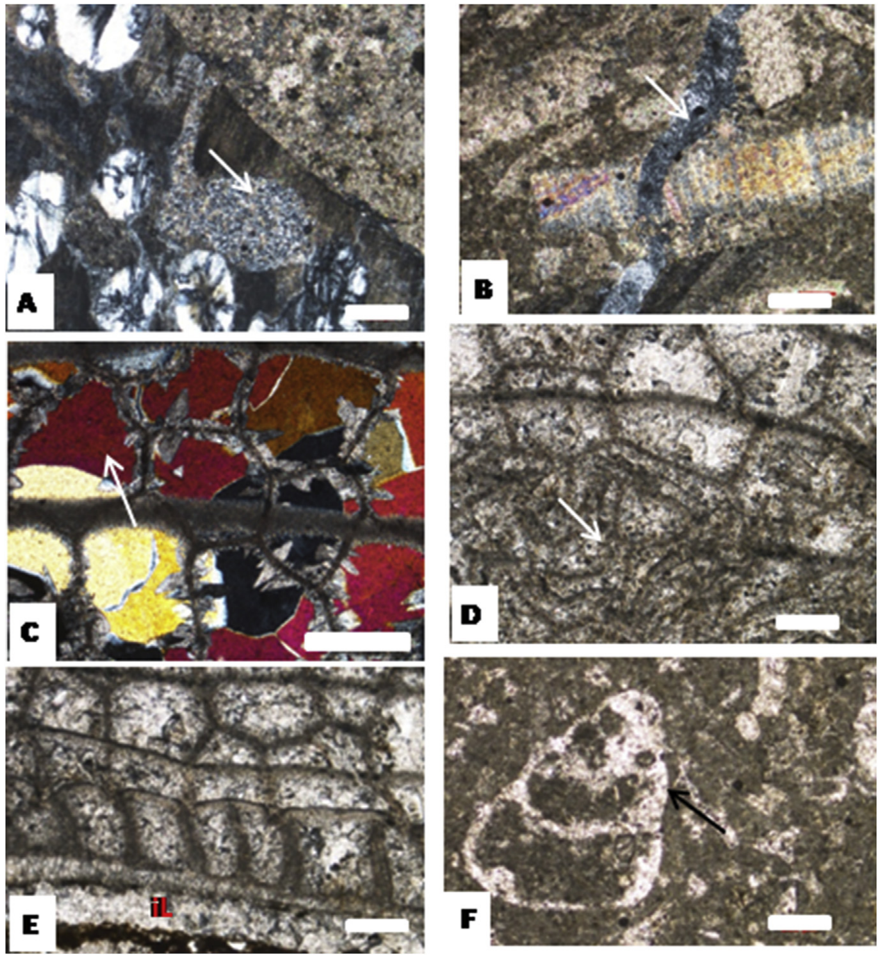

Fig. 8. A, Silicification in the outer layer of *Durania* shell, the silica filled the borings scale bare is 0.3 mm. B, Fracture cutting the matrix and skeletal fragments, then filled with silica materials, scale bare is 0.3 mm. C, Silica materials filled the cellular structure of outer layer, scale bare is 0.6 mm. D, Note the compaction destroyed cellular structure, scale bar is 0.3 mm. E, the replacement of the inner layer (il) with sparry calcite after dissolution, scale bar is 0.5 mm. F, aragonitic gastropod wall replaced with sparry calcite during dissolution diagenesis, scale bar is 1 mm.

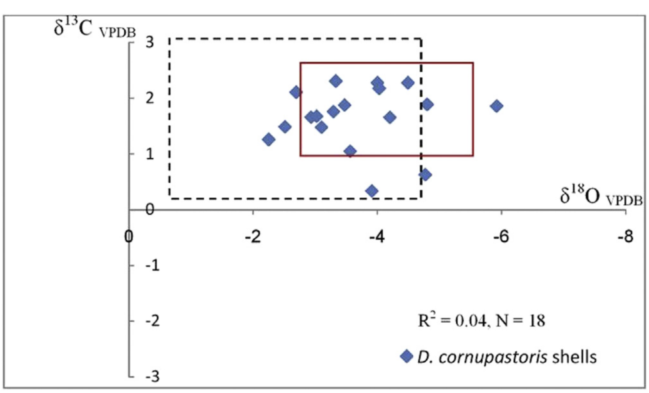

Fig. 9. Cross plots of $\delta^{18}O$ versus $\delta^{13}C$ data showing isotopic covariance that detected in the Turonian *D. cornupastoris* shells from El-Hassana dome at Abu Roash area. The present isotope compared with those from the Campanian rudists from Turkey (*red rectangle* Immenhauser et al., 2005), And from the Cenomanian-Maastrichtian tropical marine carbonates (dotted black rectangle, Prokoph et al., 2008). N is number of samples, R^2 is a correlation coefficient; VPDB is Vienna Pee Dee Belemnite. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

environment that indicated higher water energy. The *Durania* shells are in life position and show upward growth and they are very tightly packed showing typical characters of the elevator morphotype (Fig. 6A and B). In places, the *Durania* shells are disoriented and forming an open fabric (Fig. 6A). The absence of suitable hard substrate may have lead to the settlement of the *Durania* juvenile on the shell of an adult *Durania* (Fig. 6C). The rarity of juveniles is related to the thin and weakly calcified shells, which are prone to dissolution (Green et al., 2004). The Abu Roash biostrome is composed mainly of *D. cornupastoris.* The biostrome is nearly 500 m long and 12 m thick that presents an irregular topography (Fig. 7). The abundance (up to %90) of *D. cornupastoris* in the biostrome indicates the development of the favorable ecological conditions. Based on the field observations, the *Durania* biostrome is associated with coralline sponge and gastropods. The species diversity is low indicating that the rudist may have prevented the infaunal organisms from digging the substrate. The associated organisms are mainly gastropods and the coralline sponge *Millestroma nicholsoni* indicating very shallow marine environments (Fürsich and Werner, 1991).

In terms of sequence stratigraphy, the Turonian succession at Abu Roash area was described in detail by Abdel-Gawad et al. (2011). They stated that *Durania* biostrome shows a vertical succession from base to top as follow: echinoid and gastropoda wackestone followed by *Durania* and coralline sponges rudstone/bafflestone facies and topped with high-energy bioclastic grainstone facies (Fig. 7). Coarsening upward trend of the bioclasts is observed on the *Durania* biostrome that

Table 1
Measurements and shapes of RV of *Durania cornupastoris* described in the Mediterranean Tethys. Measurements are in milimeters, - no measurement and shape. [*]according to figures.

	Width between		No. of ribs of Ib	shape			diameter	height of RV
	Vb-Pb	Ib-Pb		Vb	Ib	Pb		
d'Orbigny (1850) Macé-Bordy (2007)	Vb > Pb	Ib>Pb	***3–4***	flat/slightly projecting	bulge	flat/slightly projecting	41–51	91
Dacqué (1903)	Vb > Pb	Ib>Pb	_	concave	_	concave	_	210
Toucas (1909)	Vb > Pb	Ib>Pb	***3***–8	flat	bulge	flat	_	_
Parona (1911)	Vb > Pb	Ib>Pb	***8***[*]	slightly convexe	***flat***[*]	deep groove	***?70***[*]	_
Pejović (1957)	Vb > Pb	Ib>Pb	_	_	_	_	_	_
Polšak (1967)	Vb > Pb	Ib>Pb	***3–4***	flat/slightly concave	***bulge***[*]	flat	_	40-115[*]
Skelton in Cobban et al. (1991)	Vb > Pb	Ib<Pb	***3–4***	flat/distinctly concave	project	flat	80	48–80
El-Sabbagh and El-Hedeny (2003)	***Vb > Pb***[*]	***Ib<Pb***[*]	***3-4***[*]	concave	shallow flat	concave	115	180
Hamama (2010)	_	***?Ib<Pb***[*]	***2-3***[*]	***concave***[*]	***bulge***[*]	***concave***[*]	_	***50***[*]
Chikhi-Aouimeur (2010)	Vb > Pb	Ib>Pb Ib<Pb	6–8 ***3–4***	flat/concave	bulge	flat/concave	_	***80-110***[*]
Özer and El-Sorogy (2017)	Vb > Pb	Ib<Pb	***3***–8	flat/concave	bulge	flat/concave	110–140	95–170
This study	Vb > Pb	Ib ≤ Pb	***4***–6	flat/slightly concave	bulge	flat/slightly concave	60–80	85–170

Table 2
Comparison of the width of Ib between *Durania arnaudi* and *Durania cornupastoris.* Measurement is in milimeters.

Durania arnaudi		*Durania cornupastoris*	
Parona (1901)	8–9	10	d'Orbigny (1850),Macé-Bordy (2007)
Toucas (1909)	5–6	10	Toucas (1909)
Douvillé (1910, 1913)	10	?30	Parona (1911)
Parona (1912)	10	_	Pejović (1957)
Parona (1926)	5–6	8	Polšak (1967)
Polšak (1967)	5	7–10	Skelton in Cobban et al. (1991)
Razgallah et al. (1994)	10	8–10	Hamama (2010)
Caffau (1999)	7	8–20	Chikhi-Aouimeur (2010)
Chikhi-Aouimeur (2010)	10	12–20	Özer and El-Sorogy (2017)
Özer and Ahmad (2015)	10	6–15	This study

indicated increasing water energy at the crest with decreasing the accomodation space.

Some of the processes in which the rudist shells were exposed after death were described in the Cretaceous rudist biostromes of Europe (Sanders, 1999, 2001; Ruberti and Toscano, 2002). The *Durania* biostrome at El-Hassana Dome was overprinted by the following taphonomic processes: disarticulation, fragmentation, boring and diagenesis (Fig. 8).

Disarticulation: Although up to 98% of the *Durania* right valves in the given area are usually preserved as complete valves (Fig. 6), the taphonomic analysis reveal that upto 55% of the examined rudist shells are disarticulated. Although the disarticulation is a measure of the degree of taphonomic distortion in Bivalvia (Boucot et al., 1958), this phenomenon is not reliable to determine the degree of transportation or sorting. This view has been confirmed by the low rate of abrasion and breakage of the right valves of *Durania cornupastoris*. At least in equal terms between the two valves, it must be borne in mind that the morphology of *Durania* valves is different from those in other non-rudist bivalve individuals. Even with the rudist groups there is a difference in morphologies of the shells (Vicens and Gili, 1995; Gili and Michael, 1998; Steuber, 1999, 2002; Götz, 2007). The *Durania* shell is very inequivalve (Gili, 1992), where the left valve (free valve) is much smaller than the right one (attached valve). Therefore, the absence of *Durania* LVs does not indicate their transportation from the growth position, but is probably due to a phase of high water energy after death. The shell cavity of the right valves can continue to exist empty of matrix and thereafter filled with sparry calcite. The shell cavity can also be filled with muddy matrix and bioclastic fragments. This phenomenon may be due to the effect of high energy water.

Silicification: It is one of the diagenetic features that was recorded in the rudist biostrome of Abu Roash area (Mansour, 2004). The silica filled the available spaces such as borings, fractures or the cellular shell structures (Fig. 8A–C).

Boring: Sponge borings such as *Entobia* are distributed in the right valve of the *Durania.* The *Entobia* borings indicated water depth 10–30 m (Vodrážka, 2006; Callapez et al., 2015; El-Shazly et al., 2016). These borings are filled with silica (Fig. 8A).

Compaction and fragmentation: The compaction and fragmentation that affect Abu Roash *Durania*, which is typical bivalves (Briggs, 1995; Zuschin et al., 2003), were observed in the field and under microscope (Figs. 6B and 8D). Compaction destroyed the polygonal cells in the outer layer of *Durania* resulting bioclastic debris (Fig. 8B, D). Moreover, the right valves were deformed from circular to elliptical outlines

Table 3
Measurements and shapes of RV of *Durania arnaudi* described in Egypt. Measurements are in milimeters.

		Width between		No. of ribs of Ib	shape			diameter	height of RV
		Vb-Pb	Ib-Pb		Vb	Ib	Pb		
Abu Roash	Douvillé (1910, 1913)	Vb > Pb	Ib = Pb	2 (in young forms)	concave	bulge	concave	80	_
	De Castro and Sirna (1996)	_	_	4 (2 in young forms)	flat	_	flat	80–120	_
	Abdel-Gawad et al. (2011), Salama (2012)	_	_	_	***concave***[*]	***bulge***[*]	***concave***[*]	120	200
Sinai	Abdel-Gawad et al. (2004)	_	_	_	_	_	_	_	70[*]
	Aly et al. (2005)	_	_	_	flat	_	flat	10–30	18–75
	EL Qot (2006) (copy of Abdel-Gawad et al., 2004)	-	-	-	-	-	-	-	-
	Hamama (2010)	_	_	_	concave	bulge	concave	_	_
	Hannaa (2011)	_	_	_	_	_	_	_	_
	Salama (2012)	Vb > Pb	_	_	_	_	_	120	200

Table 4
Measurements and shapes of RV of *Durania arnaudi* described in the Mediterranean Tethys and Mexico. Measurement is in milimeters.

	width between		No. of ribs of Ib	shape			diameter	height of RV
	Vb-Pb	Ib-Pb		Vb	Ib	Pb		
Parona (1901)	_	***Ib < Pb****	***2-3****	_	***bulge****	***concave****	100	***70-80****
Toucas (1909)	Vb > Pb	Ib<Pb	1–4	concave	bulge	concave	_	_
Pervinquière (1912)	Vb > Pb	***Ib = Pb****	_	concave	***bulge****	***concave****	120	200
Parona (1912)	***Vb > Pb****	***Ib < Pb****	***2-3****	concave	bulge	concave	65–70	100
Parona (1926)	***Vb > Pb****	***Ib < Pb****	***3-4****	***concave****	***bulge****	flat	_	***70****
Polšak (1967)	***Vb > Pb****	Ib<Pb	***2-3****	concave	***bulge****	concave	_	_
Pleničar (1973)	Vb > Pb	_	2	_	_	_	_	_
Accordi et al. (1982)	***Vb > Pb****	_	2–3	concave	bulge	concave	***50x65****	_
Razgallah et al. (1994)	***Vb > Pb****	***Ib < Pb****	***3****	***concave****	***bulge****	***concave****	***70****	***60****
Caffau (1999)	***Vb > Pb****	***Ib < Pb****	***2-3****	***concave****	***bulge****	***concave****	_	***130****
Oviedo (2005)	Vb > Pb	Ib<Pb	1–3	concave	***bulge****	concave	_	11–20
Chikhi-Aouimeur (2010)	***Vb > Pb****	Ib ≥ Pb	3–4	concave	less prominent	concave	***50x60****	***130****
Özer and Ahmad (2015)	Vb > Pb	Ib<Pb	3–4	concave	bulge	concave	30	40

(Fig. 6B). We can not rule out the effects of Late Cretaceous tectonics (Syrian Arc System) as a cause of this distortion. The effect of tectonics on the fossils was recently discussed on the Gulf of Suez area of Egypt (Abu Sharib et al., 2017). Shell fragmentation results from physical or biological processes (Zuschin et al., 2003). The *Durania* fragmentation is widespread in the open fabric and less in the highly-packed fabrics (Sanders, 2001). Fragmentation is also found in high energy environments. The breakage of shells is also caused by bioerosion. However, the degree of fragmentation is low in the *Durania* biostrome, due to the resistance of the thick shell wall. The *Durania* shell thickness is the most important factor that reflects the shell strength. Moreover, the transportation of the shells is difficult, so most shells were preserved in situ.

Dissolution: It was observed that the dissolution was more effective on the aragonitic inner shell layer that was replaced by blocky calcite spar, while the outer calcite shell layer retained its composition and shell structure (Fig. 8E). The dissolution indicated that the rudists were exposed to meteoric conditions during sea-level fall. The formely aragonitic walls of gastropod shells were also replaced (Fig. 8F).

8. Stable isotope analysis of *Durania*

The oxygen- and carbon-isotope signals of the Late Cretaceous carbonate platforms are well preserved in many rudists (Steuber, 1996; Huck et al., 2013; Frijia et al., 2015; Salama et al., 2016). The isotope analyses at Abu Roash were limited to the well-preserved *D. cornupastoris* specimens. The *D. cornupastoris* shells with any diagenetic features like fractures or veins were avoided. The effects of diagenetic alteration were tested by plotting $\delta^{18}O$ values against $\delta^{13}C$ values (Fig. 9). The observed carbon and oxygen isotopes of the Abu Roash *Durania* shells are not significantly correlated ($R^2 = 0.04$, N = 18) (Fig. 9). This weak covariation is evidence of the absence of diagenetic alterations (Frijia et al., 2015). The $\delta^{13}C$ and $\delta^{18}O$ values of the *Durania* shells are consistent with the marine isotopic signatures during the Cretaceous Period (Prokoph et al., 2008; Immenhauser et al., 2005) (Table 5).

The carbon-isotope data from eighteen *D. cornupastoris* shells range between 0.34‰ and 2.31‰ for $\delta^{13}C$ values. According to Fassel and Bralower (1999), the $\delta^{13}C$ values for the typical Cretaceous molluscan and marine cements are between 1.5‰ and 3.5‰. Although the isotopic analyses were in the same species, they have variable $\delta^{18}O$ and $\delta^{13}C$ values. The $\delta^{18}O$ values fluctuate between −4.77 and −2.25‰ with a mean value of −3.51‰. The same species in the same ecological niches exhibted variable isotopic signatures, which may be related to the variations in food supply, temperature and other factors (Wendler et al., 2013; Dubicka et al., 2018). According to Ullmann et al. (2010), variable carbon and oxygen isotopes in Holocene oysters are due to annual seawater temperature and/or environmental changes. Moreover, the temperature is one of the main factors that affected the shell growths of bivalves (Peharda et al., 2016). Thus, the $\delta^{18}O$ from preserved *Durania* shells should reflect the seawater paleotemperature and salinity (El-Shazly et al., 2011). By using the equation of Anderson and Arthur (1983), the mean paleotemperatures from $\delta^{18}O$ of *D. cornupastoris* range between 29 °C and 33.5 °C (using $\delta^{18}O_{sw}$ values of −1.00‰ and −1.5‰ VSMOW), which is consistent with a warm Turonian age (Huber et al., 2018). Thus the large size of *Durania* shells may be related to the warmest conditions (Walliser et al., 2018). Although $\delta^{13}C$ values in the Turonian rudists of Sinai (Salama et al., 2016) are similar to those of Abu Roash, the $\delta^{18}O$ values of the *Durania* shells show high values when compared with the Turonian rudists of Sinai. We can not separate this observation, for example, from the absence or scarcity of Turonian ammonites at Abu Roash in comparison with the Sinai platform. This point needs further study to interpret the scarcity or absence of the rudists and their associations in Cretaceous carbonate platforms at different Egyptian localities.

9. Conclusions

The identification of *Durania cornupastoris* of El-Hassana dome at Abu Roash area has been the subject of controversy among researchers over the past years. The new material of *Durania* described here, and its comparison with the previously defined *Durania cornupastoris* and *Durania arnaudi* in literature, allows to refute some of the previous identifications. The morphological data of the collected rudist specimens from El-Hassana dome allowed us to propose the *Durania cornupastoris* rather than *Durania arnaudi*. The radial bands and interbands of

Table 5
$\delta^{13}C$ and $\delta^{18}O$ isotope results from 18 samples of *D. cornupastoris* shells, El-Hassana Dome, Abu Roash area, north Western Desert.

$\delta^{18}O_{(VPDB ‰)}$	$\delta^{13}C_{(VPDB ‰)}$	$\delta^{18}O_{(VPDB ‰)}$	$\delta^{13}C_{(VPDB ‰)}$	$\delta^{18}O_{(VPDB ‰)}$	$\delta^{13}C_{(VPDB ‰)}$
−2.93	1.66	−3.33	2.31	−4.56	1.05
−3.02	1.68	−4.49	2.28	−4.77	0.63
−4.20	1.66	−4.03	2.18	−2.51	1.49
−2.25	1.26	−5.92	1.86	−3.10	1.48
−3.91	0.34	−4.80	1.89	−2.69	2.11
−3.29	1.76	−3.47	1.88	−4.00	2.28

El-Hassana Dome specimens ornamented with many salient ribs. Most of the *Durania* specimens figured as *Durania arnaudi* in the previous studies, should be assigned to *Durania cornupastoris*. The shells of *D. cornupastoris* are elevator, moderately to densely packed in growth position. They are mainly associated with coralline sponges that indicated shallow marine environment. Many taphonomic phenomena were recorded on the right valves of *D. cornupastoris* including boring, silicification, compactions and fragmentations. The isotopic data supported that the Abu Roash rudists in in warm seas similar to the Mediterranean Tethys.

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Appendix A. Supplementary data

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