Advances in Basic and Applied Sciences 2 (2024) 113-129

Advances in Basic and Applied Sciences

journal homepage: https://abas.journals.ekb.eg/

Macrofaunal communities and microfacies analysis of the upper Campanian-Maastrichtian Sudr Formation at the Galala Plateaus, north Eastern Desert, Egypt: paleoenvironmental and paleobiogeographical implications

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ARTICLE INFO

Article history:
Received 19 October 2023
Received in revised form 25 November 2023
Accepted 1 January 2024
Available online 31 January 2024

doi: 10.21608/ABAS.2024.243686.1030

Keywords: Bivalves; Gastropods; Microfacies analysis; Sudr Formation; Paleobiogeography; Egypt.

ABSTRACT

The Upper Cretaceous deposits are widely distributed and well exposed in northern Egypt. Important upper Campanian-Maastrichtian carbonate deposits outcrop at the Northern and Southern Galala Plateaus, north Eastern Desert, represented by Sudr Formation. Sudr Formation is lithologically investigated, sampled, and the included fauna are collected for taxonomic and paleobiogeographic studies. Four gastropod species, belonging to three genera and three families, as well as twelve bivalve species, representative of twelve genera and nine families, are identified. Two gastropod species; *Cerithium buddha* Noetling, *Potamides temalacaensis* Perrilliat et al., and four bivalve species; *Gryphaeostrea canaliculata* (Sowerby), *Venilicardia truncata* (Sowerby), *Calva* (*Egelicalva*) *buttensis* (Anderson), *Lyriochlamys dentata* (Nilsson), are recorded for the first time from the Upper Cretaceous deposits of Egypt. The microfacies analysis of the carbonates of Sudr Formation revealed four distinct microfacies types, each with characteristic bioclasts and textural features. These microfacies types suggest open-marine, high-energy shallow subtidal shoal to low-energy deep subtidal environments. The paleobiogeography of the recorded bivalve taxa is highlighted, revealing two endemic species to Egypt; *Nucula chargensis* Quaas and *Meretrix rohlfsi* (Quaas). On the other hand, the other identified bivalve species show wide distribution over a broad geographical area, including North Africa, East and West Africa, Middle East, Asia, Europe, South America, and North America. The bivalve distribution in the present study suggests a strong affinity to the southern Tethyan Province. potential applications in various fields, such as pharmaceuticals, and materials science. Additionally, the synthesis of fluorescent sensors and potential inhibitors for enzymes is discussed.

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1. Introduction

Egypt was located at the southern rim of the Neo-Tethys during the Late Cretaceous time [1]. A major transgressive phase characterized the Campanian-Maastrichtian time in northern Egypt [2], resulting in the deposition of carbonate and marly facies [3]. The upper Campanian-Maastrichtian carbonate deposits are extensively exposed in Sinai, Gulf of Suez, north Eastern Desert, and northern and central Western Desert. These outcrops are represented by Sudr Formation at Northern and Southern Galala Plateaus, north Eastern Desert [4]. The Sudr Formation underwent extensive literature concerning the stratigraphic aspects [5-19], foraminiferal content [3, 20-28], and calcareous nannoplankton content [29-31]. So far, the macrofaunal content of Sudr Formation in north Eastern Desert received no attention. Therefore, the objectives of the present work are to highlight the stratigraphy of Sudr Formation, to systematically study the included gastropods and bivalves, to discuss the paleobiogeography of the recorded bivalves, and to deduce the paleoenvironmental conditions through microfacies analysis.

2. Geologic setting

During the Late Cretaceous, Egypt was situated at the southern edge of the Neo-Tethys [16, 32, 33], and an extended carbonate platform covered North Africa due to the sea-level rise [2, 34]. Hemipelagic sediments of deep carbonate platform, consisting of carbonate and marley facies, were developed in northern Egypt during the Campanian-Maastrichtian time [3].

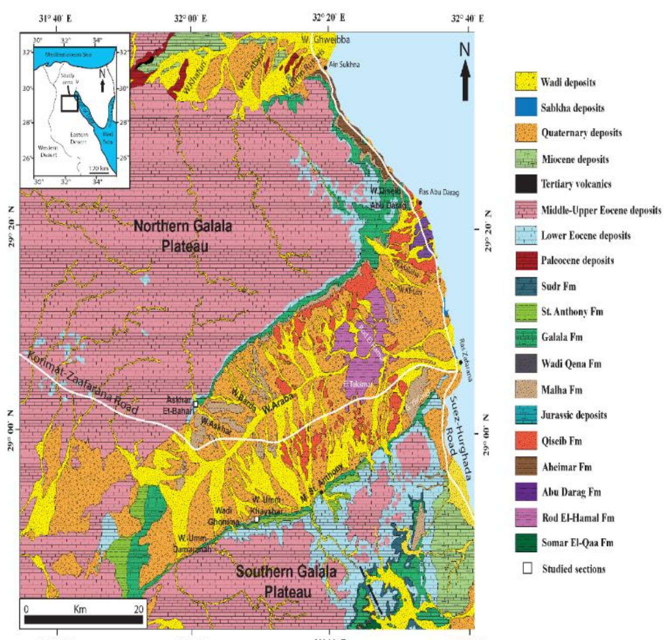

Fig.1. Location map and geological map of the study area, modified after Abd-Elhameed et al. [134].

The study area encompasses the Northern and Southern Galala plateaus, separated by Wadi Araba, in north Eastern Desert, where the upper Campanian-Maastrichtian outcrops are represented by Sudr Formation (Fig.1).

Ghorab [4] proposed the term Sudr Formation to describe the chalk sequence at Wadi Sudr area, west-central Sinai. At the study area, the lower part of Sudr Formation is made up of greyish, fossiliferous limestones, yellowish marly limestones, and white cavernous limestones, while the upper part of Sudr Formation consists mainly of snow-white chalky limestones (Fig.2). Sudr Formation has been assigned to late Campanian-Maastrichtian age based on the planktonic foraminiferal content, e.g. *Globotruncanella havanensis* (Voorwijk), *Globotruncana aegyptiaca* Nakkady, and *Gansserina gansseri* (Bolli) [35].

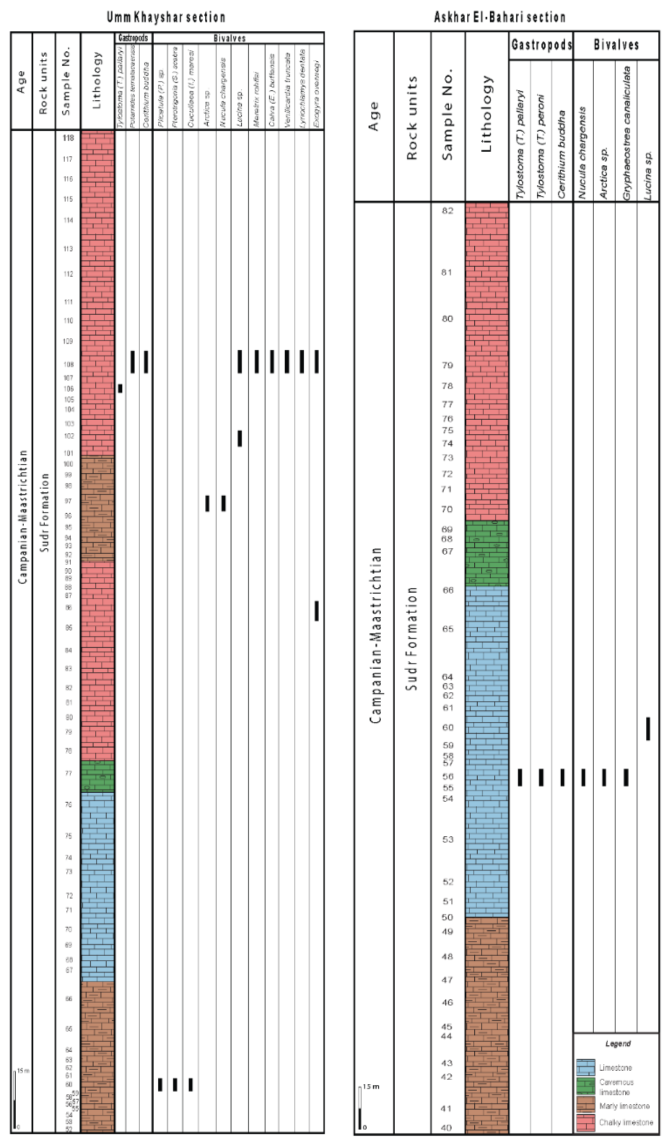

Fig.2. Lithostratigraphic sections of the upper Campanian-Maastrichtian Sudr Formation at Umm Khayshar and Askhar El-Bahari areas, with the distribution of the identified fauna.

3. Materials and methods

Two sections, representing the upper Campanian-Maastrichtian Sudr Formation (Fig.2), were measured, studied, sampled for microfacies analysis, and their molluscan content were collected bed by bed for systematic and paleogeographical studies. The studied sections are; Umm Khayshar section at the northern scarp of the Southern Galala Plateau (Lat. 28° 55′ 34″ and Long. 32° 10′ 25″) and Askhar El-Bahari section at the southern scarp of the Northern Galala Plateau (Lat. 29° 03′ 04″ and Long. 32° 01′ 09″).

The different microfacies types are identified following the classification scheme of Dunham [36], with modifications of Embry and Klovan [37] and Scholle [38]. The taxonomic study of the molluscan content follows the classifications of Wenz [39], Perrilliat et al. [40], and Bouchet and Rocroi [41] for gastropods, and the classifications of Moore [42], Amler et al. [43], Bieler et al. [44], and Sørensen et al. [45] for bivalves. Moreover, the morphological terminology follows the glossary of Cox [46]. All linear measurements (given in millimeters) were taken using a Vernier Caliper. Abbreviations used for gastropod measurements are as follows: H: height, D: diameter, Hl: height of last whorl, Ha: height of aperture, Wa: width of aperture, Sa°: spiral angle (in degrees). Abbreviations used for bivalve measurements are as follows: L: shell length, H: shell height, C: shell thickness. All the materials are housed in the Museum of the Geology Department, Faculty of Science, Helwan University, Egypt.

4. Systematic Paleontology

Class: Gastropoda Cuvier [47]
Subclass: Prosobranchia Milne Edwards [48]
Clade: Caenogastropoda Cox [46]
Family: Tylostomatidae Stoliczka [49]
Genus: *Tylostoma* Sharpe [50]
Subgenus: *Tylostoma* Sharpe [50]
Tylostoma (*Tylostoma*) *pallaryi* (Péron and Fourtau [51])
Fig.3a, b
[51] *Pseudomelania Pallaryi* Péron and Fourtau, p.270, pl.1, fig.22.
[52] *Tylostoma pallaryi* (Péron and Fourtau); Fawzi, p.91, pl.7, figs.1-3.
[53] *Tylostoma* (*Tylostoma*) *pallaryi* (Péron and Fourtau); Mekawy, p.167, pl.3, fig.5.
[54] *Tylostoma* (*Tylostoma*) *pallaryi* (Péron and Fourtau); Kassab and Abdelhady, p.11, fig.8f.
Material. Five specimens from the upper Campanian-Maastrichtian Sudr Formation at Umm Khayshar and Askhar El-Bahari areas (UCG-39-43).
Measurements (in mm).

	H	D	Hl	Ha	Wa	Sa°
Range	35-40	23-27	24-31	16-22	8-15	63°-70°
Mean	37	25	27	19	11	68°

Remarks. Shells are turriculated of medium size. Spire is moderately high, representing about 30 percent of the shell height, and acute, with spiral angle of about 68°. The body whorl represents two thirds of the shell height. Suture line is slightly depressed. The present species can be distinguished from the Cenomanian *Tylostoma athleticum* Greco by the more inflated body whorl, and can also be distinguished from the Cenomanian *T. globosum* (Sharpe) by the less globular shell.
Distribution. *Tylostoma* (*Tylostoma*) *pallaryi* has been reported from the Cenomanian of the United Arab Emirates [55], Cenomanian of Algeria [56], Cenomanian-Turonian of Egypt [57], Cenomanian of Iraq [58], and Maastrichtian of Saudi Arabia [59].
Tylostoma (*Tylostoma*) *peroni* Pervinquière [60] Fig.3c, d
[60] *Tylostoma Peroni* Pervinquière, p.4, Fig.13.
[53] *Tylostoma* (*Tylostoma*) *peroni* Pervinquière; Mekawy, p.167, pl.3, Fig.6.
Material. Two specimens from the upper Campanian-Maastrichtian Sudr Formation at Askhar El-Bahari area (UCG-46, 47).
Measurements (in mm).

	H	D	Hl	Ha	Wa	Sa°
Range	38-41	24-26	17-19	23-24	15-16	75°-77°
Mean	40	25	18	24	16	76°

Remarks. Shells are globular of medium size. Spire is low, consisting of 2 to 3 whorls. The body whorl is large, representing more than two thirds of the shell height. Suture line is depressed. The present species can be distinguished from the Cenomanian *Tylostoma* (*Tylostoma*) *pallaryi* by the larger shell size and the lower spire.
Distribution. *Tylostoma* (*Tylostoma*) *peroni* has been recorded from the Santonian-Campanian of Tunisia [60] and Turonian of Egypt [53].
Family: Cerithiidae Fleming [61]
Genus: *Cerithium* Bruguière [62]
Cerithium buddha Noetling [63]
Fig.3e, f
[63] *Cerithium buddha* Noetling, p.60, pl.15, figs.4-5.
[55] *Cerithium buddha* Noetling; Metwally, p.339, pl.2, Fig.4.
[59] *Cerithium buddha* Noetling; Gameil and El-Sorogy, p.132, Fig.4f, g.
Material. Eight specimens from the upper Campanian-Maastrichtian Sudr Formation at Umm Khayshar and Askhar El-Bahari areas (UCG-93-100).

Measurements (in mm).

	H	**D**	**Hl**	**Ha**	**Wa**	**Sa°**
Range	17-20	9-12	5-7	3-4	3-5	24°-27°
Mean	18	10	6	3	4	25°

Remarks. The specimens are represented by medium-sized turriculated shells. Spire is longitudinal, consisting of 5 to 6 rounded whorls, with narrow spiral angle (about 25°). Suture line is slightly depressed.
Distribution. *Cerithium buddha* has been documented from the Maastrichtian of Pakistan [63], United Arab Emirates [55], and Saudi Arabia [59].
Family: Potamididae Adams and Adams [64]
Genus: *Potamides* Brongniart [65]
Potamides temalacaensis Perrilliat et al. [40]
Fig.3g
[40] *Potamides temalacaensis* Perrilliat et al., p.11, fig.5(17-20).
Material. One specimen from the upper Campanian-Maastrichtian Sudr Formation at Umm Khayshar area (UCG-101).
Measurements (in mm).

	H	**D**	**Hl**	**Ha**	**Wa**	**Sa°**
UCG-101	28	13	-	-	-	28°

Remarks. The shell is turriculated of medium size. Spire is longitudinal, with numerous convex whorls and narrow spiral angle (about 28°). Suture line is slightly depressed. Surface is sculptured with nodes by the intersections between axial ribs and spiral lirae.
Distribution. *Potamides temalacaensis* has been reported from the Maastrichtian of Mexico [40].
Class: Bivalvia Linnaeus [66]
Order: Ostreoida Férussac [67]
Family: Gryphaeidae Vyalov [68]
Subfamily: Exogyrinae Vyalov [68]
Genus: *Exogyra* Say [69]
Exogyra overwegi (von Buch [70])
Fig.3h, i
[70] *Exogyra overwegi* von Buch, p.152, pl.4, figs.1, 2.
[71] *Ostrea fourneti*; Coquand, p. 229, pl.21, figs.1-3.
[72] *Exogyra overwegi* von Buch; Abbas, p.70, pl.ix, figs.9, 11.
[73] *Exogyra overwegi* von Buch; Quarto di Palo, p.101, Pl.13, figs.8-9.
[74] *Exogyra overwegi* von Buch; Kassab and Zakhera, p.330, fig.2.
[75] *Exogyra overwegi* von Buch; Hewaidy et al., p.101, fig.8d.
Material. Three specimens from the upper Campanian-Maastrichtian Sudr Formation at Umm Khayshar area (UCO-162).
Measurements (in mm).

	H	**L**	**C**	**H/L**	**C/L**	**C/H**
Range	66-70	65-73	30-38	0.8-1.2	0.41-0.5	0.46-0.52
Mean	68	70	32.5	0.97	0.46	0.48

Remarks. The three well-preserved left valves are very large sized and exogyriform, ranging from high-oval to subrounded in outline, with strongly curved antero-dorsal margin. Umbo is opithogyrate, strongly twised, and the umbonal region is narrow. Ventral region is extended; ligament area is inclined and large. Adductor muscle scar is subrounded, large, and located at the center of the left valve. Anterior margin is convex, while posterior margin is concave. Ornamentation consists of concentric growth lamellae, crossed by radial ribs.
The present species differs from *Exogyra (Costagyra) olisiponensis* Sharpe in the lack of the spinose radial ribs and the presence of fine commarginal ribs instead. Moreover, *Exogyra (C.) olisiponensis* is only known from the Albian to the Coniacian [57], unlike *Exogyra overwegi* that ranges from the Santonian to the Maastrichtian.
Subfamily: Gryphaeostreinae Stenzel [76]
Genus: *Gryphaeostrea* Conrad [77]
Gryphaeostrea canaliculata (Sowerby [78])
Fig.3j, k
[78] *Chama canaliculata* Sowerby, pl.26, fig.1.
[79] *Gryphaeostrea canaliculata* Sowerby; Cleevely and Morris, p.458, fig.6.
[80] *Gryphaeostrea canaliculata* Sowerby; Malchus et al., p.124, figs.1-3, 5-11.
Material. Three specimens from the upper Campanian-Maastrichtian Sudr Formation at Askhar El-Bahari area (UCO-1222).
Measurements (in mm).

	H	**L**	**C**	**H/L**	**C/L**	**C/H**
Range	19.5-21	13.5-15	3.8-4.5	1.38-1.45	0.27-0.33	0.18-0.31
Mean	20	14	4	1.43	0.29	0.2

Remarks. The shell is small, opisthocline to orthocline, and ovate to elliptical. The left valve is rather convex, higher than long, with coiled opishthogyrous beak and narrow umbo. The right valve is concave, somewhat oval, higher than long, with a small opisthogyrous beak and insignificant umbo.

Ornamentation consists of subconcentric growth lamellae in some specimens.

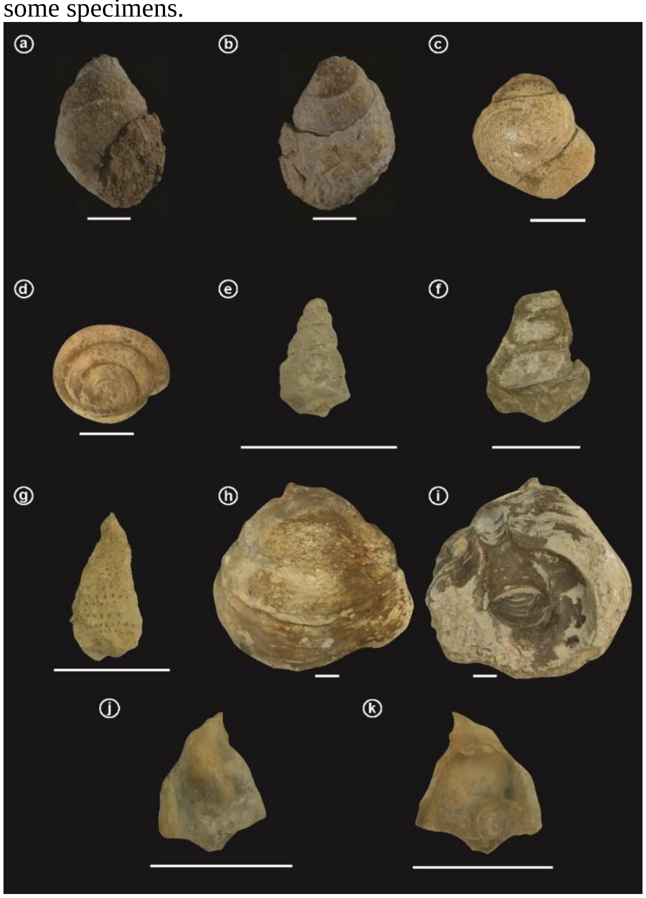

Fig.3. (**a, b**) *Tylostoma* (*Tylostoma*) *pallaryi* (Péron and Fourtau), UCG-39; (**a**) aperture view, (**b**) apical view. (**c, d**) *Tylostoma* (*Tylostoma*) *peroni* Pervinquière, UCG-46; (**c**) aperture view, (**d**) apical view. (**e, f**) *Cerithium buddha* Noetling; (**e**) aperture view, UCG-93, (**f**) aperture view, UCG-94. (**g**) *Potamides temalacaensis* Perrilliat et al., adaperture view, UCG-101. (**h, i**) *Exogyra overwegi* (von Buch), UCO-162; (**h**) external view of left valve, (**i**) internal view of right valve. (**j, k**) *Gryphaeostrea canaliculata* (Sowerby), UCO-1222; (**j**) external view of left valve, (**k**) internal view of right valve. Scale bar = 2 cm.

Order: Lucinida Gray [81]
Family: Lucinidae Fleming [61]
Genus: *Lucina* Bruguiére [62]
Lucina sp.
Fig.4a, b
Material. Six specimens from the upper Campanian-Maastrichtian Sudr Formation at Umm Khayshar and Askhar El-Bahari areas (UCB-17-22).
Measurements (in mm).

	H	L	C	H/L	C/L	C/H
Range	22-26	22-28	5.4-8	0.9-1.1	0.22-0.28	0.23-0.27
Mean	24	25	6.5	1	0.25	0.25

Remarks. Shells are medium-sized, subcircular, inequilateral, equivalved and moderately inflated (C/L=0.25 on average). Postero-dorsal margin is straight to slightly convex, and higher than antero-dorsal margin. Antero-dorsal margin is slightly concave. Posterior margin is strongly convex. Anterior margin is rounded, meeting regularly convex ventral margin in rounded curve. Umbones are small, prosogyrate, and located almost at mid-length of valve. Lunule is narrow and elongated oval. Some specimens display faint growth lines.

The present species differs from *Lucina (Dentilucina) subnumismalis* d'Orbigny in the less prominent umbones of the latter and being more elongated below umbones. It also differs from *L. masylaea* Coquand in the larger size, and the deeper, wider, and longer lunule of the latter.

Order: Cardiida Férussac [67]
Family: Arcticidae Newton [82]
Genus: *Arctica* Schumacher [83]
Arctica sp.
Fig.4c, d
Material. Nine specimens from the upper Campanian-Maastrichtian Sudr Formation at Umm Khayshar and Askhar El-Bahari areas (UCB-150-158).
Measurements (in mm).

	H	L	C	H/L	C/L	C/H
Range	22-26	22-28	5.4-8	0.9-1.1	0.22-0.28	0.23-0.27
Mean	24	25	6.5	1	0.25	0.25

Remarks. Internal moulds are of medium size, suboval to subtrigonal in outline, inequilateral, equivalved, and valves are evenly inflated. Posterior margin is obliquely truncated. Anterior margin is strongly convex. Umbo is prosogyrate. Pallial line is prominent along the entire margin. Postero-dorsal margin is convex and higher than the antero-dorsal margin. Antero-dorsal margin is slightly concave. No ornamentation preserved.

The present species differs from *Arctica picteti* (Coquand) in the straight postero-dorsal margin of the latter and being strongly elongated. It also differs from *Arctica inornata* (d'Orbigny) in the more prominent beaks and shallow antero-dorsal margin of the latter.

Genus: *Venilicardia* Stoliczka [84]
Venilicardia truncata (Sowerby [85])
Fig.4e, f
[85] *Venus truncata* Sowerby, p.342, pl.17, fig.3.
[86] *Venilicardia truncata* (Sowerby); Jaitly and Mishra, p.258, fig.5f, g.
Material. Six specimens from the upper Campanian-Maastrichtian Sudr Formation at Umm Khayshar area (UCB-159-165).
Measurements (in mm).

	H	L	C	H/L	C/L	C/H

Range	15-18	16-20	8-12	0.7-0.95	0.51-0.7	0.5-0.77
Mean	16	18	10	0.88	0.59	0.63

Remarks. Internal moulds are of medium size, sub-rhomboidal, inequilateral, equivalved, and strongly inflated. Anterior margin is well rounded. Posterior margin is short and subrounded. Postero-ventral margin is slightly truncated. Postero-dorsal margin is gently convex. Umbo is prominent, broad, and prosogyrate. Surface is ornamented with regular, concentric growth lines.

Family: Veneridae Rafinesque [87]

Genus: *Calva* Popenoe [88]

Subgenus: *Egelicalva* Saul and Popoeno [89]

Calva (*Egelicalva*) *buttensis* (Anderson [90])

Fig.4g, h

[90] *Trigonocallista buttensis* Anderson, p.140, pl.59, fig.1.

[89] *Calva (Egelicalva) buttensis* (Anderson); Saul and Popenoe, p.36, figs.191-210.

[86] *Calva (Egelicalva) buttensis* (Anderson); Jaitly and Mishra, p.258, fig.5i, j.

Material. Seven specimens from the upper Campanian-Maastrichtian Sudr Formation at Umm Khayshar area (UCB-159-165).

Measurements (in mm).

	H	L	C	H/L	C/L	C/H
Range	18-20	18-22	8-14	0.8-1.1	0.45-0.67	0.5-0.7
Mean	19	20	11	0.95	0.55	0.58

Remarks. Internal moulds are of medium size, ovate to trigonal, inequilateral, equivalved, and moderately inflated. Anterior and posterior margins are broadly rounded. Posterior margin is truncated. Postero-ventral margin is gently convex. Antero-ventral margin is strongly convex. Umbo is pointed, prosogyrate, and situated at a quarter of the shell length from the anterior margin.

Genus: *Meretrix* Lamarck [91]

Meretrix rohlfsi (Quaas [92])

Fig.4i, j

[92] *Cytherea rohlfsi* Quaas, p.224, pl.24, figs.23-25; pl.25, figs.1-4.

[72] *Meretrix rohlfsi* (Quaas); Abbass, p.148, pl.22, fig.16.

[74] *Meretrix rohlfsi* (Quaas); Kassab and Zakhera, p.340, fig.4(8).

[75] *Meretrix rohlfsi* (Quaas); Hewaidy et al., p.24, fig.11j.

Material. Fifteen specimens from the upper Campanian-Maastrichtian Sudr Formation at Umm Khayshar area (UCB-304-318).

Measurements (in mm).

	H	L	C	H/L	C/L	C/H
Range	23-27	24-28	14-18	0.85-1.17	0.54-0.7	0.51-0.77
Mean	25	26	16	0.96	0.62	0.64

Remarks. Shells are medium-sized, subtriangular in outline, equivalved, and inequilateral. Antero-dorsal margin is concave below the umbo. Postero-dorsal margin is gently convex. Ventral margin is convex, meeting the anterior and posterior margins in rounded curves. Umbo is prosogyrate, and located anteriorly. Lunule is ovate and wide. Surface is ornamented with concentric lamellae, separated by narrow interspaces.

Fig.4. (**a, b**) *Lucina* sp., UCB-17; (**a**) external view of left valve, (**b**) external view of right valve. (**c, d**) *Arctica* sp., UCB-150; (**c**) external view of left valve, (**d**) external view of right valve. (**e, f**) *Venilicardia truncata* (Sowerby), UCB-159; (**e**) external view of left valve, (**f**) dorsal view. (**g, h**) *Calva* (*Egelicalva*) *buttensis* (Anderson), UCB-217; (**g**) external view of right valve, (**h**) dorsal view. (**i, j**) *Meretrix rohlfsi* (Quaas), UCB-304; (**i**) external view of right valve, (**j**) dorsal view. Scale bar = 1 cm.

Order: Pectinida Gray [81]

Family: Pectinidae Wilkes [93]

Genus: *Lyriochlamys* Sobetskii [94]

Lyriochlamys dentata (Nilsson [95])

Fig.5a

[95] *Pecten dentatus* Nilsson, p.20, pl.10, fig.9.

[96] *Chlamys dentata* (Nilsson); Dhondt, p.15.

[45] *Lyriochlamys dentata* (Nilsson); Sørensen et al., p.31, fig.8l.

Material. Thirteen specimens from the upper Campanian-

Maastrichtian Sudr Formation at Umm Khayshar area (UCB-324-336).
Measurements (in mm).

	H	L	H/L
Range	18-27	16-25	0.98-1.2
Mean	22	21	1.05

Remarks. Shells are medium sized and drop-shaped. Right anterior auricle is winged and elongated. Left anterior auricle is large and covered with radial ribs. Posterior auricles are obtusely angled and much smaller. Surface is ornamented with numerous tripartite ribs and scabrous spinelets.
Family: Plicatulidae Gray [81]
Genus: *Plicatula* Lamarck [97]
Subgenus: *Plicatula* Lamarck [97]
Plicatula (Plicatula) sp.
Fig.5b
Material. Two incomplete specimens from the upper Campanian-Maastrichtian Sudr Formation at Umm Khayshar area (UCB-345, 346).
Measurements (in mm).

	L	H	H/L
Range	42-43	40-44	0.95-1.02
Mean	43	42	0.98

Remarks. Shells are medium-sized, ostreiform, inequilateral, nearly equivalved, with plicate margins. Valves are slightly convex to flattened. Inflated beak is in the left valve, and small attachment area is in the postero-dorsal region of the right valve. Umbos are orthogyrate and low. Ventral margin is rounded and joined to anterior and posterior margins in a rounded curve. Ornamentation consists of tuberculated radial ribs, separated by concave interspaces.
The present species differs from *P. ferryi* Coquand in having a strongly curved, orbicular shell. It also differs from *P. multicostata* Forbes in having narrower interspaces than the radial ribs and more strongly curved shell.
Order: Trigonioida Dall [98]
Family: Trigoniidae Lamarck [99]
Genus: *Pterotrigonia* Van Hoepen [100]
Subgenus: *Scabrotrigonia* Dietrich [101]
Pterotrigonia (Scabrotrigonia) scabra (Lamarck [99])
Fig.5c
[99] *Trigonia scabra* Lamarck, p.63, no.2.
[102] *Trigonia scabra* Lamarck; Zittel, p.161, pl.9, fig.2a-c.
[103] *Trigonia orientalis* Douvillé, p.168, pl.21, figs.14, 15.
[72] *Trigonia scabra* Lamarck; Abbass, p.89, pl.15, figs.1, 2, 3, 5, 7, 8.
[104] *Pterotrigonia (Scabrotrigonia) scabra* (Lamarck); Cox, p.487, fig.73(1).
[105] *Pterotrigonia (Scabrotrigonia) scabra* (Lamarck), Kora et al., pl.2, fig.12.
[106] *Pterotrigonia (Scabrotrigonia) scabra* (Lamarck), El-Hedeny, p.713, fig.5.

Material. Ten specimens from the upper Campanian-Maastrichtian Sudr Formation at Umm Khayshar area (UCB-349-358).
Measurements (in mm).

	L	H	C	H/L	C/L	C/H
Range	32-55	26-57	8-20	0.8-1.04	0.2-0.31	0.21-0.32
Mean	50	42	11	0.84	0.22	0.26

Remarks. Shells are medium-sized, semilunate, equivalved, strongly inequilateral, and moderately to highly inflated. Postero-dorsal margin is concave. Anterior margin is strongly convex, meeting convex ventral margin in rounded curve. Posterior end is elongated and compressed. Umbos are narrow, more or less pointed, and opisthogyrate. Flanks are covered with well-developed sharp, slightly-curved costae, separated by wide and smooth interspaces.
Order: Nuculoida Dall [98]
Family: Nuculidae Gray [107]
Genus: *Nucula* Lamarck [91]
Nucula chargensis Quaas [92]
Fig.5d, e
[92] *Nucula chargensis* Quaas, p.195, pl.31, figs.34-36.
[108] *Nuculana chargensis* Quaas; Fourtau, p.1.
[72] *Nucula (Nucula) chargensis* Quaas; Abbass, p.6, pl.1, figs.15, 17.
[109] *Leionucula chargensis* (Quaas); Azab et al., p.230, pl.1, figs.4-8.
[75] *Nucula chargensis* (Quaas); Hewaidy et al., p.9, fig.7b.
Material. Three specimens from the upper Campanian-Maastrichtian Sudr Formation at Umm Khayshar and Askhar El-Bahari areas (UCB-359-361).
Measurements (in mm).

	L	H	C	H/L	C/L	C/H
Range	9-19	14-18	3-8	0.9-0.97	0.3-0.41	0.38-0.39
Mean	17	16	6	0.94	0.35	0.38

Remarks. Shells are small-sized, oval, and equivalved. Umbo is terminal and opisthogyrate. Hinge line is curved. The posterior margin is convex and longer than the anterior margin. Ventral margin is strongly convex. Lunule is narrow and elongated. Escutcheon is small and oval. All specimens are internal moulds with no ornamentation. The present species differs in *Nucula cretacea* Coquand in having less elongated shell and less convex ventral margin.
Order: Arcoida Stoliczka [84]
Family: Cucullaeidae Stewart [110]
Genus: *Cucullaea* Lamarck [97]
Subgenus: *Idonearca* Conrad [111]
Cucullaea (Idonearca) maresi (Coquand [112])
Fig.5f, g
[112] *Arca maresi* Coquand; p.130.
[113] *Cucullaea cf. maresi* Coquand; Dacqué, p.371, pl.36, fig.4.

[57] *Cucullaea (Idonearca) maresi* (Coquand); El-Qot, p.24, pl.2, figs.9-13.
[114] *Cucullaea (Idonearca) maresi* (Coquand); Mekawy, p.206, pl.1, fig.8.
[115] *Cucullaea (Idonearca) maresi* (Coquand); El-Qot et al., p.191, pl.1, figs.6a-b.
Material. Six specimens from the upper Campanian-Maastrichtian Sudr Formation at Umm Khayshar area (UCB-391-396).
Measurements (in mm).

	L	H	C	H/L	C/L	C/H
Range	55-70	48-55	46-50	0.75-0.88	0.67-0.89	0.87-0.99
Mean	58	50	48	0.86	0.83	0.96

Remarks. Shells are large-sized, subtriangular to subtrapezoidal, longer than high (H/L = 0.86 on average), equivalved, and inequilateral. Umbo is prominent, broad, slightly prosogyrate, and located anteriorly. Posterior part is longer than anterior one. Ventral margin is slightly curved. Posterior margin is nearly straight, meeting ventral margin in acute angle. Ornamentation not preserved except some faint radial ribs in some specimens.

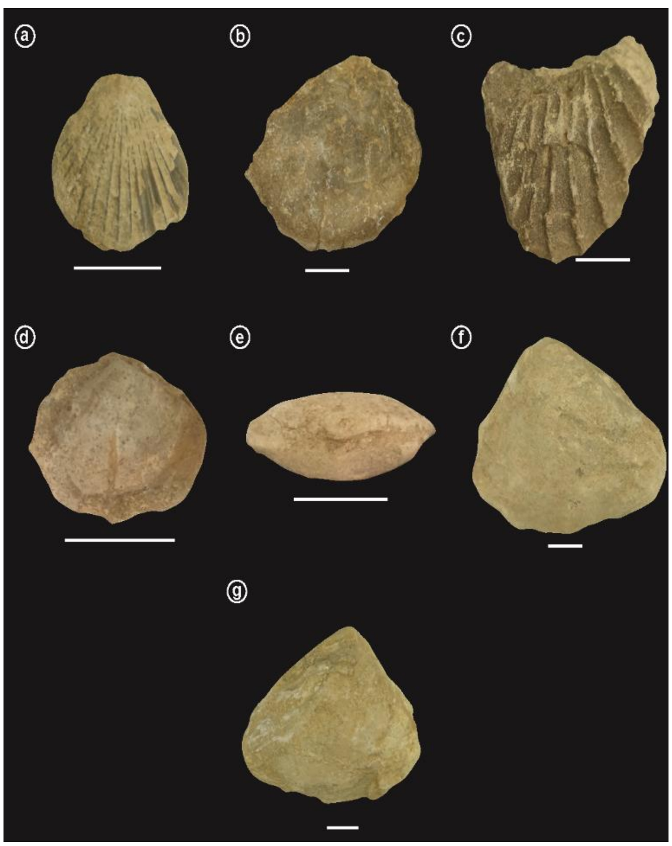

Fig.5. (**a**) *Lyriochlamys dentata* (Nilsson), external view, UCB-324. (**b**) *Plicatula* (*Plicatula*) sp., internal view of right valve, UCB-345. (**c**) *Pterotrigonia (Scabrotrigonia) scabra* (Lamarck), external view, UCB-349. (**d, e**) *Nucula chargensis* Quaas, UCB-359; (**d**) external view of left valve, (**e**) dorsal view. (**f, g**) *Cucullaea (Idonearca) maresi* (Coquand), UCB-391; (**f**) external view of left valve, (**g**) external view of right valve. Scale bar = 1 cm.

5. Microfacies and paleoenvironmental interpretation

The microfacies analysis of the fossil-bearing limestones of Sudr Formation allowed the identification of four microfacies types; bioclastic rudstone, sandy bioclastic grainstone, bioclastic packstone, and bioclastic wackestone. The recognized microfacies types are described based on their components, supported with photomicrographs, compared with the Standard Microfacies Types (SMF) of Flügel (2004) and the Facies Zones (FZ) of Wilson (1975), and interpreted with respect to their depositional environments (Figs.6-8).

5.1. Bioclastic rudstone (MFT-1)

Description: It contains a diverse faunal content in a groundmass of sparry calcite cement with few fine, subangular quartz grains and euhedral, zoned dolomite crystals (Fig.6a). The faunal content is represented by many chondrodontid bivalve shells, with well-preserved foliated wall structure (Fig.6b). Many algal plates and echinoid fragments are also recorded in this microfacies (Fig.6a).

Occurrence: This microfacies is recorded from the upper part of Sudr Formation.

Interpretation: The high abundance of faunal assemblages in this microfacies (e.g. bivalves, echinoids, and green algae) indicates open-marine settings, with well-oxygenation and normal salinity conditions. The sparitic cement suggests high water energy. Therefore, this microfacies reflects a deposition in a high-energy, open-marine, shallow subtidal shoal environment (Fig.8). This microfacies is correlated with SMF-12 of Flügel [116] and Facies Zone (FZ-6), Platform margin shoal, of Wilson [117].

5.2. Sandy bioclastic grainstone (MFT-2)

Description: This microfacies includes highly diversified biota in a groundmass of sparite, with moderately-sorted, fine to medium, subangular to angular quartz grains, ooids, few glauconite grains, and ferruginous material. Bivalve oyster shells, gastropod shells, brachiopod spines, echinoid fragments, crinoid columnals, and halimedacean algal plates are the main skeletal components (Figs.6c, d).

Occurrence: It is recorded from the middle and upper parts of Sudr Formation.

Interpretation: The faunal content of this microfacies indicates open circulation conditions. The sparitic cement as well as the presence of ooids suggest high-energy conditions.

It can be concluded that this microfacies is reflective of a high-energy, shallow subtidal shoal environment, with open circulation conditions (Fig.8). This microfacies is correlated with SMF-11 of Flügel [116] and Facies Zone (FZ-6), Platform margin shoal, of Wilson [117].

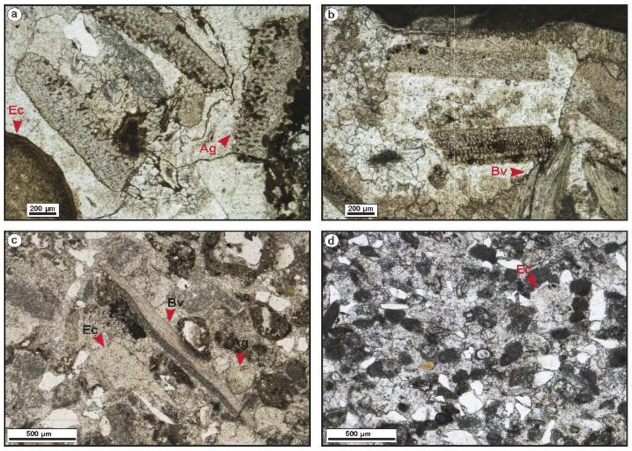

Fig.6. (**a, b**) Bioclastic rudstone (MFT-1), with echinoids (Ec), algal plates (Ag), and bivalve shells (Bv). (**c, d**) Sandy bioclastic grainstone (MFT-2), with algal plates, echinoids, and bivalve shells.

5.3. Bioclastic packstone (MFT-3)

Description: This microfacies encompasses highly diversified faunal content in a ground mass of microcrystalline calcite cement, with ferruginous patches. The faunal content includes bivalve shell fragments, gastropod shells with characteristic baby-bottom structure, brachiopod shells, planktonic foraminiferal tests, ostracod shells, echinoid plates and spines, halimedacean and dasycladacean algal plates (Fig.7a-c).

Occurrence: It is recorded from various intervals within Sudr Formation.

Interpretation: The high diversity of the faunal components of this microfacies suggests open-marine settings, with well-oxygenated and normal salinity conditions. The micritic cement suggests a low-energy environment. The planktonic foraminifera imply deep subtidal settings. Therefore, a deposition in a low-energy, open-marine, deep subtidal environment is proposed (Fig.8). This microfacies is correlated with SMF-12 of Flügel [116] and Facies Zone (FZ-4), Slope, of Wilson [117].

5.4. Bioclastic wackestone (MFT-4)

Description: The groundmass of this microfacies consists mainly of microcrystalline calcite cement, with fine to medium, sand-sized, subangular to angular quartz grains. The skeletal components are represented by bivalve shell fragments and planktonic foraminiferal tests (Fig.7d).

Occurrence: It is recorded from the upper part of Sudr Formation.

Interpretation: The recorded skeletal components reflect open circulation conditions, and the micritic cement indicates low water energy. The planktonic foraminifera suggest deep subtidal settings. Therefore, a low-energy, open-marine, deep subtidal environment is proposed (Fig.8). It is correlated with SMF-12 of Flügel [116] and Facies Zone (FZ-4), Slope, of Wilson [117].

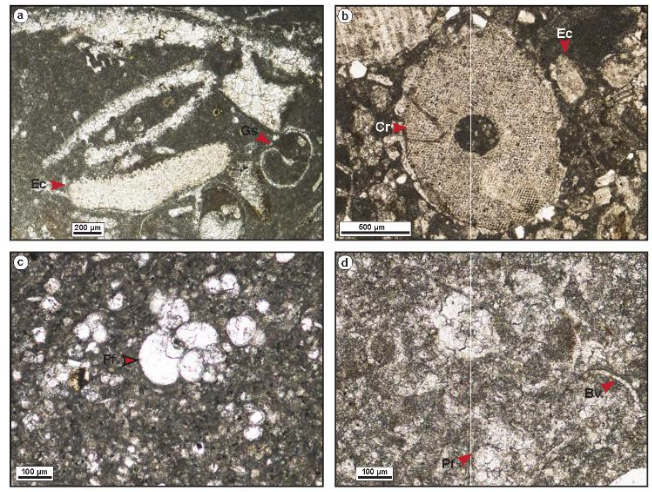

Fig.7. (**a-c**) Bioclastic packstone (MFT-3), with gastropods (Gs), echinoids, crinoids (Cr), and planktonic foraminifera (Pf). (**d**) Bioclastic wackestone (MFT-4), with bivalves (Bv) and planktonic foraminifera (Pf).

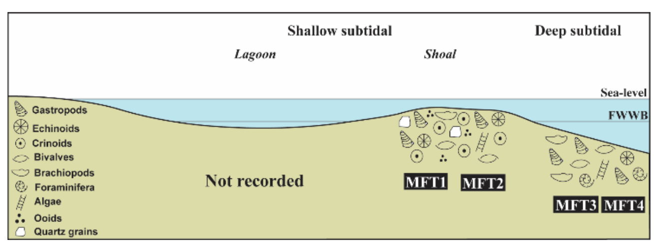

Fig.8. Depositional model for the upper Campanian-Maastrichtian successions in the study area.

6. Paleobiogeography of bivalves

The recorded fauna from the upper Campanian-Maastrichtian successions at the Northern and Southern Galala plateaus is dominated by bivalve taxa. Therefore, the paleobiogeography of bivalves is discussed in order to highlight their distribution inside and outside Egypt. Among the identified upper Campanian-Maastrichtian bivalves, two species are endemic to Egypt; *Nucula chargensis* Quaas and *Meretrix rohlfsi* (Quaas) [75, 118].

The other bivalve species, e.g. *Exogyra overwegi* (von Buch), *Gryphaeostrea canaliculata* (Sowerby), *Venilicardia truncata* (Sowerby), *Calva (Egelicalva) buttensis* (Anderson), *Lyriochlamys dentata* (Nilsson), *Pterotrigonia*

(Scabrotrigonia) scabra (Lamarck), and *Cucullaea (Idonearca) maresi* (Coquand), show wide distribution in North Africa (seven species), East and West Africa (three species), Middle East (two species), Asia (four species), Europe (five species), South America (one species), and North America (one species) (Figs.9, 10; Table.1).

Pterotrigonia (Scabrotrigonia) scabra is the most widely distributed species, being recorded from Italy, France, United Kingdom, Portugal, Bulgaria, Germany, Austria, India, Kazakhstan, Madagascar, Tunisia, Libya, and Egypt [72, 84, 105, 106, 119-125]. A more or less similar distribution characterizes *Exogyra overwegi* that has been reported from Afghanistan, Turkey, Oman, Algeria, Tunisia, Libya, Morocco, and Egypt [73, 75, 126-128] (Fig.9).

Gryphaeostrea canaliculata has been recorded from Poland, United Kingdom, France, Denmark, Bulgaria, Jordan, Madagascar, Angola, Mozambique, and Libya [126, 127, 129, 130], while *Cucullaea (Idonearca) maresi* has been reported from Peru, Congo, Libya, and Egypt [57, 114, 115, 131, 132] (Fig.10). The presence of *Gryphaeostrea canaliculata*, *Cucullaea (Idonearca) maresi*, and *Pterotrigonia (Scabrotrigonia) scabra* in North, East, and West Africa reflects a possible marine connection during the Maastrichtian through the Trans-Saharan epicontinental Sea-way. The occurrence of *Cucullaea (Idonearca) maresi* in South America (Peru) suggests a westward migration from Western Tethys to South Atlantic.

Venilicardia truncata has been documented from the United Kingdom, Russia, and India [86]. *Lyriochlamys dentata*, on the other hand, has been recorded from Sweden, Germany, and France [45, 96, 133]. *Calva* (*Egelicalva*) *buttensis* has been reported from India and USA [86]. The distribution of bivalves during the Campanian and Maastrichtian times shows a strong affinity of the recorded fauna to the South Tethyan Province and a moderate affinity to the North Tethyan Province (Figs.9, 10).

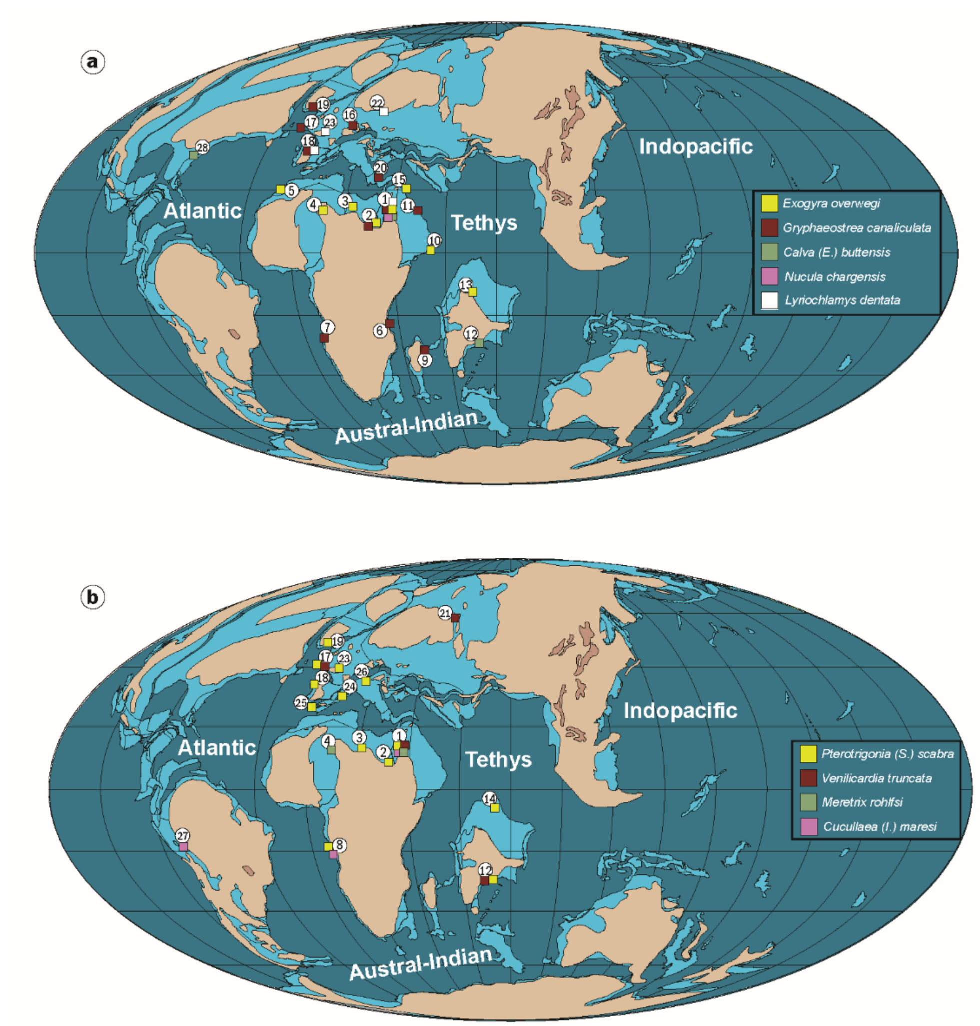

Fig.9. (**a, b**) Late Campanian-Maastrichtian paleogeographic map, showing the distribution of the recorded bivalve species. The base map is modified after Blakey [135]. (1. Egypt; 2. Libya; 3. Tunisia; 4. Algeria; 5. Morocco; 6. Mozambique; 7. Angola; 8. Congo; 9. Madagascar; 10. Oman; 11. Jordan; 12. India; 13. Afghanistan; 14. Kazakhstan; 15. Turkey; 16. Poland;

17. United Kingdom; 18. France; 19. Denmark; 20. Bulgaria; 21. Russia; 22. Sweden; 23. Germany; 24. Italy; 25. Portugal; 26. Austria; 27. Peru; 28. USA).

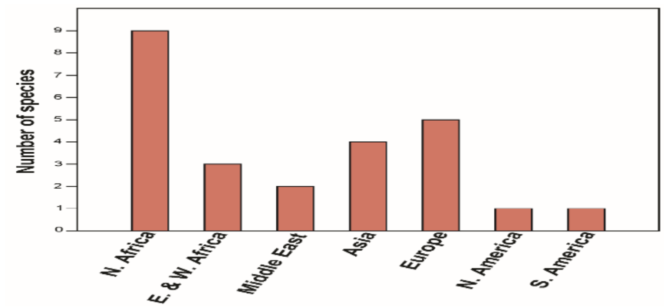

Fig.10. Distribution of the recorded upper Campanian-Maastrichtian bivalve species (based on number of species) in North Africa, East and West Africa, Middle East, Asia, Europe, South America and North America.

Table.1. The paleobiogeographical distribution of the studied bivalves in and outside Egypt. (+) recorded. (1. Egypt; 2. Libya; 3. Tunisia; 4. Algeria; 5. Morocco; 6. Mozambique; 7. Angola; 8. Congo; 9. Madagascar; 10. Oman; 11. Jordan; 12. India; 13. Afghanistan; 14. Kazakhstan; 15. Turkey; 16. Poland; 17. United Kingdom; 18. France; 19. Denmark; 20. Bulgaria; 21. Russia; 22. Sweden; 23. Germany; 24. Italy; 25. Portugal; 26. Austria; 27. Peru; 28. USA).

Taxa	N. Africa					E. & W. Africa				Middle East		Asia			Europe												S. America	N. America
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Exogyra overwegi	+	+	+	+	+					+			+		+													
Gryphaeostrea canaliculata	+	+				+	+		+		+					+	+	+	+	+								
Venilicardia truncata	+											+					+				+							
Calva (E.) buttensis	+											+																+
Meretrix rohlfsi	+			+																								
Lyriochlamys dentata	+																	+				+	+					
Pterotrigonia (S.) scabra	+	+	+					+				+		+			+	+	+				+	+	+	+		
Nucula chargensis	+																											

Cucullaea (I.) maresi	+							+																			+	

Conclusions

Sudr Formation represents the upper Campanian-Maastrichtian outcrops at Northern and Southern Galala Plateaus, north Eastern Desert, Egypt, deposited due to a great sea-level rise. It is made up of fossiliferous limestones, marly and cavernous limestones, followed by snow-white chalky limestones. The taxonomic study of the faunal content of Sudr Formation allowed the identification of four gastropod species, belonging to three genera of the families Tylostomatidae, Cerithiidae, and Potamididae, and twelve bivalve species, belonging to twelve genera of the families Gryphaeidae, Lucinidae, Arcticidae, Veneridae, Pectinidae, Plicatulidae, Trigoniidae, Nuculidae, and Cucullaeidae. Among the identified taxa, the gastropods *Cerithium buddha* Noetling and *Potamides temalacaensis* Perrilliat et al., and the bivalves *Gryphaeostrea canaliculata* (Sowerby), *Venilicardia truncata* (Sowerby), *Calva* (*Egelicalva*) *buttensis* (Anderson), and *Lyriochlamys dentata* (Nilsson) are recorded for the first time from Egypt. The carbonates of Sudr Formation are distinguished into grainstone, rudstone, packstone, and wackestone. The most common bioclasts include bivalves, echinoids, planktonic foraminifers and dasycladacean algae. Microfacies analysis of the studied carbonates reflected a deposition in open-marine, high-energy shallow subtidal shoal to low-energy deep subtidal environments. The paleobiogeographic analysis of the recorded bivalves revealed two endemic species to Egypt; *Nucula chargensis* Quaas and *Meretrix rohlfsi* (Quaas), while the other species show wide distribution in North Africa, East and West Africa, Middle East, Asia, Europe, South America, and North America. Such distribution reflected a strong southern Tethyan affinity and a moderate northern Tethyan affinity.

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