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Palaeoenvironmental interpretation of the structures and textures of the Miocene sediments in the Strymon basin, Northern Greece

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Abstract: *For the purpose of lithological analysis the Miocene sedimentary sequences in the Strymon basin, Northern Greece have been observed and described in detail concluding in subdividing them into a new lithostratigraphic shape . These investigations in this analysis, through the study of data of the sedimentary structures and textures led to the interpretation of the depositional environments in the Miocene basin.*

Keywords: Miocene sediments, Palaeoenvironmental interpretation, sedimentary structures, Strymon basin, Northern Greece

Introduction

The Strymon basin occupies the northern part of Greece where Miocene sedimentary sequences are generally accessible and well exposed. During the field work 22 sedimentological sections were measured (Fig. 1) [2].

The 22 studied sections are geographically distributed mainly in the northwest, southeast and east of the basin. Fourteen of them (1-14) are located in the northern side of the Strymon basin, eight (15-22) - in its southern side to Strymonikos gulf. The first seven (1-7) are located in the northwestern part, near the city of Serres and the remaining seven (8-14) are located in the northeastern part of the basin, near the border with Drama field. They were numbered from west to east, depending on their position in the region and their transfer on the map was made with the help of GPS.

The described sections are as follows: At the northern side, 1. Section Kato Christos, 2. Section Ano Christos, 3. Section Kato Christos-Lefkonas, 4. Section Lefkonas-1, 5. Section Vissiani, 6. Section Lefkonas-

2, 7. Section Perdikari, 8. Section Nea Zichni, 9. Section Tris Ierarches, 10. Section Lefkothea-1, 11. Section Lefkothea-2, 12. Section Palia Lefkothea, 13. Section Kriopigi, 14. Section Alistrati. At the southern side, 15. Section Therma, 16. Section Kastri, 17. Section Strymon-1, 18. Section Kerdylia-2, 19. Section Kerdylia-1, 20. Section Paleokomi, 21. Section Amfipoli, 22. Section Kormista.

In order to elucidate the conditions of sedimentation in the studied area, a detailed lithological description of the rock species by color, structural and textural features, stratification, types of contacts between the sediment bodies (erosion, abrupt or gradual transition) was made.

For the purpose of lithofacial analysis, recorded sedimentological structures of rocks, belonging to the following groups were observed and described in detail (based on the Gradzinski classification etc.) [10]. Furthermore, depositional environments were separated.

Sedimentary structures and textures

The types of structures and textures observed and described in the sediments of the studied sections belong to the following groups:

1. *Depositional structures*

1.1. Parallel bedding

1.2. Cross bedding (planar cross bedding, through cross bedding, wedge shape cross bedding, wavy bedding, ripple marks).

1.3. Flaser bedding

1.4. Graded bedding

2. *Erosional structures* (erosional channels, cut and fill channel-fill)

3. *Deformational structures* (load casts, dykes)

4. *Biogenic structures* (bioturbation, borings, hardground)

Depositional environments

The depositional environments identified in the study area are the following [2]:

1. *Alluvial fans* depositional environment

2. *Fluvial* depositional environment

3. *Lacustrine* depositional environment

4. *Deltaic* depositional environment

5. *Lagoon* depositional environment

6. *Shallow marine (Shelf)* depositional environment

Description of the depositional environments

1. Alluvial fans depositional environment

Alluvial fans are very characteristic of arid and semiarid regions. They have a conical shape and are formed as a result of deposition of terrigenous material in suspension with water at the bottom of the highlands [6]. The formed distinct rock layers are mainly breccias, breccia-conglomerates and conglomerates with lack of internal sedimentary structures. The thickness of the layers ranges from several tens centimeters to several meters, but it is usually hard to distinguish the different layers due to fast deposition [31].

These sediments, which are formed in the environments of alluvial fans, are seen in the first packets of the sections Ano Christos, Lefkonas-1, Vissiani, Perdikari and the whole section of Alistrati. They are very characteristic and with them begins the Neogene sedimentation in the Strymon basin. They are separated in the Lefkonas Formation [26].

The sediments attached to the above mentioned packets of the relevant sections, consist of unsorted poorly cemented breccias with the size of the pieces varying from gravels to up to 1 m thick blocks, from medium to fine-grained unsorted conglomerates, from medium to fine-grained breccia-conglomerates in the form of splice channels lenses and large olisthostroms.

Individual, very coarse terrigenous clasts, are surrounded by abundant matrix, they do not contact each other and lack internal structures and fossils. Normal and reverse gradation is observed. In the lower packets of sections Ano Christos (photo 1, Table I) and Lefkonas-1 (photo 2, Table I) the sediments have conical shape, but in the section of Alistrati debris flows are observed in proximal alluvial fan and also gradation textures, of both reverse gradation and normal and reverse gradation (photos 3,4 &5, Table I). All photos and tables are presented in Supplementary File

2. Fluvial depositional environment

Rivers are the main arteries for the transportation of terrigenous material, as over 90% of terrigenous sediments are formed in marine basins as a result of river transport. The rest is due to wind transport, glaciers and coastal erosion. Rivers as well as being arteries for transporting material, are also systems of Sedimentation, especially their basins.

Deposition of sediments occurs in riverbeds, in distribution channels, in floodplains and river terraces. The grain size of the particles and their textural and structural features are determined by the size of the river, the quantity of material carried by the river current and the seasonal changes in its flow [20].

Figure 1. Simplified geological map of the Strymon basin with measured section location

River or fluvial environments are the best-studied deposition environments because they are directly observed at present time. Fluvial sediments can generally be distinguished in coarse-grained, formed in river channels, cross and fine-grained deposited on floodplains.

River facies associate mainly with continental, deltaic or shallow marine depositional environments. Typical of fluvial environments are the lack of marine fauna, the prevalence of root systems, parts of stems and plant leaves, pollen and rare freshwater molluscs and vertebrates' bones. The most common fossils and their traces remain in flood plains [31].

Sediments formed in fluvial environments are observed in the first packets of the following geological sections: Vissiani, Lefkonas-2, Perdikari, Lefkothea-1, and Kastri from P.6 to P.9. Their textural and structural features are typical of such environments and are released in the Lefkonas and Humniko Formations [26].

The sediments attached to the above packets of the relevant sections, consist of: coarse-grained poorly cemented sandstones and medium-grained breccia-conglomerates with erosional boundary, coarse-grained sands in splice channels (multistory channels-coalescent), traction carpets, in which conglomerate clasts are oriented in one direction, cross bedding, palaeotransport to the west, load casts and trough cross bedding. In these sediments, the layers of medium-grained conglomerates are gravel bars and the splice channels sandstones are sandstones sects, in the Vissiani section, (photos 6,7,8 & 9, Table II).

The sediments consist of poorly cemented unsorted and sorted, medium- to coarse-grained sandstones with layers of thin laminations siltstones and layers of splice channels gravely sandstones, sometimes with coal lenses, medium-grained polymictic (quartz-amfibol-gneiss) breccia-conglomerates and splice channels medium-grained polymictic breccia-conglomerates with trough cross bedding, in section Lefkonas-2 (photos 10, 11, Table II).

The sediments are made up of unsorted, massive medium to coarse-grained sands, separate layers of medium-grained breccia-conglomerates with graded bedding passing in sands which form high consistency psphytic (traction carpet). Trough cross bedding, wedge shape cross bedding, load casts, parallel lamination and wavy bedding are also observed, in section Perdikari (photos 12, 13, 14, 15 & 16, Table II).

The sediments are composed of medium to coarse-grained breccia-conglomerates like channel filling sediments rich of abundant plant detritus, in section Lefkothea-1 (photo 17, Table II).

The sediments are formed by siltstones, medium- to coarse-grained sandstones and gravely sandstones with normal graded bedding. Large scale wedge shape-cross bedding, erosion river valley (incised valley), and erosional boundary are observed as well, in section Kastri (photos 18, 19 & 20, Table II).

3. Lacustrine depositional environment

Lacustrine environments of sedimentation are characteristic of lakes formed in topographic depressions in the ground where there is passing of water mainly from rivers, which loss is due to either the flowing of rivers or evaporation. The balance between water inflow and outflow, as well as evaporation, controls the water level and its chemistry.

Lakes are fresh water, with high water level and low chemistry when there is intense water inflow and the balance is controlled solely by its outflow. In the case of limited water inflow, balance is controlled by the high levels of evaporation, which increases water chemistry and lakes become salted [1].

Lake environments are particularly sensitive to climate change. For lakes located in hot and humid climate and intense water inflow, the formation of marshes with rich vegetation and deposition of peat and coal is characteristic. In lakes formed in arid climate, low water inflow and intense evaporation lead to the

formation of large amount of evaporites. Fossils are one of the most important factors in recognizing ancient lacustrine environments [31].

Freshwater lakes are rich in life, which is represented by poor systematic composition, but with a large amount of copies. This distinguishes them from Coastal-marine environments where biocenoses are of systematically varied composition and with a large amount of copies.

Fauna consists mainly of gastropods, bivalves, ostracoda, arthropods. Algae are an important component of lake biocenoses. These are mainly Charophyta, found in many ancient lake sediments. They cannot live in high salinity, and are therefore a good indicator of freshwater lakes. A good indicator of fresh water is also the presence of some members of algae (Diatomea) [34].

The lacustrine lithofacies are close in size to the sediments deposited in similar bathymetric areas of marine environments. The only infallible criterion by which they can be recognized is fossil recordings. Finding them in association mainly with other continental facies is also a reliable sign of their separation from the marine ones. Sediments formed in freshwater (lacustrine) facies are observed in both sides of the basin and are separated in the formations of Humniko and Kriopigi [26].

In the northern side of the basin they are observed in the following sections: in the upper two packets of Lefkonas-1 section, (photo 21, Table III), an alternation of fine horizontally layered varves with a well-marked parallel lamination, characteristic of a lacustrine environment, is observed along with the presence of Charophyta *Chara sp.*, which indicate fresh water. In section Palia Lefkotea (whole) a notable parallel lamination of sediments is observed (photo 22, Table III). The massive presence of diatoms flora, represented by *g. Aulacoseira*, in this section and in the upper packet of Kriopigi section, confirms the lacustrine environment (photo 23, Table III).

Similar environments, typical of lacustrine facies, are found in some sections of the southern side of the basin. In the Strymon-1 section in packets 1 to 5, the sediments show lacustrine environments, where medium-grained to coarse-grained arcose sands, solidly cemented medium-grained sandstones, layers of medium-grained gravelites, medium-grained mostly quartz conglomerate with half-rounded pieces leaning into channel erosion pockets, were probably formed by rivers flowing into a lake (photos 24 & 25, where Ripple-marks are seen, Table III).

In section Kerdylia-1, ripple marks of the medium-grained to fine-grained sands with an unsorted, embossed, medium-grained, not cemented conglomerate layer (photo 26, Table III), are probably formed by rivers flowing into the lake and the presence of Charophyta (*Chara sp.*) in clay limestone (photo 27) Table III, confirm the same environment.

The sequence of sediments in the sections of Amphipoli (photos 28 & 29, Table III) and Kormista (photos 30&31 Table III) also indicates lacustrine facies, where the same diatom taxon of the *g. Aulacoseira*, characteristic of living freshwater lake environments, is observed.

Sediments attached to the aforementioned sections, (more in sections Palia Lefkothea, Kriopigi, Kormista and less in Amphipoli), consist mainly of a monotonous clay-calk-silty sedimentation which is alternated in places from differently grained thin to medium-thin sandstones, to clay sandstones and sandy clays. Strands of lignite appear in some places.

4. Deltaic depositional environment

Deltas are places of sedimentation, where rivers flow into the sea basin. There the river's velocity decreases rapidly and two different in density and salinity environments collide. This is the place where there is the most intense deposition of sediment material [5, 23, 31].

Deltaic deposits are very thick, often up to 10 km and during the growth of a delta to the sea basin gradation of strata are observed, with the most coarse-grained deposits present in the upper parts of the sections. Such sediments, which are formed in deltaic environment are observed only at the section Lefkothea-2 and are separated in the Humniko formation [26].

These sediments are attached to the first two packets of the relevant section and consist of alternating clays and argillites with overlying channel sands, load casts, parallel bedding and layers of medium to coarse conglomerates and differently grained sandstones which are sandy bars.

There are very well exposed deltaic structures, like large scale planar cross bedding and small scale trough cross bedding in the sediments with layer truncation and sandy dykes. In vertical direction an increase in the size of terrigenous grains which shows coarsening upward, characteristic of deltaic sections, is observed. Parallel bedding and cross bedding are also observed (photos 32, 33, 34 & 35, Table IV).

5. Lagoon depositional environment

These depositional environments are part of sea bays, which are separated from the open sea basin through barrier islands or coral reefs. The sea basin has a decisive influence over them. They are separated from the open sea basins, so that the dynamics of the marine environment is weaker and there are no strong waves.

The deposits are mainly silty and rarely sandy. In some cases, the barrier that separates them from the sea does not allow a connection with the open sea basin and thus isolated lagoons with increased or decreased salinity are formed. At low salinity conditions, their end parts often become marshy and a type of coal is formed, whereas at high salinity conditions evaporites are formed. Fauna in the lagoons is often endemic,

because of the abnormal salinity and is therefore presented with poor systematic composition and a large amount of copies [31].

Such sediments, which are formed in the lagoon environment are observed in the northern side of the basin in the following sections: Kato Christos (the whole section), Ano Christos from p.5 to p.7, Kato Christos-Lefkonas in p.2, Lefkonas-2 in p.2, Perdikari from p.4 to p.12, Nea Zichni and Tris Ierarches in the whole sections and Lefkothea-1 from p.1 to p.5.

These sediments attached to the above packets of the relevant sections consist of: poorcement fine-medium-coarse grained and in places detritus sands, of poorcement to stablycement polymictic medium to coarse thick sandstones, layers and lenses of lignites, sandy organogenic limestones, nodular sandy limestones, detritus limestones, sandy limestones, very thick white limestones, massive solid limestones, clay siltstones, clay sandy siltys, silty clays, poor cement limestone marls, polymictic gravelite layers and medium-coarse conglomerates. All these sediments are separated in the Humniko formation [26].

In the first packet of the Kato Christos section, layers and lenses of coal are found in the sediments, within which sulfate minerals are observed, a fact explained by the formation of generated lagoonal coal-bearing sequences type coal in the lagoon environments at low salinity conditions, as their outskirts become marshy. In the above packets the layers with abundant fauna, which are probably sandy bars in the Coastal zone and designated brackish fauna, indicate low salinity of the water, (photos 36 & 37, Table V).

In the above packets of section Ano Christos (photos 38 & 39, Table V), after the salinity reduction, deposition of nodular limestones containing fauna, the sandstones with gravelite pieces and clay siltstones may have been formed in the lagoon environment.

In section Kato Christos-Lefkonas (photos 40 & 41, Table V), an alternation of fine to medium thickness sandstones with fine to medium-coarse sands with a very distinctive parallel lamination (parallel bedding) and patch reefs built entirely of thick-shelled mollusks are observed. In some places gravelites with well smoothed mainly quartz grains are also observed. The fauna of bivalvia found in them indicates refreshed environment.

These characteristics of the sediments probably show that they were formed in refreshed lagoon environment. In the above packets of section Lefkonas-2, (photos 42 & 43, Table V), the observed sediments of medium-coarse breccias-conglomerates, medium to very coarse thickness sandstones and detritus limestones with very well defined cross bedding, trough cross bedding, and large scale cross bedding structures, along with the found fragments of bryozoa and broken shells of bivalves, probably indicate a refreshed lagoon environment.

In section Perdikari from p.4 to p.12, the observed sediments of very well defined and multiple structures, like parallel lamination, channel filling with breccia-conglomerates, tabular cross bedding, parallel

lamination and load casts, flaser bedding, large scale planar cross bedding, wedge shape cross bedding, bioturbation, debris flow, wavy parallel lamination and load casts, climbing Ripple marks along with the specified mollusk brackish fauna, show their probable formation in a refreshed lagoon environment (photos 44 to 53, Table V).

In sections Nea Zichni and Tris Ierarches, the lithological composition of the sediments and the brackish nature of the found fauna show their probable formation in a refreshed lagoon environment. The lithological composition of the sediments in the section Lefkothea-1, in the first packets p.1 to p.5, and the found oppressed fauna in brackish environment (photo 54, Table V) show probably their formation in a coastal lagoon.

6. *Shallow marine (shelf) depositional environment*

Continental shelves are relatively flat and smooth spaces surrounding continents in their part which is covered by the waters of the sea basins. They may have a width from several up to 300 kilometers and a depth from 0 to 200 m. This area of sedimentation can generally be divided into littoral and neritic zone.

The littoral zone covers the shallowest parts of the sea basin where tidal activity has a decisive impact on sedimentary deposition, whereas when tides are absent - the surf zone is to a depth of 10-20 m. There are varied depositional sediments and they are characterized by very distinct sedimentary structures which allow the segregation of this sub-environment in palaeogeographic reconstructions [31].

The Neritic zone extends from the sea basin to a depth of approximately 20 to 200 m, depending on the size of the shelf area in the various sea basins. It is characterized by the development of organogenic reefs and carbonate platforms and the exceptional variety and richness of flora and fauna [30].

On the continental land side there are lagoons, in which sometimes small isolated reefs (patch reefs) are developed. The skeleton of the reef is composed of colonial corals, bryozoa, thick mussels and other reef-builders.

Such sediments which are formed in the depositional environments of shallow marine (shelf) conditions are observed in the northern and southern side of the basin in the following sections: Ano Christos from p.2 to p.4, Kato Christos-Lefkonas p.1, Vissiani p.2, Perdikari p.3, Therma whole section, Kastri from p.1 to p.5, Strymon-1(whole section), Kerdylia-2 from p.1 to p.2 and Paleokomi (the whole section).

These sediments attached to the above packets of the relevant sections consist mainly of fine-thick, medium and coarse-thick organogenic limestones, as some of them are massive. At one point they form a small isolated reef. These limestones in places become clay limestones with thin to medium layers of polymictic sands, clay sands, calcareous sandstones, silty clays, sandy clays and clay silty and they are separated in the Dafni and Humniko formations [26].

On the north side of the basin in the section Ano Christos from p.2 to p.4, the transgressive limit of the sediments which covers the sediments of p.1, as well as the defined fauna found in them show their formation in the environment of shallow marine shelf (photos 54, 56 & 57, Table VI).

In section Kato Christos-Lefkonas, p.1 (photo 58, Table VI), bioherms (patch reefs), built entirely of thick-shell mussels, which are separated from fine to medium-sands with bivalves and gastropod shells, are indicators of shallow marine (shelf) environment with normal salinity and warm water.

In the one of Vissiani p.2 (photos 59, 60, 61 & 62, Table VI), the observed structures of load casts and wedge shape cross bedding, along with thick-shell undeterminable mussels in the sands and the specified representatives of bivalves and gastropods in organogenic limestones, show probably the formation of these sediments in shallow marine (shelf) environment.

In section Perdikari, p.3 (photo 63, Table VI,) the observed varied systematically in composition macrofauna of colonial corals, echinids, bivalves and gastropods, as well as of typical foraminifera among biotritus fine-sandy limestone, shows an environment with normal salinity, warm water and beach facies.

On the southern side, the same sedimentary environment is repeated in the following sections: Therma the whole section (photo 64, Table VI), where the lithological characteristics of the sediments, along with the specified fauna, show that they may have been formed in shallow marine (shelf) environment with reduced salinity.

In Kastri section p.1 to p.5 (photos 65, 66 & 67, Table VI), where the lithological character of the sediments and the observed textures as hard ground, borings and graded bedding, with normal and reverse gradation and gravel to fine-grained conglomerate pieces of quartz, are typical indications of marine transgression and shallow marine (shelf) environment.

In the one of Strymon-1 p.6 (photo 68, Table VI), very thick organogenic limestones with fragments of molluscs and crinoids show that the sediments were formed probably in shallow marine (shelf) environment with reduced salinity.

Finally, in section Kerdylia-2, coarse-grained sandstones with parallel bedding of p.1, and limestones of p.2 (photo 69, Table VI), with diverse taxonomic composition of macro- and micro-fauna, some members of which are characteristic of beach facies, indicate shallow marine (shelf) environment of formation. In the above packets of the section of p.3 to p.8, fauna is not found, but the mentioned brackish fauna gives grounds to assume that the sediments were deposited in an environment with reduced salinity [32].

In the section of Paleokomi, the lithological character of the sediments with a characteristic fauna shows probably shallow marine (shelf) environment of formation with mild refresh of marine waters.

Conclusion

During the elaboration of this work, the Miocene sedimentary sequences in the Strymon basin are studied by 22 geological sections and they are formally subdivided into four formations in ascending order: Lefkonas Formation, Dafni Formation, Houmnikon Formation and Kriopigi Formation [26].

For the first time these 22 studied sections in the Strymon basin are described in detail, with 17 of them being new, 2 supplemented or refined and 3 shown schematically without being described in detail.

The new sections are: Kato Christos, Kato Christos-Lefkonas, Lefkonas-1, Vissiani, Lefkonas-2, Nea Zichni, Lefkothea-1, Lefkothea-2, Palia Lefkothea, Kriopigi, Alistrati, Therma, Kastri, Strymon-1, Kerdylia- 1 Amphipoli and Kormista [2]. The refined sections are Paleokomi and Tris Ierarches [3]. Sections Ano Christos, Perdikari and Kerdylia-2 are given schematically by Karistineos, [14] and Syrides, [32].

In conclusion, they are separated in continental, transitional and shallow marine (shelf) environments of deposition based on the characteristics of the observed sedimentary structures and textures and the interpretation of the fossils found and identified in their habitat.

The sedimentological character of the Lefkonas Formation given above supports its alluvial fan and fluvial origin.

The Dafni Formation represents shallow marine deposits which indicate the first Miocene transgression in the Strymon basin.

The sedimentation of the Houmnikon Formation is more complex. The brackish paleoenvironments are realized in small deltas, low salinity lagoons, lakes and rivers in the upper part of the succession.

Finally, the Kriopigi Formation sediments are deposited in lacustrine environments.

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