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Paleontology and taphonomy of Kuphus polythalamius (Linnaeus 1767), Navab anticline, Central Iran

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Abstract
The Burdigalian carbonate of the Central Iran contains very well-preserved specimens of Kuphus polythalamius. The tube of Kuphus polythalamius is a calcareous secretion that enables Pelecypoda to live in the mud of shallow seas. This research focusses on the Paleontology and taphonomy of the Kuphus polythalamius of the Member F (Qom Formation) in the southeast of Kashan located in the Central Iran. The Member F is 60 meters thick and composed of medium bedded limestone. The scattering of the larger benthic foraminifera in the study area indicates the existence of the Borelis melo curdica-Borelis melo melo assemblage zone of Burdigalian age. The presence of Kuphus polythalamius among the porcelaneous foraminiferal and green algal assemblage demonstrate that carbonate generation happened in warm tropical to subtropical marine. The surface of some samples contains distinct horizons of beekite, indicating a break in sedimentation, which is expanded as a silica crust on carbonate tubes.
Keywords: *Kuphus polythalamius, Beekite, Member F, Qom Formation, Central Iran*.

1. Introduction
The Burdigalian was an important stage for the evolution of the Tethyan Seaway. During this time, an extensive of marginal and non- marine sediments deposited in Central Iran and the Zagros zone. Deposition of c3,c4, d.e and f - Mmembers of the Qom Formation initiated deposition of the final sea transgression in Central Iran (e.g. Mohammadi et al. 2013).The f - Member is likely one of the most important lithostratigraphic units according to variety and affluence of Miocene *Kuphus polythalamius* (Linnaeus 1767). *K. polythalamius* is one of the biggest Pelecypoda in the world (Huber 2015).
Although *K. polythalamius* is a part of the usual wood-boring Pelecypoda family Teredinidae (generally identified as shipworms), it has been in different ways presented to burrow into mud and/or rotting wood (Distel et al. 2017).*K. polythalamius* is also among the few shallow-water marine species and the only teredinid species determined to harbor sulfur-oxidizing chemoautotrophic (thioautotrophic) symbionts (Shipway et al. 2018). The tubes of *K. polythalamius* are calcareous secretions in which animals live.Despite of detailed studies carried out the microfossils of the Qom Fm. (e.g. Daneshian and Ramezani Dana 2007; Daneshian and Aftabi 2010; Amirshahkarami et al. 2010; Daneshian and Ghanbari 2017) unfortunately there are few articles about *Kuphus polythalamia* in Iran. Therefore aim of this study is try to examine this significant fauna and resuscitate their taphonomy and plaeoenvironment as well.

2. Materials and Methods
To study the *Kuphus polythalamius* (Linnaeus 1767) of f- Member deposits in southeastern Kashan city, one section was prepared at the southern flank of Navab anticline. The f- Member contains about 60 m of whitish-yellow limestone with rich *Kuphus polythalamius* (Linnaeus 1767) contents in its upper part. 40 tubes of *Kuphus polythalamius* (Linnaeus 1767) in different dimensions and shapes collected from the last part 15 meters of the f-Member. Their diameter branching angles and forms were recorded in the field.
A number of 20 samples were explained to investigate microfossil characteristics at f- Member deposits. Sampling intervals were generally between 3 m. The selection of samples was primarily based on changes in sedimentary parameters. Microfossil characteristics were explained in thin sections from 20 samples. The thin sections were digitally photographed under transmitted-light.

3. Regional setting and stratigraphy
The Navab anticline is located (33°51'N, 51°40' E) 21 km southeast Kashan city. Based on Kamali et al. (2012), Navab anticline is located in Qom-Zefreh fault zone, central Iran basin (Fig1a). Berberin and King (1981) beleaved that central Iran was a back-arc environment during the Eocene- Oligocene time that was infilled by a sequence of continental, Lower Red Formation. Post-rift cooling and thermal subsidence resulted to the expansion of the Qom Formation during the late Oligocene–early Miocene (Gholamian et al. 2021). The Qom Formation lies disconformably on Lower Red Fm. (Fig 1b). The Upper contact of the Qom Formation and the Upper red Formation is marked by an unconformity. The Qom Fm. in Navab anticline with 460-m thickness cintains medium to thick bedded and massive limestone, marl, sandstone

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and gypsm. The outcrops of the f- Member at Navab anticline contains wellpreserved and abundant large benthic foraminifera, echinoderms remains and molds of pelecypoda and gastropods. Based on Daneshian and Aftabi (2010) the presence of subspecies of *Borelis melo melo* and *Borelis melo curdica* in the upper part of the Qom Formation at the Navab anticline shows *Borelis melo curdica - B. melo melo* assemblage zone which indicate the Burdigalian age. James and Wynd (1965) placed the first appearanceof *Borealis melo* in the Burdigalian.

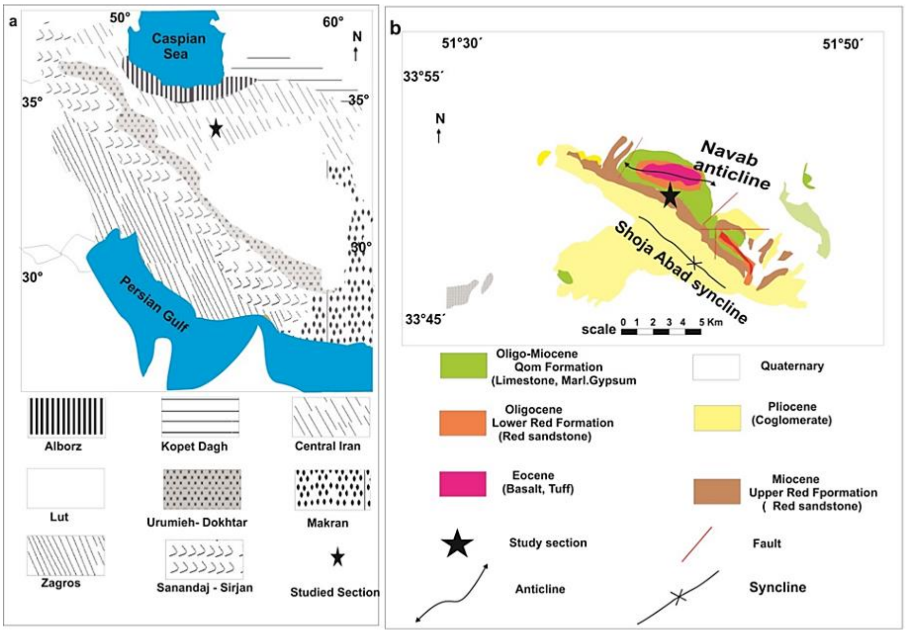

Fig 1. a) Map of the study site in central Iran (adopted from Heydari et al. 2003); b) The geological map of the Navab anticline (modified after Khalatbari Jafari and Alavi Mahabadi 2021).

4. Systematics

Linnaeus (1767) named Serpula arenaria a serpulid polychaete made of calcareous (Shipway et al. 2018). He subsequently changed it to *Serpula polythalamius*. In 1770, Guettard reported the name *Kuphus* for this genus, discovering that it was not a worm but a mollusc became the entrenched name for the living species.

Class Bivalvia Linnaeus 1758
Subclass Heterodonta Neumayr 1884
Order Myoida Stoliczka 1870
Suborder Pholadina H.Adams and Adams 1858
Superfamily Pholadacea Lamarck 1809
Family Teredinidae Rafinesque 1815
Subfamily Kuphinae Tryon 1862
Genus *Kuphus* Guettard 1770
Kuphus polythalamius (Linnaeus 1767)
Fig. 2

1767 *Serpula polythalamia* Linnaeus 12, p.1266
1770 *Kuphus* Guettard
1Material: 44
Description: The tube of Kuphus polythalamius is large, cylandrical-shaped, and occasionally washed up on beaches. Its length may reach 75 cm and a diameter of 5 cm. In some cases the initial part of tube tube is blocked (Fig. 3-a) and rarely two branches of the siphons are observed (Fig. 3-b). According to Figure 3 in some cases, the growth lines on the outer surface of the *Kuphus* tubes sometimes grows regularly and sometimes irregularly, also external elements are sometimes seen in their shells. *Kuphus* limestone tubes are mostly grown vertically (Fig. 3-c), but could be found from different angles and even horizontally.
Distribution: *Kuphus* is cosmopolitian and which is widespread in the European, North American and Northwestern Pacific coastal areas. It has been reported from the mid-Eocene and has a wide geographical range in the Oligocene and Lower Miocene as well as have spread from east and west India to Madagascar and southern France (Zammit Maempel 1993). *Kuphus* has also been presented from Asmari Fm. in the Zagroz zone (Douglas 1927). Nowadays, it inhabits the shallow waters in the in the western Pacific Ocean, the western and eastern Indian Ocean (Distel et al. 2017).

5. Discussion

For many years the genus *Kuphus* was mistakenly attributed to various types of fossils. For example, in Poland it was considered as a part of the jaw of dinosaur (Pożaryska and Pugaczewska 1981). Zhu et al. (2007), were misidentified the thick calcitic tubes of the teredenid bivalve *Kuphus* Before, the tubes were formerly mistaken for worm tubes, but the concentric laminations of their wall and the division of the narrow end of each tube into two separate siphonal canals, reveal their real nature (Zammit Maempel 1979).

Unlike other Teredinidae, *Kuphus polythalamius* (Linnaeus 1767) that we describe here were found burrowing in light grey limestone with low input of woody debris (Distel et al. 2017). An important feature of tubes of *Kuphus* in the Nawab anticline is their high density in sediments.

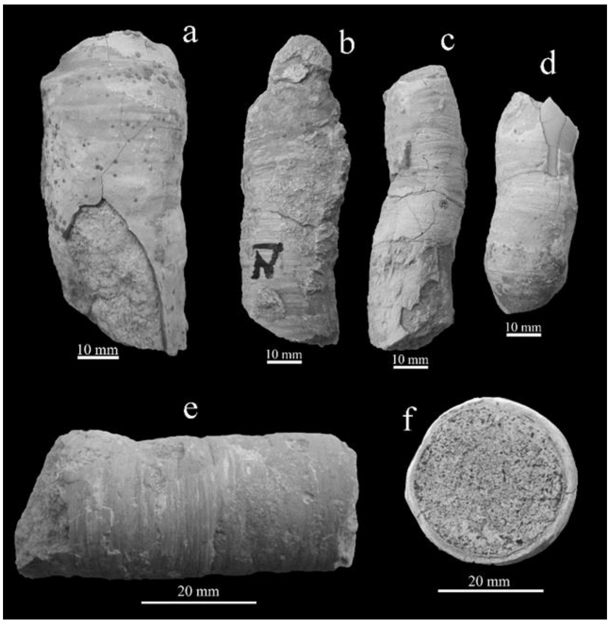

Fig 2. Tubes of *Kuphus* (Beekite is seen on "a") and f is a cross-section of Tubes of *Kuphus*.

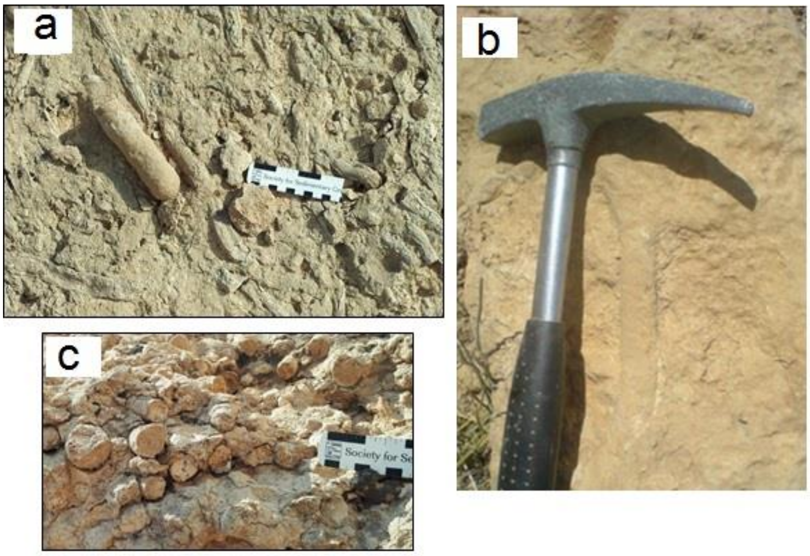

Fig 3. a) The frontal of the tubes were sealed by a calcareous cap; b) the posterior end of the tube with two distinctly separate siphonal tubes; c) Growth of Tubes of *Kuphus* perpendicular to the layering surface.

6. Sedimentary environment

The tube of *Kuphus* is found in thick-bedded, light brown layers of the upper part of the f-Member (Fig. 4), The tube of *Kuphus* in different dimensions have been reported at the Burdigalian deposits in the Central Iran (Fig.5a). In some layers, the density of the tube of *Kuphus* reaches more than 70% (Fig.5b).

The limestone layers of f-Member that contain *Kuphus* are often associated with allochems which are including about 10 % internal mold of bivalves and gastropods (Fig. 5c), and 10% echinoderms. In some samples, subordinate amounts of red algae (*Lithothamnium* sp. and *Mesophyllum* sp.) and foraminifera (rotalides and miliolid, Figs 5c,d) are also present.

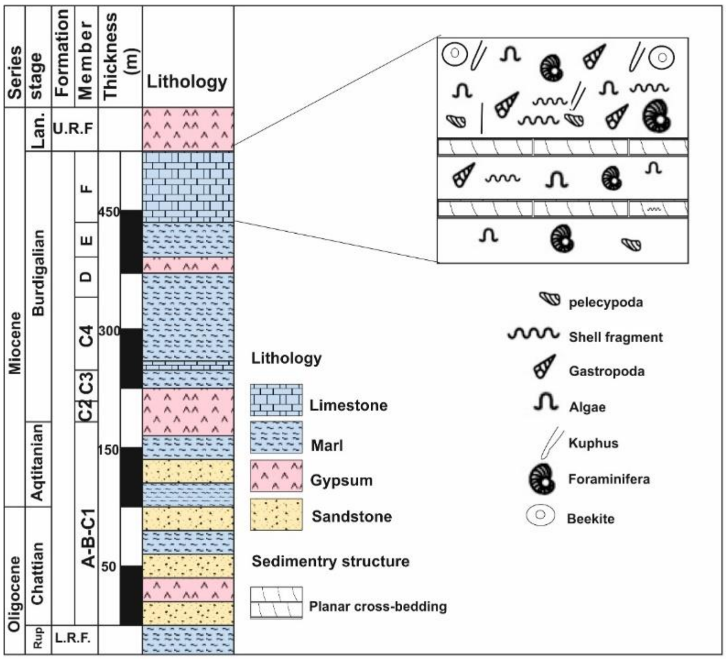

Fig 4. Stratigraphic column of Qom Formation in Navab section

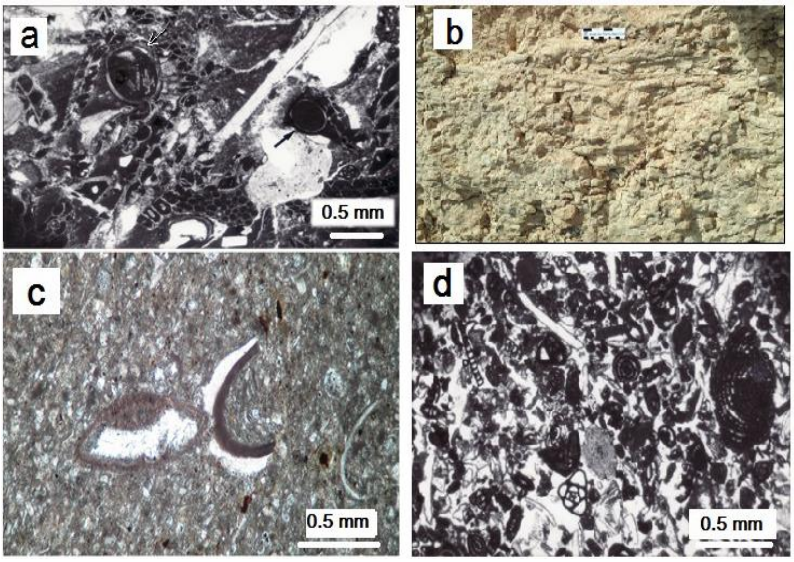

Fig 5. a) Thin section perpendicular to the layer, Bivalve shells (*Kuphus*), foraminifers (milliolides) and Bryozoa (*Smittinella*) packestone, 15X;, The *Kuphus* shell is composed of several layers like adult specimens; b) High density of the tube of *Kuphus* in the f- member; c) wackestone with rotalid and *Kuphs* ; d) Bioclastic porcelaneous foraminifera bioclast wackestone-packstone.

Despite the fragility of the tube of *Kuphus*, their good preservation indicates a relatively calm sedimentary environment during their lifetime. *Mesophilum* and *Lithothamnium* can be found in a variety of paleobathymetric settings but at shallow depths, their frequency are greatly reduced (Perrin 1995), and therefore occure in the relatively shallow water biofacies of the f-member. The persence of imperforate foraminifera shows shallow photic zone (Bassi and Nebelsick 2010; GhasemShirazi et al. 2014). The presence of rotalides in these layers confirms a shallow environment. Based on the mentioned allochems in the *Kuphus* layers we suggest a quiet and shallow marine environment.

Some of the tubes of *Kuphus* contain beekite-encrusted clasts (Fig. 6). Beekite is expanded as 1–5 mm concentric silica loops of fine-crystalline quartz in a confined space. It organized by substitution of carbonates.

As Holdaway and Clayton (1982) showed Three distinct morphologies of silica were formed by the relativerates of silica supply and carbonate dissolution: (a) a fine-scale replacement of the original shell microstructure where silica was abundant; (b) a concentric ring morphology called‘beekite’ where silica supply was limited, and (c) a granular white crust formed wherecarbonate dissolution was restricted.

The organization of beekites need a partly long time, with non-deposition and fluctuating arid/semiarid situations (Kazanci and Varol 1993) with periodic (episodic) and effective rainfall that causes significant fluctuations in groundwater levels, it does not require many silica resources, such as an active volcano or igneous material around it (Kazanci and Varol 1993; Mayer and Pena Dos Reis 1985). The presence of beekite encrustation on the tubes of *Kuphus* indicates considerable breaks in sedimentation. Silicification happened during early diagenesis as aresult of bacterial decay of organic matter intimately associated with skeletal fragments, within a sediment of restricted permeability (Holdaway and Clayton 1982). A build-up of CO_2 probably caused dissolutionof skeletal carbonate, and bicarbonate released from this caused local precipitation of silica (Holdaway and Clayton 1982).

7. Ecological features of *Kuphua polyhalmius*

Kuphus polythalamius is a species of shipworms, marine bivalve molluscs in the family Teredinidae. While there are four extinct species of *Kuphus*, the only extant species is *Kuphus polythalamius* which burrows in black, organic-rich sediments in a marine bay, setting it apart from wood-boring shipworms (Huber 2015). The tube of *Kuphus polythalamius* is identified as a crypt and is a calcareous secretion designed to enable the animal to live in its preferred habitat, the mud of mangrove swamps, lived in a shallow, warm and completely marine environment (Zammit Maempel 1993). Today, its habitat includes mangrove areas saltwater. Also, it is seen as immersed in sludge rich in organic material and wood chips (Distel et al. 2017).

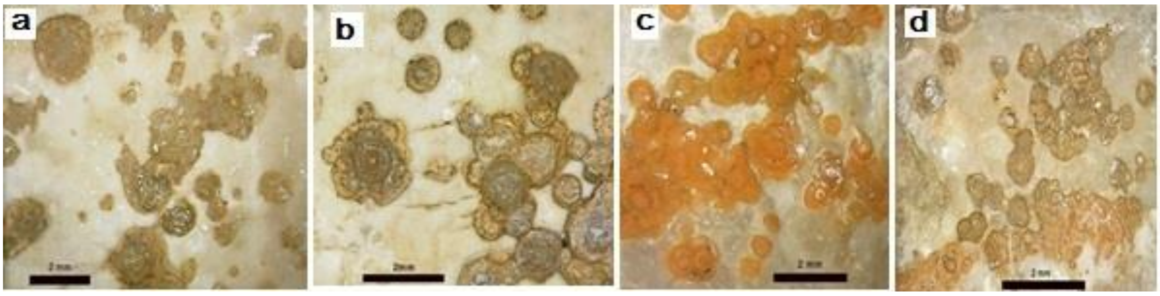

Fig 6. (a-d) Silicification (beekite) on the outer shell of *Kuphus* in the The topmost carbonate beds of the f- Member

Mostly exceeding 1 m in body length, *Kuphus polythalamius* has been reported to occur in shallow coastal waters of the Indo-Pacific in proximity to mangrove forests and coral reefs and in substrates including mud, gravel, and sand (Turner 1969).

The samples of *Kuphus* studied are burrowing pelecypoda in the growth stages. The end of the front section of the tubes were signet by a calcareous cap (Fig. 4a) that covers the excavation face of the burrow (Zammit Maempel 1993; Distel et al. 2017; Shipway et al. 2018). Although this cap must be attract occasionally to allow the animal to grow and extend its tube. The larvae of *Kuphus polythalamius*, unlike other Teredinidae that dig in the wood and feed on it, at first set on wood and later shift into the sediment, where this species may grow to large scales, Therefore this species is both wood-eating and sediment-eating (Shipway et al. 2019; Distel et al. 2017). *Kuphus polythalamius* in the Navab anticline exist in the present Sultan Kodarat sea wetland, southwest of Mindanao Island, Philippines, (e.g. Shipway et al. 2019), which enables the ecological features of this animal to be clarified. The sediments in Sultan Kodarat sea are full of rotten wood which their source is mostly from continental forests along the sea. In this area, huge specimens of *Kuphus* do not grow inside wood but are fixed and buried in thick black mud at a depth of about three meters from the surface of the wetland. They are difficult to feed and sometimes their openings are located at the closed end of the lime tube. Altamia et al. 2019 showed that that the visceral mass of *Kuphus* is 0.1 times its length.

Although their muscles have grown a lot, they still have their own digestive system, so some parts of their digestive system are weakened or removed. Shipway et al. (2019) showed that *Kuphus* did not need to swallow food to feed in anaerobic environment, and because of their highly degraded digestive system, bacteria made it easier for them to digest food. Also, this type of nutrition helps this species to achieve large dimensions (Shipway et al. 2019).

Kuphus polythalamius uses water-soluble hydrogen sulfide as an energy origin to turn Co_2 into nutrients. This is done using bacteria inside the gills and its body hosts a symbiotic symbiotic bacterium called *Thiosocius teredinicola* (Altamia et al. 2019). As an energy source for the production of organic carbon to facilitate the nutrition and growth of *Kuphus*, this bacterium uses hydrogen sulfide and without the enzymes of this bacterium, the cellulose that makes up wood and other plant materials are not fully digestible (Altamia et al. 2019; Distel et al. 2017). In the upper part of the f-Member, Tubes of *Kuphus* have grown vertically, less commonly, these are preserved in other attitudes, including horizontal. It seems that they have sometimes grown intertwined for maintaining survival due to the lack of suitable space for the free growth of the organism. During Late Burdigalian, shallow- marine sedimentation of the upper part of the Qom Fm. was replaced by the terrestrial depositional environment of the Upper Red Fm. over much of Central Iran. The f- Member sediments indicate a marine regression across Central Iran in Burdigalian which was deposited on a ramp like platform (Jalali et al. 2017). Based on frequency analysis, the inner ramp is the uttermost environment in the Navab anticline. The abundance of *Kuphus* tubes, indicates soft to firm substrate, and on the other hand, the low diversity and small number of other fossils, such as Foraminifera, indicate hard biological conditions.

8. Conclusion

This is the first study of fossil *Kuphus polythalamius* and their potential utilization as paleoecological indicators. The f- Member in the Navab anticline mainly consists of inner ramp carbonate succession in Burdigalian age. The paleoecological studies of the *Kuphus* in Navab anticline illustrate a shallow photic zone with soft and fine grain substrate dominated during the deposition of the f- Member. The very high density of the tube of *Kuphus* indicates their suitable biological conditions. The abundance and association of large benthic foraminifera and algae with *Kuphus* show a shallow photic zone of warm marine.The presence of beekite on the outer surface of the tube of *Kuphus* indicate considerable breaks in sedimentation in f- Member deposits.

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