Lithofacies palaeogeography and biostratigraphy of the lowermost horizons of the Middle Triassic Hallstatt Limestones (Argolis Peninsula, Greece)

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Abstract Condensed ammonoid beds of the Hallstatt facies (Anisian–Ladinian) are widespread around the Ancient Theatre of Epidaurus, in the locality Theokafta of the Argolis Peninsula (eastern Peloponnesus). The Hallstatt Formation in Argolis appears, generally, in the form of lensoid bodies of variable sizes, inclination and direction and is always found overlying a formation consisting of keratophyric tuffs. In fact, the contact of the keratophyric tuffs with the overlying limestones, specifically evidenced by an in situ brecciated zone, is stratigraphic and constitutes the base of the Hallstatt Limestones. The contact of the Hallstatt Limestones with the overlying radiolarites is stratigraphic as well.

Lithofacies and biostratigraphic research has focused on the lowermost horizons of the Hallstatt Limestones of Anisian age (average thickness about 1.30 m), where a dense sampling has been performed, followed by detailed facies analysis. The lowermost horizons of the Hallstatt Limestones of Theokafta represent typical hiatus beds/concretions sensu Wetzel and Allia (2000), characterized by discontinuous sedimentation and erosion. They consist of red ammonoid-bearing hemipelagic limestones with calcium carbonate nodules floating in an enriched Fe-oxides matrix with dispersed lensoid/prismatic calcium carbonate crystals. This part of the section is characterized by condensed sedimentation, due to significant lowering of the rate of sedimentation and includes omission surfaces, firmgrounds and hardgrounds along certain horizons. Nine lithostratigraphic units have been distinguished in the lowermost horizons of the Hallstatt Limestones, including radiolarian packstones, volcaniclastic facies, packstones/floatstones with ammonoids and lag deposits.

Tselepidis (2007) defined nine distinct ammonoid biozones from the Anisian to Ladinian, documenting deposition of the Hallstatt facies during a low depositional rate over nearly 5 million years (using the timescale of Gradstein et al., 2004). The biozones: Japonites/Paracarocordiceras, Hollandites, Procladiscites/Leiophyllites, zoldianus, trinidosus, Reitziiites/Parakellnerites and the Nevadites (Anisian) and the biozone curionii (Lower Ladinian). Although sedimentation was very condensed, it didn’t reach the level of mixing fauna.

Synsedimentary and early burrowing processes differentiated the primary texture characteristics of the deposited sediments. Multiphase diagenesis occurred not very deep below the sediment surface and includes boring and/or encrustation, burial and cementation. The deposition of the studied Hallstatt Limestones is considered to be due to anaerobic oxidation of organic matter, which provided excess alkalinity, inducing carbonate precipitation. Sedi-

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mentation took place on differentially-subsided deep swells. After drowning, the swells were covered by pelagic carbonate deposits. Further slight rotation of blocks, along listric faults, may have led to additional differential subsidence of the blocks. Shelf bathymetry and third-order sea-level changes played a significant role in the formation of the Hallstatt beds. In terms of sequence stratigraphy, the studied hiatus concretions and beds are considered genetically linked to rising or high sea-level, formed at the initiation of transgressions, as well as during the time of maximum rate of transgression, in areas where the sediment input was strongly reduced (“condensed section”).

Taking into consideration the present location of the Hallstatt Formation, in the context of the Hellenides, an area suitable for the deposition of the Hallstatt Limestones, should be located between the sub-Pelagonian (western part of the Pelagonian zone) and Pindos geotectonic zones, which during the Triassic corresponded to a platform slope and a deep ocean, respectively. The widespread Middle Triassic Han Bulog Limestones (ammonoid-bearing pelagic limestones) from Triassic successions of the Eastern Alps (Dinarides, Hellenides) may have formed partly in similar slope environments.

Key words Middle Triassic, Hallstatt Formation, facies analysis, ammonoid biozonation, condensed pelagic sedimentation, palaeoenvironment, eastern Peloponnesus

1 Introduction

Ammonoid-bearing pelagic carbonate formations on top of platforms, following a significant stratigraphic break, are very common in Middle Triassic sequences of the southern and eastern Alps (Assereto, 1971; Schlager and Schollnberger, 1974; Epting et al., 1976; Brandner, 1984; Angiolini et al., 1992; Brack et al., 2007; Monnet et al., 2008). These formations are condensed, red, micritic, sometimes nodular, rich in cephalopods, conodonts and molluscs, and are known as “Hallstatt-type limestones”. The Hallstatt horizons are of particular stratigraphic and geologic interest, as far as the relationship of the Hallstatt facies with surrounding formations and the determination of the stratigraphic level that coincides with the beginning of Hallstatt facies deposition.

Hallstatt facies correspond to hiatus beds/concretions characterized by discontinuous sedimentation and erosion. Hiatus concretions are hypothesized to form during early diagenesis by reworking of carbonate sediments, after a break in sedimentation or seafloor erosion (Voigt, 1968; Raiswell, 1987, 1988; Spears, 1989; Wetzel and Allia, 2000). A prerequisite for the growth of concretions is that they should remain for a considerable time within the sulfate reduction zone (7000 years; Coleman and Raiswell, 1993). The identification of such horizons has a great stratigraphic and sedimentologic value, as they indicate markers of significant interruption of sedimentation that otherwise would not be noticed (Fursich and Baird, 1975; Baird, 1976). Such discontinuity surfaces are commonly not manifested as biostratigraphic gaps (e.g., Wilson, 1985). The hiatus beds, and specifically the hiatus concretions are characterized by a multiphase diagenetic history that occurs not very deep below the sediment surface and includes exhumation, boring and/or encrustation, burial and cementation (Savrda and Bottjer, 1988).

In terms of sequence stratigraphy, hiatus concretions and beds are genetically linked to rising or high sea-level (e.g., Van Wagoner et al., 1988). They are thought to form during the initiation of transgressions (e.g., Voigt, 1968; Fursich et al., 1991), as well as during the time of maximum rate of transgression in areas where sediment input is strongly reduced (“condensed section”). Similar deposits, considered to have formed during sea-level highstand, were also reported from drowned carbonate platforms by Kendall and Schlager (1981).

However, this simple sequence-stratigraphic interpretation of hiatus beds and condensed sections, is not always valid, because hiatus beds seem to form more frequently during times of tectonic activity than times of intense sea-level changes (Wetzel and Allia, 2000). Other processes, such as a differential subsidence, may produce sediment starvation or seafloor erosion, providing the necessary conditions for formation of hiatus concretions (e.g., Hesselbo and Palmer, 1992).

The Hallstatt facies occur in the following areas of Greece: in Chios Island (Skythian–Lower Anisian; Bender, 1970; Jacobshagen and Tietze, 1974; Gaetani et al., 1992; Mertmann and Jacobshagen, 2003), in Hydra Island (Anisian–Carnian; Römermann, 1968; Angiolini et
analysis, extended the interval of Hallstatt facies deposition from the lower Anisian to the lower Norian and considered that a submarine slide, in the frame of a syn-sedimentary tectonism, relocated the Hallstatt Formation in-between the radiolarites. On the other hand, Dürkoop et al. (1986), considered that the stratigraphic contacts of the Hallstatt facies with the underlying keratophyric tuffs, as well as with the overlying radiolarites, was stratigraphic, reaching up to the Upper Norian (Sevatian).

Red, micritic, ammonoid-bearing limestones of the Hallstatt facies are widespread around the Ancient Theatre of Epidaurus, in the Argolis Peninsula (Figs. 1, 2, 3). Detailed sampling of the Hallstatt facies was conducted in one of the most spectacular sequences, which is situated in the broader area of Epidaurus, 600 m NW of the Ancient Theatre of Epidaurus, in the locality of Theokafta.

The Theokafta outcrop is composed of the following lithologic formations, from base to top: the keratophyric tuffs, the limestones of the Hallstatt facies, the radiolarites and the limestones with cherts (Figs. 4, 5).

The formation of the keratophyric tuffs extends throughout the broader area of Argolis, and is in contact with different formations each time (e.g., the Hallstatt, the radiolarites and the limestones with cherts), resulting in different age estimations. For instance, as substrata of the Hallstatt Limestones, the keratophyric tuffs should be considered older than Lower Anisian, whereas as substrata of the formation of limestones with cherts, should be older than Lower Ladinian.

The Hallstatt Formation in Argolis appears, generally, in the form of lensoid bodies of variable sizes, inclination and direction and is found always overlying the keratophyric tuffs, although due to inversion tectonics the keratophyric tuffs appear in places, to overlie the Hallstatt Limestones (Bender et al., 1960; Jacobshagen, 1967; Bannert and Bender, 1968; Pelosio, 1973; Bachmann and Jacobshagen, 1974; Krystyn and Mariolakos, 1975; Tselepidis et al., 1989; Geol. Sheet Ligourio 1:25000 IGME). In fact, the contact of the keratophyric tuffs with the overlying limestones, as evidenced by an in situ brecciated zone, is stratigraphic and constitutes the base of the Hallstatt Limestones. Due to tectonism, the Hallstatt Formation has, in places, undergone fragmentation and significant translocation. The outcrop studied, at the eastern slopes of the Theokafta Hill (Fig. 2), which appears in the form of a lensoid body with thickness reaching 82 m, is the most significant outcrop of the Hallstatt facies in the Argolis Peninsula, not only referring to its dimensions, but also because of its richness in macro- and microfauna,

### 2 Stratigraphic location and geological setting of the Hallstatt facies in Argolis

Hallstatt Limestones exposed in the Argolis Peninsula have been investigated since the start of the twentieth century. Renz (1906a, 1906b), first confined Hallstatt facies to the Triassic at the Theokafta locality, following the discovery of the ammonite *Joanmites diffisus* HAUER by Douvillé (1900), attributing to an Upper Anisian–Middle Carnian age.

In the Argolis Peninsula, the Hallstatt Limestones is considered to overlie stratigraphically, volcaniclastic formations consisted of keratophyric tuffs (Renz, 1910a, 1910b, 1939, 1955; Bender, 1962; Tselepidis et al., 1989). Bender and Kockel (1963) attributed an Early Triassic age to the keratophyric tuffs, suggesting that the Hallstatt facies began in the upper Anisian. Jacobshagen (1967), Bannert and Bender (1968) and Pelosio (1973) also refer to Hallstatt facies as condensed horizons of Upper Anisian–Carnian age that are normally deposited on the tuffic substrata.

The Hallstatt facies is overlain by a radiolaritic formation, although in places there appears to be a lateral transition between these two formations. However, according to other authors, the whole lithostratigraphic series is reversed (Bender, 1962; Bender and Kockel, 1963), whereas Baumgartner (1985) suggested that the contact of the radiolaritic sedimentary rocks with the Hallstatt facies, as well as with the keratophyric tuffs is tectonic, and suggested that the Hallstatt Formation, in association with the keratophyric tuffs, acted as an olistolith that was translocated in-between the radiolarites.

Krystyn and Mariolakos (1975), based on conodont
which covers the entire stratigraphic evolution of the Triassic. Additionally, in Theokafta, the relationship of the Hallstatt facies with the underlying (keratophyric tuffs) and the overlying formations (radiolarites) is very clear (Fig. 4).

Concerning the relationship of the Hallstatt facies with the stratigraphically overlying radiolarites, it has not yet been clarified as to whether the radiolarites were deposited before or after the deposition of the Hallstatt Limestones (Fig. 6). As it was previously noted, the radiolarites are,
Fig. 2. Limestones of the Hallstatt facies around the Ancient Theater of Epidaurus in the Argolis, Peninsula.

Fig. 3. Red, micritic, ammonoid-bearing limestones of the Hallstatt facies from the locality Theokafta of Epidaurus (Argolis Peninsula). Age: Upper Anisian (Illyrian, biozone *Nevadites*).
The Theokafta outcrop is composed of the following lithologic formations, from base to top: keratophyric tuffs, limestones of the Hallstatt facies, radiolarites and limestones with cherts. The contact of the Hallstatt Limestones with the underlying keratophyric tuffs and the overlying radiolarites is stratigraphic.

An overview of the studied geological section.

in places, in direct contact with the keratophyric tuffs, as well (Fig. 7). In the studied sequence, radiolarites are tectonically overlain by the limestones with cherts (Fig. 6) and have been dated as Lower Ladinian–Middle Liasic, on the basis of conodonts (Krystyn and Mariolakos, 1975). The limestones with cherts are considered to have been deposited in a neighboring area, to that of the Hallstatt Limestones, directly upon the keratophyric tuffs. The Hallstatt Limestones started to be deposited in the Lower Anisian, whereas deposition of the limestones with cherts should have started later, possibly in the Lower Ladinian. In the area of Theokafta, both the “packet” radiolarites/limestones with cherts, as well as, the “packet” keratophyric tuffs/radiolarites, are inversely stratified (Figs. 6, 7). Inverse stratification is the result of post Upper Jurassic compressional tectonism, resulting in folding and over-

Fig. 4 The Theokafta outcrop is composed of the following lithologic formations, from base to top: keratophyric tuffs, limestones of the Hallstatt facies, radiolarites and limestones with cherts. The contact of the Hallstatt Limestones with the underlying keratophyric tuffs and the overlying radiolarites is stratigraphic.
thrusting (Fig. 8).

3 Lithostratigraphy

The studied section is situated in a very short distance north of the “Asklpieion” of Ancient Epidaurus, at the eastern slopes of Theokafta. Due to a system of faults, normal to the stratification, fragmentation and significant horizontal translocation of the resulted blocks is observed.

Starting from the lower part of the section, along the contact with the keratophyric tuffs, towards the top, a formation of brownish-reddish limestones is observed, averaging 8 m in thickness (lithologic units A0 to A8). It is characterized by layers enriched in ammonoids and nautiloids, orientated parallel to the stratification, as well as by concentrations of Fe- and Mn-oxides, along specific
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Lithofacies and biostratigraphic research has been focused on the lowermost horizons of the Hallstatt Limestones of Anisian age (average thickness about 1.30 m), where a dense sampling has been performed, followed by detailed facies analysis (lithologic units A0 to A3). That part consists of two characteristic lithological units (Fig. 11):

The first lithological unit, comprises the layers A1 and A2. Layer A1, a thin layer averaging 4–5 cm in thickness, is friable mylonitic volcanic material, located between the Hallstatt Limestones and the underlying keratophyric tuffs e.g., this layer marks the beginning of carbonate sedimentation. In fact, the uppermost portion of layer A1 is a thin layer, averaging 3–4 cm in thickness, consisting of fragments of macrofauna and reworking, fine-grained, volcanic keratophyric material. Layer A2 represents the initial layer of the Hallstatt facies (with the subdivisions A2/1a, A2/1b, A2/2, A2/3 and A2/4). Layer A2/1a, averaging 8–10 cm in thickness, is characterized by a brecciated appearance, due to the presence of abundant, mainly angular lithoclasts and crystal clasts of variable size. The lithoclasts are volcanic surfaces (Figs. 9, 10).

Fig. 8 Radiolarites overthrusted on the keratophyric tuffs and limestones with cherts overthrusted on radiolarites, due to inverse stratification.
in origin and are derived from the underlying keratophytic tuffs. In most cases they have suffered calcitization. Layer A2/1b, averaging 5 cm in thickness, is a brownish-reddish limestone that developed on an irregular, eroded surface. Layer 2/2 consists of a lower brecciated facies averaging ~7 cm in thickness, whereas the upper part consists of a biomicrite rich in ammonoids. The studied lowest part of the section is characterized by condensed sedimentation. Synsedimentary and early burrowing differentiate the primary texture characteristics of the deposited sediments. Omission surfaces and hardgrounds *sensu* Bathurst (1975) and Bromley (1978), are very common along certain horizons. The hardgrounds...
4 Facies analysis of the lowermost horizons of the Hallstatt Limestones

The lowermost horizons of the Hallstatt Limestones of Theokafta represent typical hiatus beds/concretions sensu Wetzel and Allia (2000), characterized by discontinuous sedimentation and erosion (Fig. 11). They consist of red ammonoid-bearing hemipelagic limestones with calcium carbonate nodules floating in an Fe-oxides enriched matrix with dispersed lensoid/prismatic calcium carbonate crystals.

Starting from the contact with the underlying ker-
tophyric tuffs and towards the top, the following nine lithostratigraphic horizons appear (A/A, A1, A2/1a, A2/1b, A2/2, A2/3, A2/4, A3/1, A3/2), and include radiolarian packstones, volcanioclastic facies, packstones/floatstones with ammonoids and lag deposits:

Strat. Unit A/A: The lowermost carbonate horizon which overlies the basal volcanic rock (keratophytic tuffs).

Facies: Radiolarian packstones (Fig. 12A).

Microcomponents: Radiolarians (micritized and calcified), benthic foraminifera, ostracods and molluscs.

Texture: Nodular. Nodules are surrounded by a blackened rim enriched in Fe-oxides. Dissolution surfaces, along the contacts of coalescing nodules, are marked by Fe-oxide microstylolites. (Fig. 12B).

Interpretation: Limestones with autochthonous hemipelagic faunal elements (radiolarians) and allochthonous reeal detritus (foraminifera, ostracods).

Lithologic Unit A: It comprises the layers A1 and A2 and averages 3–4 cm in thickness.

A1

Strat. Unit: Volcaniclastic horizon (averaging 4–5 cm in thickness), consisting of fragments of macrofauna and reworked, fine-grained, volcanic keratophytic material. It is characterized as “mylonite” due to its friable character, which lies between the keratophytic tuffs and the overlying Hallstatt Limestones and marks the start of carbonate sedimentation. It consists of relic crystals of feldspars (plagioclase), quartz and mafic minerals, as well as lithoclasts (lag deposit). All components are derived from the underlying keratophytic tuffs and are gradually assimilated by a ferruginous micritic and/or crystalline matrix consisting of dispersed lensoid/prismatic calcite crystals (Figs. 12C, 13A). Calcium carbonate nodules occur in places, and are assimilated as well by the same matrix (Fig. 12D), including plagioclase, quartz, mafic minerals (kerostilb and rarely biotite) and angular to subrounded lithoclasts of variable size, gradually decreasing upward. Plagioclase crystals are medium basic (andesine) and quartz crystals show magmatic erosion. All components have been derived from the underlying volcanic rock (keratophytic tuff) and are cemented by and intensively impregnated by Fe- and Mn-oxides as well as matrix that gradually assimilates them.

Upper part: Start of Hallstatt sedimentation. Red coloured limestones.

Facies: Packstones/floatstones with ammonoids (Fig. 13D).

Microcomponents: Radiolarians, benthic foraminifera (Arenovidalina chialingchiangensis HO and Nodosariidae), molluscs, brachiopods, ostracods, echinoderms and gastropods.

Texture: Nodular in places. Lime nules are surrounded by a matrix enriched in Fe- and Mn-oxides. Bioclasts show evidence of boring and are coated by Fe-oxide rims. Biomolds are filled with geopetal fill (pelmicrite/sparitic cement).

Interpretation: Strongly condensed sediments due to low rate of sedimentation. Limestones with autochthonous hemipelagic bioclasts (ammonoids, radiolarians, filaments) and allochthonous reeal detritus (benthic foraminifera, ostracods, gastropods). Oxygen-rich bottom water.

Age: Ammonoids of the species Megaphyllites chiosensis FASTINI-SESTINI are recorded for the first time in the study area. Fastini-Sestini (1981) recorded the above species in Chios and defined it as Aegean in age (lower Anisian). Assereto (1974) referred to beds with Megaphyllites evolutus WELTER of lower Aegean age, whereas Bender (1970) considers them as Lower Anisian. In the study area these beds are considered to be lower Anisian, and possibly upper Skythian (Tselepidis et al., 1989).

A2/1b

Strat. Unit: Hallstatt horizon averaging 5 cm in thickness. It consists of a brownish-reddish limestone that has developed on an irregular, eroded surface.

Facies: Red packstones/floatstones with ammonoids (Fig. 14A).

Microcomponents: Gastropods, molluscs, echinoderms, ostracods, radiolarians and benthic foraminifera.

Texture: Bioclasts are dissolved, and biomolds are filled geopetally. Abundant relic crystals of quartz, plagioclase and mafic minerals (kerostilb) and a few lithoclasts; all components are derived from the underlying keratophytic tuff. Discontinuities are marked by Fe-oxides and have a tendency to form immature hardgrounds. Nodules
are rare in this facies.

**Interpretation:** Strongly condensed sediments due to low rate of sedimentation. Limestones with autochthonous hemipelagic bioclasts (ammonoids, radiolarians, filaments) and allochthonous reefal detritus (benthic foraminifera, ostracods, gastropods). Oxygen-rich bottom water.

**Age:** Fauna includes the species *Leiophyllites confucii* (DIENER) and *Leiophyllites suessi* (MOJSISOVICS), in association with *Procladiscites cf. brancoi* MOJSISOVICS, *Procladiscites sp.*, *Beyrichites*, *Ptychites* and *Discoptychites*. The association of *L. confucii* and the genus *Procladiscites*, according to Assereto et al. (1980), suggests a lower Anisian age (Ageean). This age has been attributed to similar layers of Chios.

The age of lower Anisian is supported by the presence of the foraminifera *Tolypanmina gregaria* and Duostomminidae, which appear for the first time in this layer at Argolis, in the study section of Theocafta.

An analogous age (Ageean–Bithinian) is attributed by Krystyn (1975) to layers with *L. confucii* and *Procladiscites*, which are referred as the lowest horizon of the “Hallstatt” facies. Later on, Krystyn (1983) confines the age of this horizon to the Bithynian, in the Biozone *ismidicus* (upper Bithynian), which is considered as the oldest biozone of the Hallstatt facies.

However, from the lowest layers of the Hallstatt facies in Theocafta, among others, the species *M. chiosensis* have been determined, suggesting that the base of this horizon should have an older age and it be included in the Biozone *osmani* (lower Bithynian), and may be even older. In conclusion, in the lowest 15 cm of the section, the Biozones *osmani* (A1) and *ismidicus* (A2) appear, followed by the development of a hardground surface.

**A2/2**

**Strat. Unit:** Hallstatt horizon

**Lower part:**

**Facies:** Packstones/floatstones with ammonoids, rich in ammonoids (lower 5 cm, in thickness). Towards the top they are in contact with wackestones–packstones with calcified radiolarians occur (Figs. 15B, 15C).

**Microcomponents:** Molluscs, echinoderms, gastropods, ostracods, filaments, and foraminifera.

**Age:** According to Pelosio (1973), identified species are predominantly those of the family Ptychitidae (more than 70%): *Ptychites stolicskai* MOJSISOVICS, *P. canavarii* MARTELLI, *P. oppeli* MOJSISOVICS, *Flexoptychites flexuosus* (MOJSISOVICS), *F. cf. studeri* (HAUER), *F. cf. gibbus* (BENECKE), *Discoptychites sp.* “*Paraceratites*” *trinodusus* (MOJSISOVICS), “*P. elegans*” (MOJSISOVICS), “*Paraceratites*” sp. *Semiornites* sp., *Monophyllites sphaerophyllus* (HAUER), *Megaphyllites sandalinus* MOJ-
Gymnites obliquus (BEYRICH), Proarcestes escheri (MOJSISOVICS).

According to Mojsisovics (1882), Arthaber (1914), Jacobshagen (1967), Pelosio (1973) and Assereto (1974), the species Paraceratites is confined to this horizon and in association with species from the family Ptychitidae and the species Semiornites coincide with the Biozone trinodosus (Illyrian).

Microfauna are similar to that of the previous horizon, except for the observed decrease of A. chialingchiangensis HO and extinction of M. insolita (HO), which favours an Illyrian age.

A zone of condensed fauna, referred to as the balatonicus–trinodosus zone, developed in Epidaurus above the ismidicus zone, and is considered to be Pelsonian–Illyrian in age (Krystyn, 1983).

The above data show that although sedimentation was very condensed, condensation did not reach the level of mixed fauna, and for that reason it is possible to differentiate several biozones.

**Upper part:** Thickness about 3 cm.

**Facies:** Comprised of small clasts of volcanic origin (plagioclase, titanomagnetite, lithoclasts) and a few bioclasts. Clasts of volcanic origin are arranged parallel to each other.

**Lithologic unit B:** Includes layers A3 and A4, which correspond to the characteristic reddish-brownish, nodular limestones of the Hallstatt facies, with the unique occurrence of macrofauna and averages 1 m in thickness (Fig. 11). These layers are rich in Fe- and Mn-oxides that mark hardground horizons.

**A3**

**A3/1**

**Strat. unit:** Hallstatt horizon. Homogeneous, massive limestone characterized by brownish-reddish colour, averaging 1 m in thickness.

**Facies:** Packstones/floatstones with ammonoids (Fig. 15).

**Microcomponents:** Molluscs, gastropods, echinoderms, ostracods, radiolarians, filaments and foraminifera.

**Texture:** Condensed sediments. Discontinuities are marked by Fe-oxides and correspond to immature hardgrounds (firmgrounds). Glauconite has been observed to fill cavities along hardgrounds. Several microstylolites transect the matrix, resulting in a nodular texture.

**Interpretation:** Limestones with autochthonous hemipelagic faunal elements (ammonoids) and allochthonous reefal detritus (foraminifera, ostracods, gastropods).

**Age:** The lower part of this layer is poor in macrofauna, whereas within the upper part a characteristic fauna has been detected including Parakellnerites sp., Ptychites cf. oppeli MOJSISOVICS, Proarcestes sp. and Procladisites sp., which taking into consideration the conodonts microfauna included, as well, corresponds to the Biozone Parakellnerites (Krystyn and Mariolakos, 1975; Krystyn, 1983). The Biozone Parakellnerites follows the Biozone trinodosus, both corresponding to Illyrian, however, due to the lack of characteristic fauna, in-between these horizons, the boundary was not determined.

**A3/2**

**Strat. Unit:** Hallstatt horizon, averaging 25 cm in thickness.

**Facies:** Packstones/floatstones rich in ammonoids with a parallel orientation, enriched in Fe-oxides, and containing dissolution seams. Ammonoids molds are filled with geopetal fill.

**Microcomponents:** Echinoderms, molluscs, gastropods and foraminifera (To lymphaminina gregaria WENDT, Arenovidalina chialingchiangensis HO, Duostomiidae, Ataxophragmiidae and Nodosariidae).

**Texture:** Ammonoids with a parallel orientation.

**Interpretation:** Limestones with autochthonous hemipelagic faunal elements (ammonoids) and allochthonous reefal detritus (foraminifera, gastropods).

**Age:** Ammonoids include Nevadites humboldtensis SMITH, Proarcestes bramandei (MOJSISOVICS), P. esminensis (MOJSISOVICS), P. subtridenticus (MOJSISOVICS), Sturia semiarata MOJSISOVICS and the genera Anolcites, Protrachyceras, which characterize the Biozone reitzi (Nevadites). Concerning the stratigraphic position of the zone reitzi (Nevadites), Krystyn and Mariolakos (1975) and Brack and Rieber (1986) considered it to coincide with the Illyrian (Anisian), whereas Rieber (1973) and Krystyn (1983), considered it to be Fassanian (Ladinian).

In Theokafta, the Biozone Nevadites is situated on the Biozone Parakellnerites and coincides with the extinction of Ptychites and Paraceratites and the first appearance of Trachyceratidae and the genus Anolcites, as well as the genus and species Sturia semiarata and Monophyllites wengensis. According to these data, a Fassanian (Lower Ladinian) age is attributed to this horizon.

## 5 Biostratigraphy

Detailed study of the ammonoid fauna from the lowest horizons of the studied sequence in Theokafta (Epidaurus) revealed 35 genera, including five that are reported for the first time and 94 species, of which 23 are referred to as
new species. The following stratigraphic units have been distinguished (Fig. 16).

5.1 Anisian

The lowest members of the study section are attributed to the Anisian (average thickness about 1.45 m). In this interval the following stratigraphic subdivisions are distinguished, from the oldest to youngest (Fig. 16):

Aegaeian

The Aegaeian is determined by the species *Japonites* sp., *Megaphyllites* sp., *Proarcestes* n. sp. and *Ptychites oppeli*, which characterizes the Biozone *Japonites/Paracrochordiceras* or the Biozone “*Aegeliceras*” *ugra* of Chios island, that was previously determined in Theokafka. The uppermost biozone includes the new species *Proarcestes jacobshageni*, representing its appearance in Aegaeian. The identification of this stratigraphic subdivision demonstrates an age of the keratophyric tuffs as Lower Anisian (Scythian or even older).

Bithynian

The Bithynian includes the Biozones *Hollandites* and *Procladiscites/Leiophyllites*, which are very rich in fauna content (70% of the total fauna).

Biozone *Hollandites*: The Biozone *Hollandites* is determined by the presence of the genus *Hollandites*, which is accompanied by the new genera *Reflingtites*, *Proarcestes*—
Fig. 13  A–Carbonate nodules (arrow a) and relic crystals of plagioclase (arrow b), floating in a ferruginous matrix with dispersed pyrite (Layer A1), 1.6X; B–Carbonate nodule (arrow a), partially assimilated by a “mylonitic-like matrix” enriched in Fe-oxides, consisting of relic crystals of quartz and feldspa (Layer A1), 1.6X; C–Contact of the volcaniclastic facies (arrow), with the overlying Hallstatt facies, delineated by circumgranular cracking and Fe-oxides rims (Layer A2/1a, lower part), 1.6X; D–Packstones/floatstones with radiolarians, molluscs (arrow a), brachiopods (arrow b), ostracods, echinoderms, gastropods (arrow c), as well as benthic foraminifera represented by Arenoidalina chialingchiangensis HO and Nodosariidae. Meniscus cements commonly developed under bioclasts (Layer A2/1a, upper part), 1.6X.

tes, Judicarites, Danubites and Megaphyllites, as well as Sturia cf. mohamedi and Ptychites oppeli. This biozone occupies the lower part of layer A2/1b and corresponds to the lower part of the osmani biozone of the Bithynia area in Asia Minor. Instead, the Biozone Procladiscites/Leiophyllites is more appropriate the upper part of this layer, which is rich in fauna including the species Leiophyllites suessi and Leiophyllites confucii, along with the accompanied fauna Proarcestes cf. svbtridentinus, being equivalent to the remained upper part of the subzone osmani and the subzone ismidicus of Bithynia.

Pelsonian

The Pelsonian comprises the biozones Balatonites and zoldianus.

Biozone Balatonites: The biozone Balatonites is characterized by the presence of the genus Balatonites and the accompanying fauna Ptychites oppeli, P. opulentus, Flexoptychites acutus, Schreyerites ragazzenii and Reinflingites sp., which most probably corresponds to the subzone balatonicus.

Biozone zoldianus: The biozone zoldianus is characterized by the species Bulogites zoldianus and the same accompanying fauna as in the biozone Balatonites, as well as Paraceratites aff. trinodosus, Megaphyllites sandalinus, Ptychites seebachii, P. progressus, Flexoptychites flexuosus, F. gibbus, Psilosturia sp., Epigymnites incultus and
Fotini A. Pomoni and Vassilis Tselepidis: Lithofacies palaeogeography and biostratigraphy of the lowermost horizons of the Middle Triassic Hallstatt Limestones (Argolis Peninsula, Greece)

Danubites sp. The biozone zoldianus that has been recognized for first time at Theokafta, and is considered to be equivalent to the homonymous subzone of Vörös (1987, 1993) in the Balaton area of Hungary.

Illyrian

In the Illyrian, three biozones have been distinguished, namely the Biozone trinodosus, the Biozone Parakellneritates/Reitziites and the Biozone Nevadites. Krystyn (1983) suggested that the Biozone Nevadites, recorded in the Hallstatt facies, should be included in the Fassanian (Ladinian), instead of the Illyrian (Anisian), as previously was mentioned. However, the Nevadites biozone is recently considered Anisian because the Anisian/Ladinian boundary has been officially set higher (Brack et al., 2005).

Biozone trinodosus: The Biozone trinodosus is rich in fauna, mainly characteristic genera and species of the Ptychitidae family (80%), represented by the genera Ptychites, Discopychites, Flexoptychites and for first time in Argolis the genus Aristopychites. Additionally, new genera and species appear in this biozone which is characterized as a stable biozone in the alpine system, including: Sageceras walteri, Norites gondola, Bulogites cf. gosaviensis, Philippites erasmi, Lardaroceras krystyni, Lardaro- ceras sp. cf. Lardaro- ceras sp. ind. BALINI, Lardaro- ceras sp., Judicarites euryomphalus, J. arietiformis, Proarcestes bramantei, Proarcestes aff. obonii, Flexoptychites angus-

Fig. 14  A—Packstone/floatstone with ammonoids, associated with gastropods (arrow a), molluscs, echinoderms, ostracods, radiolarians (arrow b) and benthic foraminifera debris (Layer A2/1b), 1.6X; B—Packstones/floatstones characterized by a microbrecciated texture and composed of bioclasts (gastropod, arrow), feldspars and quartz crystals, in places intensively impregnated with Fe- and Mn-oxides. All components float in micritic matrix (Layer A2/2, lower part), 1.6X; C—Packstone/Floatstone with ammonoids, associated with echinoderms (arrow a), gastropods (arrow c), molluscs (arrow b) and ostracods and benthic foraminifera. Note the mollusc attacked by microborers (upper right) (Layer A2/2, upper part), 1.6X; D—Packstone/Floatstone with ammonoids, associated with benthic foraminifera (arrow a), echinoderms, gastropods, molluscs (arrow b) and ostracods (Layer A2/2, upper part), 1.6X.
to-umbilicatus, Flexoptychites studeri, Ptychites uhligi, P. breunigi, P. stoliczkai, Discopychites suttneri, D. pauli, D. domatus, D. megalodiscus, Aristopychites sp., Paraceratites cf. elegans, Epigymnites obliquus,? Anagymnites sp. In addition the following taxa have been recognized: Damabites sp., Judicarites meneghinii, Ptychites oppeli, P. opulentus, P. progressus, P. seebachii, Flexoptychites flexuosus, F. acutus, Sturia sansovinii, Psilosturia sp., Epigymnites inculitus, Proarcestes esinensis, P. jacobshageni, Megaphyllites sandalinus, Monophyllites sphaerophyllus and Leiophyllites confucii.

Biozone Parakellnerites/Reitziites: The Biozone Parakellnerites/Reitziites is unified, due to the short extent of appearance of the characteristic taxa from both biozones. In the layer that is situated in an height of 1.25 m within this biozone, the characteristic genus Parakellnerites occurs, represented by different species but mainly by Parakellnerites cf. zoniaensis; the accompanying fauna is represented by the new species Paraceratites cf. subnodosus, Nevadites sp. 1, Proarcestes extralabiatus, Sturia semiarata, while the occurrence of Flexoptychites flexuosus continues. At 1.35 m above the base, the genus Reitziites
appears for first time (Brack and Rieber, 1993). Additionally, the new species *Reitziites* n. sp. is detected in the uppermost layers of this biozone, just above the appearance of the genus *Parakellnerites* and the accompanying fauna *Joannites joannis-austriae, Sturia forojuvensis, Epigynites incultus, Procladiscites crassus* and *Monophyllites wengensis*. The genus *Reitziites* is assumed to have developed after the genus *Parakellnerites*. The short distance between the two stratigraphic layers (1.25 m to 1.35 m), where representatives of the two genera occur, complicates their stratigraphic subdivision in the section at Theokafta.

Biozone *Nevadites*: The Biozone *Nevadites* is attributed to the Anisian and specifically constitutes the uppermost biozone of the Anisian before the Ladinian. It consists of three subzones (*crassus, serpianensis, chiesense*), but in the same study is unified and is referred as *Nevadites* (*sensu lato*). In the study section, the Biozone *Nevadites* is recognized in layer A5/1, which is extremely rich in fossils, represented by the species *Nevadites* cf. *crassiornatatus*, *Nevadites* sp., *Sageceras haidingeri, Halilucites* sp.,

![Fig. 16](image-url) The principal stratigraphic subdivisions and the respective biozones of Anisian and Ladinian (Tselepidis, 2007).
5.2 The Anisian/Ladinian boundary

The subdivision of the Hallstatt-type limestones and the determination of the Anisian/Ladinian boundary is determined from data based on the fauna that is present at the Theokafa section/Epidavros and after considering all the scientific data from respective areas of the Tethys.

Since the genus *Nevadites* is attributed to the Anisian and belongs to Ceratitidae or the Aplococeratidae, we suggest that the Anisian/Ladinian boundary should be delineated by the presence of fauna of the family Paraceratidae. According to our observations, the Anisian/Ladinian boundary coincides with the first appearance of representatives of Trachyceratidae, especially of the genus *Eoprotrachyceras* (Subcommission on Triassic Stratigraphy, IUGS).

5.3 Ladinian

In the study section, the Ladinian starts at a height of 1.45 m above the base of the Hallstatt Limestones. A distinctive feature of the Anisian/Ladinian boundary is the formation of layers rich in Fe- and Mn-oxides that commonly infill joints vertical to the stratification. The boundary coincides with the base of the layer rich in ammonoids, layer A5/1, which is principally characterized by the genus *Eoprotrachyceras*.

5.4 Fassanian

The Fassanian comprises the lowermost Ladinian. In terms of the study section, only the Biozone *curionii*, at the lower part of Ladinian, is considered.

Biozone *curionii*: The Biozone *curionii* is characterized by representatives of the family Trachyceratidae, mainly of the genus *Eoprotrachyceras* and the species *Chieseiceras chiesense*, *Eoprotrachyceras* cf. *margaritosum*, *Protrachyceras* sp., *P. gredleri*, *Anolcites aff. julium*, *Megaphyllites jarbas*, etc.

6 Diagenesis

The studied Hallstatt facies corresponds to hiatus beds/concretions characterized by discontinuous sedimentation and erosion. Synsedimentary and early burrowing processes differentiated the primary textural characteristics of the deposited sediments. Multiphase diagenesis occurred not very deep below the sediment surface and includes, boring, encrustation, burial and cementation. Similar multiphase diageneric events have been described by Savrda and Bottjer (1988).

Detailed sedimentological study enabled reconstruction of diageneric events. Some layers or nodules underwent early lithification, preventing rearrangement during burial. In the uncremented beds, the effects of subsequent mechanical and chemical compaction are clearly recognizable. Grain-supported sediments developed fitted fabrics, whereas in mud-supported sediments dissolution seams were generated.

Cement types, all of which are now calcite, include micrite, fibrous and blocky cement. Micrite cement is homogeneous and/or peloidal and occurs between the components of the volcaniclastic substrata (quartz, plagioclase, and mafic minerals crystals; Fig. 12C). Fibrous cement fills voids resulting from dissolution of carbonate hells when exposed to pore fluids. The length of the crystals increases towards the center. The fibrous cement is cloudy and includes fluid inclusions and pyrite grains. Micrite and fibrous cement are usually associated with pyrite. Clear crystals of blocky cement fill the remaining pore space and voids (Fig. 15A). The fact that all cement types contain pyrite, except for the late blocky cement, indicates carbonate precipitation within the sulphate reduction zone.

7 Palaeoenvironment of deposition

The deposition of the red nodular ammonoid-bearing pelagic Hallstatt Limestones of the Argolis Peninsula, upon the carbonate-free volcaniclastic substrata, as hiatus beds/concretions, is considered to be due to anaerobic oxidation of organic matter by microbes, which provided excess alkalinity and induced carbonate precipitation. For the development of such a rich fauna of cephalopods in the Hallstatt Limestones, sunlight is necessary and likely happened on differentially-subsided and intermittently elevated “deep swells” (Hornung and Brandner, 2005; Hornung et al., 2007). After drowning, the sea mounts were covered by pelagic carbonate deposits. Further slight rotation of the blocks along listric faults may have led to additional differential subsidence of the blocks.

In terms of sequence stratigraphy, the studied Hallstatt hiatus concretions and beds are considered genetically linked to rising or high sea-level (e.g., Van Wagoner et
Conclusions

1) The Middle Triassic Hallstatt facies of the Argolis Peninsula consist of hiatus beds/concretions characterized by discontinuous sedimentation and erosion.

2) The contact of the Hallstatt facies with the underlying volcanic rock, as well as with the overlying radiolarians, is stratigraphic.

3) Nine lithostratigraphic horizons have been distinguished, including radiolarian packstones, volcanoclastic facies, packstones/floatstones with ammonoids and lag deposits.

4) Nine distinct ammonoid biozones from the Anisian to Ladinian have been defined by Tselepidis (2007), documenting deposition on Hallstatt deep swells with a low depositional rate for nearly 5 million years (using the timescale of Gradstein et al., 2004). The biozones: Japonites/Paracrochordiceras, Hollandites, Procladiscites/Letophyllites, Balatonites, zoldianus, trinidosus, Reitziites/Parakellnerites and Nevadites are included in the Anisian and the curionii in the Fassanian (lower Ladinian). Although sedimentation was very condensed, it did not reach the level of mixing fauna.

5) Sedimentation rate was very low and facies show evidence of early lithification near the sediment/water interface. Omission surfaces, firmgrounds and mineralized hardgrounds were widespread.

6) Synsedimentary and early burrowing processes differentiate the primary texture characteristics of the deposited sediments. Multiphase diagenesis occurred not very deep below the sediment surface and includes boring and/or encrustation, burial and cementation.

7) Cement types include micrite, botryoidal, fibrous and blocky calcium carbonate cement. The fact that all cement types contain pyrite, except for the late blocky cement, indicates carbonate precipitation within the sulphate reduction zone.

8) The deposition of the Hallstatt Limestones, upon the carbonate-free volcanoclastic substrata, is considered to be due to anaerobic oxidation of organic matter by microbes, which provided excess alkalinity, inducing carbonate precipitation.

9) In terms of sequence stratigraphy, the Hallstatt Limestones, as hiatus beds and concretions, are genetically linked to a rising or high sea-level. They are considered to be formed at the initiation, as well as during the time of maximum rate of transgression, in areas where the sediment input is strongly reduced (“condensed section”).

10) Hallstatt facies were deposited on differentially subsided and intermittently elevated “deep swells”. Further slight rotation of blocks, along listric faults, may lead to additional differential subsidence of the blocks.

11) Shelf bathymetry and third-order sea-level changes may have played a significant role in the formation of the Hallstatt beds.

12) The depositional area of the Hallstatt-type lime-
stones in the Hellenides and generally in the Alpine orogenetic system, was either united or there was a direct and broad communication between different palaeogeographic areas, and is confirmed by the distribution of ammonoids and lithology.

13) Hallstatt Formation deposition occurred between the sub-Pelagonian (western part of the Pelagonian zone) and Pindos geotectonic zones, which during the Triassic corresponded to a platform slope and deep ocean, respectively.

14) The Hallstatt facies of the Argolis Peninsula is considered part of the widespread Middle Triassic Han Bulog Limestones (ammonoid-bearing pelagic limestones) of the Eastern Alps (Dinarides, Hellenides), which may have been formed partly in platform slope environments, similar to those of the Southern Alps.

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