Clastic depositional environments in the area of Kassandra-Thermaikos Gulf, northern Greece

By

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Contents

1. Abstract

This study is interrelated with the previous sedimentary facies and facies associations research in the Kassandra Peninsula of the Western Greece. The procedure of facies analysis pitches in to define a reviewed geological and stratigraphic model, spot coal formations and coalification structures across the Kassandra Peninsula region.

The re-examination of four drilled cores (Kassandra 2 uncored, Kassandra 3 cored, Kassandra 3 uncored and Kassandra 4 cored drilling) revealed eight sedimentary facies that were identified and grouped in six facies associations. In this way, the feasibility of studying the evolution of a fluvio-deltaic system with tidal influences, and sporadically swampy conditions, was achieved.

In addition, a stratigraphic correlation has been established across the successions, in the attempt to feature the geological setting of the region.

Περίληψη

Η παρούσα μελέτη σχετίζεται με τις προηγούμενες μελέτες ανάλυσης ιζηματογενών λεκανών ως προς τα ιζηματογενή πετρώματα και τα περιβάλλοντα σχηματισμού τους, στη χερσόνησο της Κασσάνδρας, στη Δυτική Ελλάδα. Η διαδικασία αυτή, της ανάλυσης ιζηματογενών λεκανών έχει στόχο τον καθορισμό ενός αναθεωρημένου γεωλογικού και στρωματογραφικού μοντέλου, τον

εντοπισμό σχηματισμών άνθρακα και δομών ενανθράκωσης σε όλη την περιοχή της χερσονήσου της Κασσάνδρας.

Κατά την επανεξέταση τεσσάρων πυρήνων γεωτρήσεων (Κασσάνδρα 2 χωρίς πυρήνα, Κασσάνδρα 3 χωρίς πυρήνα, Κασσάνδρα 3 με πυρήνα και Κασσάνδρα 4 με πυρήνα) εντοπίστηκαν οκτώ ιζηματογενείς φάσεις πετρωμάτων και ομαδοποιήθηκαν σε έξι φασικούς συσχετισμούς – περιβάλλοντα σχηματισμού των πετρωμάτων. Με αυτόν τον τρόπο, έγινε δυνατή η μελέτη της εξέλιξης ενός ποταμο-δελταϊκού συστήματος με παλιρροϊκές επιρροές, και κατά διαστήματα ελώδεις συνθήκες.

Επιπλέον, διαπιστώθηκε η στρωματογραφική συσχέτιση μεταξύ των ακολουθιών, στην προσπάθεια να διερευνηθεί ο γεωλογικός χαρακτήρας της περιοχής.

2. Introduction

As for the scientific examination records of delta environments, there is plenty information but still many cases are not satisfactory analyzed. The tidal mechanisms have been extensively examined for the influence they have in both past and present development of the deltaic depositional environments, by model demonstration (e.g., Nio and Yang, 1991; Willis, 2005; Martinius and Van den Berg, 2011; Longhitano et al., 2012; Plink Björklund, 2012). Tidally - influenced deposits can be interpreted either as regressive or transgressive tidally- influenced deltaic systems (Martinius et al. 2001; Boyd et al. 2016). Unfortunately, the discussion about tidally - influenced, regressive deltas has not received the proper attention and scientific examination in contrary to the transgressive, tidally - influenced deltaic systems (Legler et al. 2013). However, some distinguished studies provide significant insights about their development (e.g., Willis et al., 1999; Mellere and Steel, 2000; Willis and Gabel, 2001; Pontèn and Plink Björklund, 2007; Tänavsuu-Milkeviciene and Plink Björklund, 2009). Even if the sedimentological clues and facies analysis are liable, it cannot be certain that the interpretation of the depositional setting is always apparent. There is some limited notable research, which focuses on delta plain deposits in contrary with examinations of delta front environments (e.g., Willis and Gabel, 2003; Rebata et al., 2006; Pontèn and Plink Björklund, 2007). Also, in the prehistoric archive (Mellere and Steel, 1995; Bhattacharya and Willis, 2001; Martinius et al., 2001; Willis, 2005; Pontèn and Plink Björklund, 2009), tidally - influenced or dominated deltaic systems are still extensively unrecognized (Plink Björklund, 2012). As a conclusion, models about delta plain development and tidally - influenced or dominated deltaic systems are required, due to their scientific examination deficiency.

From an economic point of view, deltas are known as gas, oil and coal tanks (Tyler and Finley, 1991; Bhattacharya, 2006). Delta settings reserve a huge percentage of the global hydrocarbon resources (Tyler and Finley, 1991; Bhattacharya, 2006). During the Devonian period, the land was boosted with practically non-biodegradable organic matter, due to the significant growth of plants at the time (Berner, 2003). Furthermore, the burial of the organic matter followed and caused the creation of huge coal-prone sedimentary basins (Berner, 2003). Such coal-bearing sedimentary basins can be found all over the world (Bestougeff, 1980). To provide more information and assist for the exploitation of the hydrocarbon resources, valid litho-stratigraphic correlations, and precise information on the spatial distribution of these resources in the deltaic depositional environments, are important. This is a reason why facies analysis and sequence stratigraphy of coal-prone deltaic deposits have been conducted all over the world (Mcllroy et al., 2005; Li et al., 2011; Desjardins et al., 2012; Chen et al., 2014).

This research builds on the previous work of HHRM (Hellenic Hydrocarbon Resources Management) by the re-examination of the sedimentary facies and facies associations of the Kassandra Peninsula by using drill cores of the region, to attempt a more contemporary description of the depositional environment. The purpose of this research is to develop a more probable stratigraphic model for the Eocene to Miocene Kassandra Peninsula Basin (KPB) sedimentary succession, amend existing interpretations of the KPB depositional settings, suggest sub-environments by demonstrating facies analysis, establish more accurate litho-stratigraphic correlations and detect probable coal-prone deltaic deposits in the studied region.

3. Regional geology

Geology of Chalkidiki

From a geotectonical point of view, Chalkidiki is part of the Internal Hellinides (Rodopi and Serbo-Macedonian masses). Three, out of the geotectonic zones of the Greek area can be detected in the area of Chalkidiki (Syrides, 1990).:

1. In the eastern part of Chalkidiki, the Serbo-Macedonian Mass
2. In the central Chalkidiki, the Perirodopic Zone and
3. In the western part, the Paeonian Zone (Syrides, 1990).

In particular, the Peninsula of Kassandra consists of Paionian Zone petrification, as detailed below.

Paionian Zone

The Paionian Zone is the eastern one of the three Zones that Axios Zone has been divided. This Zone contains a significant variety of semi-metamorphic sedimentary rocks (limestones, sandstones, cobblestones, phyllites, mica and calcareous shales, volcanic-sedimentary rocks), which have been deposited in an oceanic groove at the time of Mesozoic era. Also, large units of ophiolite effusions occur within these sediments. The characteristic of the Paionian Zone, is that its petrification appears in the form of large thrust structures, which appear to be cut off from each other, due to the covering of the area with recent sediments (Syrides, 1990).

Geology of the Kassandra Peninsula

The Peninsula of Kassandra is interpreted to be the south – westernmost peninsula of the Chalkidiki Peninsula, which is placed at eastern side of Thermaikos Gulf of Thessaloniki (Kristalina Stoykova, Ivan Zagorchev, Jeanne-Pierre Suc, 2012). Upper Miocene and Pliocene sediments practically constitute the whole Kassandra Peninsula (Kristalina Stoykova, Ivan Zagorchev, Jeanne-Pierre Suc, 2012). The superficial appearance of Mesozoic ophiolites, limestones, flysch, Eocene sandstones and marls with limestone lenses, is scarce and they present exclusively in the southeastern edge of the peninsula (Figure 1). However, the superficial appearance of the peninsula's petrification is generally poor due to the increased agricultural holding of the region (Kristalina Stoykova, Ivan Zagorchev, Jeanne-Pierre Suc, 2012).

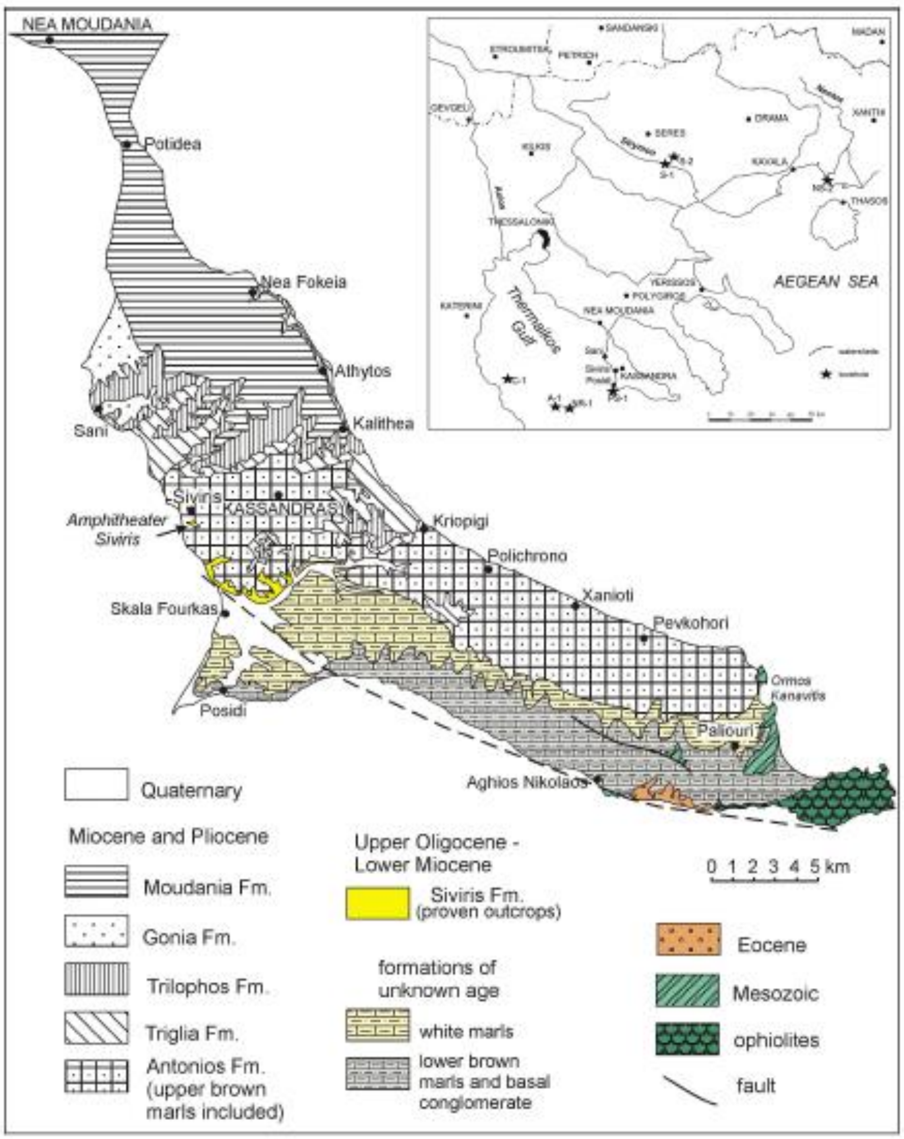

Figure 1: *Geological map of the Kassandra Peninsula (Kristalina Stoykova, Ivan Zagorchev, Jeanne-Pierre Suc, 2012).*

4. Sedimentary facies and facies associations

4.1 Matrix- to clast-supported conglomerate (F1)

Description

F1 units are greyish olive green to dark grey and typically form thick beds (from 3 m in Kass 3* to 155,7 m in Kass 2* / to 56 m in Kass 3 uncored*) consisting of sub-angular to sub-rounded clasts. This facies is usually clast-supported, even though units of matrix-supported conglomerate are also present. The matrix is sand-rich, poorly sorted and moderately- to well- cemented. F1 units are chaotic in fabric and polymictic. They include clasts of diverse lithotypes documenting the relative contribution of the different rock types. In particular, the conglomeratic units include both sedimentary and igneous clasts (sandstone and ophiolite-gabbro composition) (Figure 2). Plagioclases are very large in some igneous clasts, so that they can be identified macroscopically. As for the sandstone clasts, there is a general absence of characteristic structures, such as mud drapes and any type of lamination. F1 units are poorly - sorted gravel, with a granule to pebble range in clast sizes (2-15mm). In Kassandra 4 borehole, this facies is absent.

Interpretation

F1 facies deposits are interpreted as sedimentation in the deepest channels and bedload transportation in high- flow regimes. The strong flow regime has provided sufficient energy to transport gravels but was not powerful enough to completely remove the smaller sand grains of the matrix (Nichols 1999). The sub-angular to sub-rounded clasts do not indicate significant transportation distance of the conglomerates (Nichols 1999).

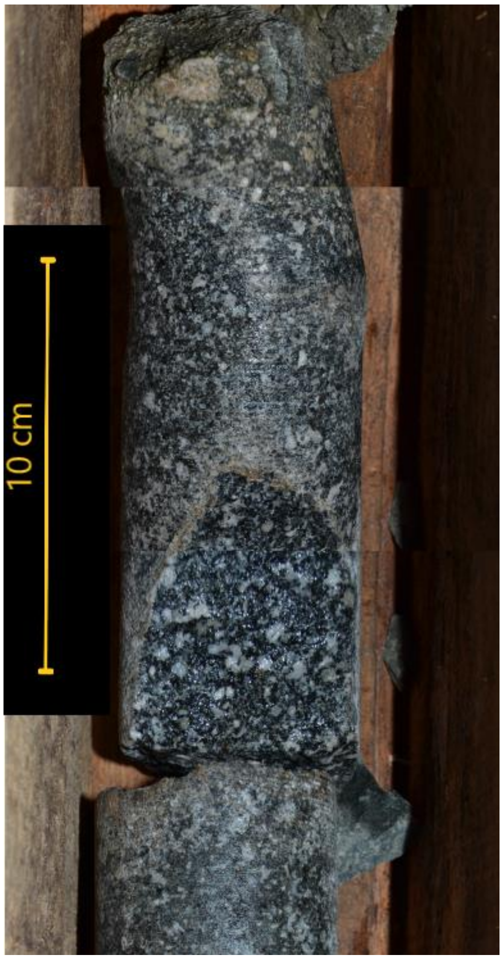

Figure 2: *F1 units. The conglomeratic units include both sedimentary and igneous clasts (sandstone and ophiolite-gabbro composition).*

Figure 3: *F2 units. This facies from small to very thick stacked sandstones and fossils can be found.*

4.2 Structureless sandstone (F2)

Description

F2 is typically grey to yellow- or pale-green- gray in color with fine grained upper sandstone- to medium grained lower sandstone- size of grains (Figure 3). Characteristic structures can be observed in mud rich sandstones, such as mud drapes, coal chips, load and flame structures (Figure 4), dispersed pebbles (Figure 17) and cementations (Figure 11). In addition, fossils can be found, in a fractured and shuttered form. Obscure planar and cross-lamination is occasionally observed. This facies from small to very thick stacked sandstones (from 8 cm to 5 m) are often amalgamated with -mostly- obscure erosional bases or they seldomly come with their mudstone bedcaps. F2 typically overlies and it is under structureless argillaceous sandstone and sandy mudstone and parallel- and cross- laminated sandstone. As for mud prone sandstone, have structureless sandstone and mudstone, parallel- and ripple cross- laminated sandstone and coal above and underneath them. Mud prone sandstone occasionally overlies structureless and/or parallel-laminated mudstone.

Interpretation

F2 is interpreted to be the outcome of quick, high-density flows that lead to the sediment placement at such a high pace, that hydraulic sorting processes did not have the time to create any significant structures (Magalhães et al. 2015). Prolonged suspension of sediment in the midst of high-density flows was due to the combination of hydraulic disruption, buoyant support and pressure created from grain-to-grain collisions (Lowe 1988).

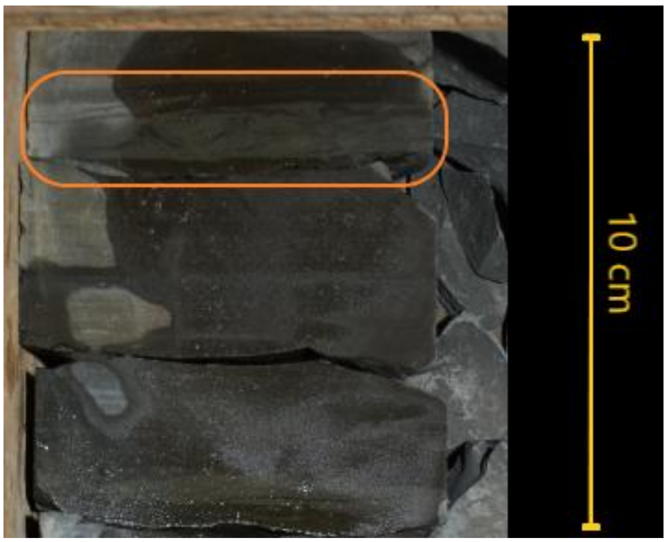

Figure 4*: In F2 units, load and flame structures can be observed.*

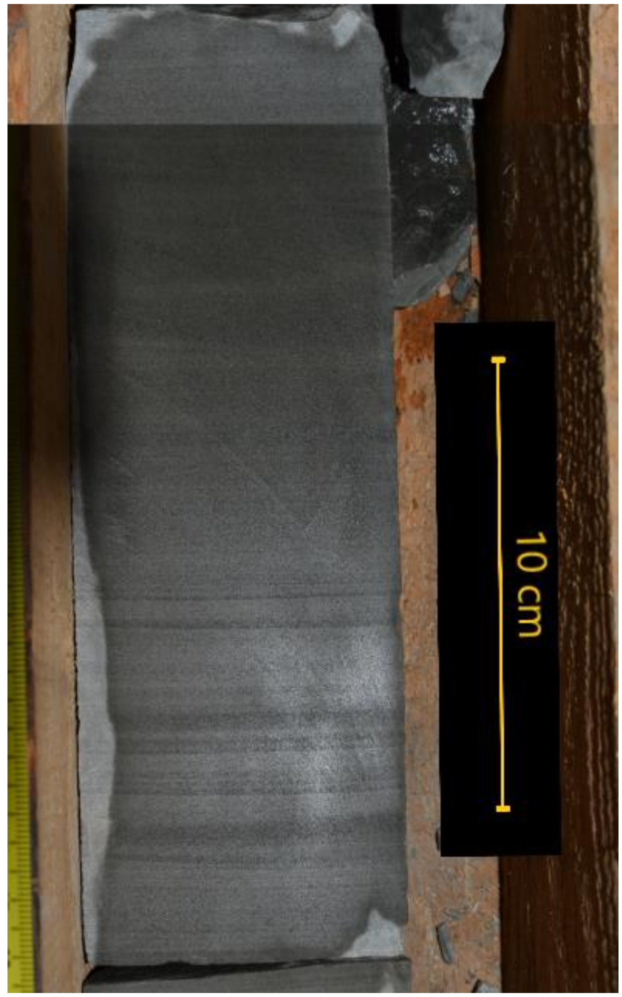

Figure 5: *F3 units present very characteristic structures of mud drapes, which create the planar lamination of the sandstone.*

4.3 Planar laminated sandstone - Horizontal to low-angle sandstone (F3)

Description

F3 units are of minor appearance and when present, are grey to yellow-green and are composed of fine grained upper sandstone- to medium-grained lower sandstone- size of grains. Obscure cross-lamination is occasionally observed. F3 units present very characteristic structures, of mud drapes, which create the planar lamination of the sandstone (Figure 5). No kind of fossils are observed. These units of stacked sandstones are small (3 cm to 20 cm).

Interpretation

Horizontal to low angle-laminated sandstones constitute the characteristic, which indicates sandy, high-energy shallow flows that have been prevented from being reconverted into subcritical bedforms (Langford & Bracken 1987; Todd 1996). The planar bed formation can be interrelated to upper flow regime conditions, where horizontal laminations are created through proximately intense shear stress fields (Best & Bridge 1992). The presence of small-scale mud drapes evinces occasional tidal influence within F3 (Plink-Björklund 2005).

4.4 Ripple high angle cross-laminated sandstone (F4)

Description

F4 units are blue grey in color and consist of medium grained lower sandstone. Mud drapes are common within these facies. Asymmetrical ripples are abundant and are arranged in sets and co-sets (Figure 6). The sandstone beds display generally non-erosional basal contacts with the underlying sediments and come with their mudstone bedcaps. F4 units consist of small to medium (1 cm to 40 cm), normally graded beds.

Figure 6: *F4 units present asymmetrical ripples which are arranged in sets and co-sets.*

Figure 7: *F5 units display irregular, contorted mud prone sandstone structures.*

Interpretation

This facies is interpreted as deposits through migration of argillaceous grains during the lower flow regime conditions, which has formed small-scale ripples (Allen 1983). The combination of asymmetrical current ripples, cross lamination and mud drapes indicate deposition through alternation friction and suspension processes with tidal influence (Miall, 1996). The presence of mud drapes is associated with oscillatory periodic low-flow regimes and tidal incidents, active during the deposition of F4 (Todd 1996).

4.5 Contorted sandstone (F5)

Description

F5 is of minor appearance and when present, are composed of greenish yellow to light grey in color, medium grained lower sandstone. F5 units form small beds, about 15 cm, distinctively display irregular, contorted mud prone sandstone structures (Figure 7), and are typically in contact with rippled, cross and low-angle parallel laminated sandstone. Mud drapes are a very common characteristic in these facies. Small-scale (cm thick) isoclinal folds are common.

Interpretation

This facies designate syn-depositional deformation. Horizontal and vertical shear stress due to bedform collapse and/or water escape during high discharge events, or duo to the combination of both processes, are the cause of small-scale deformation structures (Moretti et al. 2001). The interconnection of asymmetric structures with roughly fast basin settlement rates and sediment agglomeration, could be a possible occurrence (Owen and Moretti, 2011; Owen and Santos, 2014).

4.6 Coal (F6)

Description

F6 is made up of coal beds which small, from 3 cm to 10 cm. Lower and upper bed boundaries are gradational and horizontal. Coal is distinctively dark gray to black and often interbedded with dark-grey mudstone. Also, coal chips and coalification structures can be observed inside argillaceous sandstones (Figure 8), which are placed above and underneath the coal beds. F6 in places exhibits horizontal planar laminations.

Interpretation

Coal is thought to be formed in reducing conditions and low oxygenation levels, in a depositional environment with low sediment supply. The low-energy conditions of this setting enabled the accumulation and compaction of organic material, from which coal is formed (Thomas 2013).

4.7 Structureless massive mudstone (F7)

Description

F7 units vary moderately from grey to yellowish - green in color. This facies is characterized by sand rich mudstones and is scarcely observed with obscure parallel lamination (Figure 9). Bed thicknesses can vary from 3 cm to 1 m. F7 is occasionally interspersed with coal chips.

Interpretation

F7 is considered to be mudstone deposits formed in low-energy conditions. The lack of traction, continuous and steady deposition by suspension fallout, is the reason of the absence of any sedimentary structure and sand-prone material (Bridge 2006).

4.8 Parallel-laminated mudstone (F8)

Description

F8 units are represented by light grey to yellowish green in colour mudstone beds. Beds thickness can range from 5 cm to 10 cm. Horizontal laminations are observed up to 1 mm and they are mostly indiscernible (Figure 10). The F8 units display smooth and planar contacts with both overlying and underlying sandstone. Occasionally, deformation structures can present within this facies, as well as dispersed sand grains.

Figure 8: *Coal is distinctively dark gray to black but is sometimes interlaminated with dark-grey mudstone. Also, coal chips and coalification structures can be observed inside argillaceous sandstones.*

Figure 9: *F7 units are characterized by sand rich mudstones with obscure parallel lamination.*

Interpretation

F8 is interpreted as mudstone deposits that were formed in low-energy suspension sedimentation environment and have been reworked by weak currents, causing the lamination of the mudstones (Ponten & Plink-Björklund 2007).

Figure 10: *F8 units present horizontal laminations.*

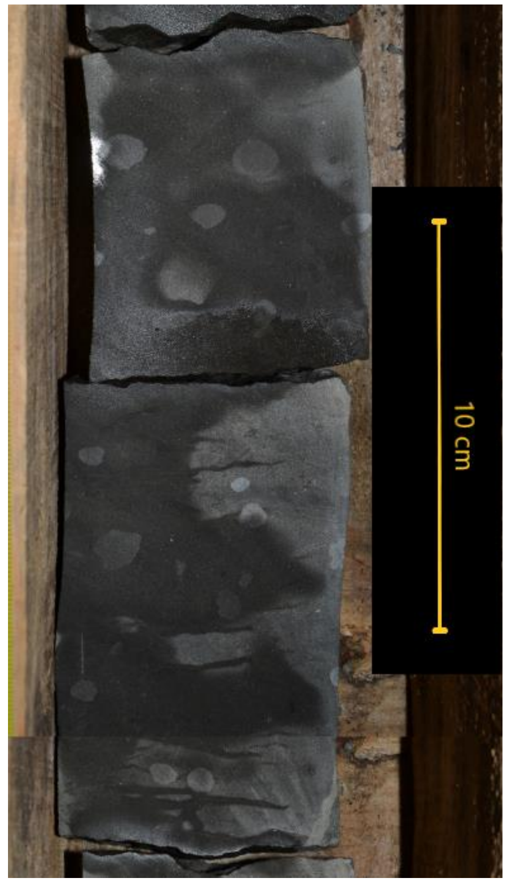

Figure 11: *F2 units present cementation structures.*

5. Facies Associations

5.1 Overbank and floodplain deposits (FA1)

Description

FA1 mostly consists of fine-grained sediment (coal, structureless massive mudstone and parallel-laminated mudstone) (Figure 12). Coal (F6) and massive sand-rich mudstone (F2) are the most plentiful facies. However parallel-laminated mudstone (F8) can also be observed in FA1 and often exhibits mud drapes. Thin-bedded, massive sandstone is not common but still present in FA1 deposits. FA1 deposits form sedimentary sequences that are from 0.1 to 0.9 meters thick and their boundaries with the overlying and underlying facies, present gradational transition. Those deposits are missing from Kassandra 4 cored drilling. FA1 is related to FA4 and FA5 and is sitting stratigraphically below F7 and F8.

Interpretation

This FA1 indicates depositional environments such as overbanks and associated floodplains. The FA1 is characterized as fine-grained, which implies that sedimentation required low-energy conditions (Bridge 2006). The fine-grained sandstone depositions indicate sedimentation of coarser material, due to slightly increased energy from singular events during a waning flow regime (Miall, 1996). The presence of coal seams, implies that some of these depositions were waterlogged palaeosols that have been created in lowland areas in close proximity to the distributary channels (Buatois et al. 2012). Nevertheless, in some cases, FA1 lacks of associated coal seams. The relation of FA1 with higher energy, channelized deposits (FA4 and FA5) further supports the conclusion of an overbank and/or floodplain setting (Hampton & Horton 2007). The lenticular shape of the mudstone bundles points at accumulation in overbank areas or localized lakes. The heterolithic bedding suggests the passage of tidal currents during the sediment deposition (Ponten and Plink-Bjorklund, 2007).

5.2 Delta front deposits (FA2)

Description

FA2 is constituted exclusively of sandstone. In particular, those deposits consist of structureless (Figure 13) and planar laminated sandstone. Those deposits are exceptionally thick, because of the amalgamation of the sandstone units. The bed thickness is ranging approximately from 1 m to 4 m / 100 m (Kass 2*) and internally, the beds display normal grading. FA2 sandstones are mud-prone with inclusions of coalification structures and with a significant number of fossil presence. FA2 commonly underlies prodelta deposits, although scarcely it overlies FA3. Those deposits are absent in Kassandra 3 uncored drilling.

Interpretation

This facies association indicates depositional environments such as the delta front section, of the delta formation. This interpretation is based on clean structureless sandstone, which indicates the absence of tidal influences (Olariu & Bhattacharya 2006). Those thick, uniformly-sorted sandstones are formed because of the continuous deposition of medium to coarse-grained material in a turbulent environment (Myrow & Southard 1991; Ghani & Bhattacharya 2007).

5.3 Prodelta deposits (FA3)

Description

FA3 is not very common, although when present, is characteristically muddier in composition than overlying and underlying facies and is made up of planar laminated, ripple high - angle laminated, structureless sandstone and structureless and parallel laminated mudstone (Figure 14). Beds range in thickness from 0,5 m to 22 m. FA3 deposits are frequently made up of mudstone with dispersed sand grains and mud prone sandstone. Fossils are common in these deposits (Kass 2*). Those deposits are missing from Kassandra 3 uncored drilling.

Figure 12: *FA1 mostly consists of fine-grained sediment (coal, structureless massive mudstone and parallel-laminated mudstone).*

Figure 13: *FA2 is constituted exclusively of sandstone (structureless sandstone).*

Interpretation

FA3 indicates a prodelta environment. The mud-dominated nature of this FA and the presence of dispersed sand grains, which are storm-related characteristic structures suggest deposition in a prodelta environment (Lowe 1976). Suspension of sediment deposition during fair-weather periods can be inferred by the occurrence of mudstone (Buatois et al. 2012).

5.4 Fluvial - dominated channelized deposits (FA4)

Description

FA4 is conglomerate- and sand- dominated and presents a range in thickness, approximately from 2 m to 3 m (Kass 3*) / 125 m (Kass 3 uncored*). These deposits form the basal conglomeratic part (F1) which is getting evolved to a sandier upper part and sometimes is characterised by the absence of muddier fine - grained deposits (F7, F8) (Kass 3*) (Figure 15). The conglomeratic part is consisted of thick beds and clasts of igneous and sedimentary origin can be detected in it. Those clasts range from 2mm to 15mm in diameter. The clasts of the conglomerate – dominated part of FA4, are sub-angular to sub-rounded. These depositions are getting evolved to an upper part, which consists of amalgamated sandstone units and conglomeratic beds that are getting thinner - bedded and show up less frequently compared to their basal equivalents. Between FA1, FA2 depositions and the underlying sediments FA4, usually there is an erosional basal contact.

Figure 14*: FA3 is characteristically muddier in composition than overlying and underlying facies (ripple high - angle laminated sandstone and structureless mudstone).*

Figure 15*: These deposits form the basal conglomeratic part (F1).*

Interpretation

FA4 is construed as braided fluvial channels. The occurrence of conglomeratic beds that usually exhibit erosional contacts with the underlying sediments supports this perception (5th order surface of Miall 1996). The clast-supported conglomerate can be explained as a bedload deposition from river flows (Nemec & Postma 1993). The increase and decrease of the flow energy causes the variance between matrix- and clast-supported conglomerate (Nemec & Steel 1984). Furthermore, the heavily amalgamated nature and the fining- upward trend further support this braided-river origin of the FA1 (Nemec & Postma 1993; Collinson 1996). Overbanks and floodplain deposits (coal and mudstone) are not present in this facies association, which implies that the deposition generated within an active channel (Miall, 1996). The active channel indicates high energy conditions with the presence of both matrix and clast-supported conglomerates being evident along with pebbles being preserved within sandstones, propounding the increase of energy from high to very high (Nichols 2009). The fluvial part of the succession is being relevant to these deposits. The lack of mud-dominated deposits, along with the huge deposits of amalgamated sandstones displays repeated cut-and-fill events and complies with low-sinuosity channels, such as braided type channels (Collinson et al. 2006). The general upward fining trend might be owing to falling flood stage or to the radical abandonment of fluvial channels (Nemec & Steel 1984; Bridge 2006).

5.5 Tidally - influenced channelized deposits (FA5)

Description

FA5 displays a characteristic finning upward trend, as the conglomeratic basal part deposits (F1) seem to get thinner – bedded and show up less frequently, till only sandstone units are present. There is also a small number of mudstone thin – bedded units inserted within sandstones. The sandy units are composed of medium grained lower- to medium grained upper- sandstone. These mud – prone sandstone beds are mostly normally - graded and can sometimes develop reverse-to-normal grading. Those sandstone - prone successions are from 3 cm (Kass 3 cored*) to 9 m (Kass 4*) / 98 m (Kass 2*) thick. Mud drapes, coal chips and generally speaking, coalification structures are very common throughout FA5 (Figure 16), and are preserved within structureless, planar, cross-laminated and contorted sandstone sets (F2, F3, F4 and F5). The difference between FA4 and FA5 is that FA5 almost completely lacks conglomeratic beds. In Kassandra 4 drilling, this facies association displays a fining-upward trend that begins with medium- to thick- bedded, medium grained upper sandstone units (F2, F3 and F4) and develops up-section into thin-bedded, fine grained upper sandstone, which is intercalated with mudstone beds (F7 and F8). Although, the fining – upward trend does not apply to Kassandra 3 cored drilling.

Interpretation

FA deposits indicate channelized deposits in an upper delta plain environment that displays some evidence of tidal currents during sedimentation. These deposits are getting evolved into tidally-influenced channelized deposits in a lower delta plain setting.

This scenario can be confirmed by the following reasons.

(a) The presence of cross laminated sandstones in a significant amount.
(b) The characteristic of the medium grained lower to medium grained upper sandstone transition and
(c) the presence of mud drapes.

Moreover, the absence of marine fossils in Kassandra 3 uncored drilling, displays deposition in a tidally influenced fluvial channel (Allen 1991). The affection by the tidal currents, can be distinguished by the transition of the fluvial channel into a tidally influenced distributary channel (Dalrymple et al. 1992). The presence of contorted sandstone (F5) in Kassandra 4 cored drilling is the result of intense liquefaction and/or fluidization, which causes irregular winding and/or deformed structures, most likely due to overloading or slumping (e.g. (Berra & Felletti 2011). The presence of overbanks and/or floodplains in between of this facies association, can be interpreted as a channelized setting, which is more likely braided and could be formed due to more scarce channel migration and/or abandonment (Nichols & Fisher 2007).

As for the "tidally-influenced channelized deposits in a lower delta plain setting" theory, could be explained by the following knowledges.

(a) The presence of basal erosional contacts in Kassandra 3 uncored drilling.

(b) The presence of tidally - influenced structures such as, planar and cross lamination (Mellere & Steel 1996; Legler et al. 2013).

(c) Fining-upward and thinning-upward trends in all the drillings, except for Kassandra 3 cored drilling (Mellere & Steel 1996; Legler et al. 2013).

(d) The bed - thickness variation of the tidal-characterized sandstone depositions in a cyclic form, indicates the rhythm of neap and water source tides (Visser 1980; Nio & Yang 1991).

(e) The mud drape structures, most likely due to mudstone erosion by the conversed tidal event (Visser 1980). Flow converse can also be explained by the bi-polar ripples, that are present in Kassandra 4 cored drilling.

(f) The overbank and/or floodplain presence in between this facies association suggest a channelized setting and indicate longer and scarcer channel migration and/or abandonment (Nichols & Fisher 2007).

Figure 16: *FA5 deposits. Mud drapes, coal chips and generally speaking, coalification structures are very common throughout FA5, and are preserved within structureless sandstone sets.*

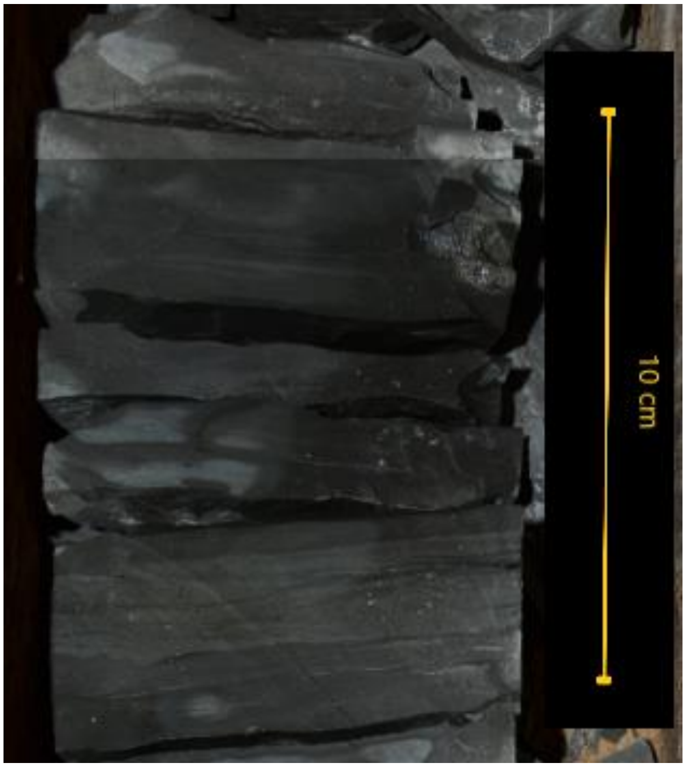

Figure 17: Dispersed pebbles inside structureless sandstone.

5.6 Swamp (coal-prone floodplain deposits) (FA6)

Description

FA6 displays coal and coal-prone deposits (Figure 8), which present a range in thickness from 3 cm to 19 cm (Kass 4*) / 4 m (Kass 3 uncored*). Coal appears as shiny black in color and forms thin beds that horizontally split in slices. Coal beds do not form sharp boundaries with the underlying sediments. Coal deposits are usually detected in between structureless mud-prone sandstone of FA1 and more scarcely they can be noticed above mudstone and/or between conglomerate (F1) that belongs to FA1 and FA3. Only Kassandra 2 uncored drilling lacks coal formations.

Interpretation

The peat mires development requires specific climatic conditions and provision of organic material. A swampy environment can provide humid climate where rainfall overcomes the evaporation procedure and the appropriate conditions that speed up the organic growth (Guion et al. 1995). The thickness of the coal ribbons in Kassandra 3 uncored drilling constitutes sound evidence of stages of peat accretion. In deltaic environments, coal deposits can be created under continuum rising of swamp water level (base level) comparative to the sediment surface that are responsible for the necessary conditions for peat formation (Davies et al. 2006). A similar environment is indicated for these deposits. Their association with delta-plain channelized deposits reflects the lateral migration of the distributary channels that rest on the former, coal-bearing floodplain area.

6. Discussion

Tidally - influenced deltaic setting in a Tertiary succession

The re-examination of the drilling data of the KPB provides an opportunity to demonstrate facies analysis to a significant possible coal-bearing sedimentary basin of Thermaikos. This study also provides the opportunity to examine the evolution of a tidally - influenced transgressive deltaic system in this region. This examination has defined a general trend of an Eocene to Miocene, tidally influenced, transgressive fluvio-deltaic depositional environment across the KPB and a deepening-downward trend. The studied area reflects the Eocene to Miocene evolution of the deltaic system, from a delta front setting to a prodelta environment. Alternatively, the area reflects the Eocene to Miocene cyclic gradual evolution of a floodplain channel into a floodplain valley. The evolution of this system is characterized by a tidal influence that wanes progressively up-section as the fluvial influence gradually increases. The action of waves remains a secondary influence to the tidal-fluvial energy balance throughout the system.

The tidal influence in this succession can be noticed by the characteristic mud drape structures, bi- directional ripple – cross lamination, dispersed pebbles and shattered fossils. These tidally-influenced structures are evident in gradually decreasing proportions from the stacked sedimentary packages to the top of the delta plain environment, with scarce tidal influence in fluvial sediments.

Prodelta environments show influence of tidal structures in the form of mud drapes. Down-section, delta front setting is distinctive due to its constitution of thick structureless sandstone deposits, but still presents strong proof of tidal influence. In particular, delta front deposits present scarce cross-lamination with mudstone interferences and shattered fossils. Amalgamation surfaces are abundant in delta front environment.

This higher degree of fluvial action as the dominant physical process on the basis of the delta front environment, and of the overlying channelized fluvial successions. Conglomeratic deposits present in channels of the upper delta plain and they demonstrate a tidally-influenced fluvial environment.

There is a cyclic tidal-influence activity in the succession. In the delta plain environment, tidal influence overcomes the energy of the fluvial setting. Also, the increase of fluvial processes is obvious by the restriction of tidally-influenced sedimentary structures in previously mentioned deposits that are interrupted by thick, fluvially-prevailed beds (Kassandra 2,3 uncored drilling).

Swampy conditions intercalate the previously mentioned depositions and indicate low energy environments, advantageous for coal formation. Swamp depositions usually present in between prodelta deposits.

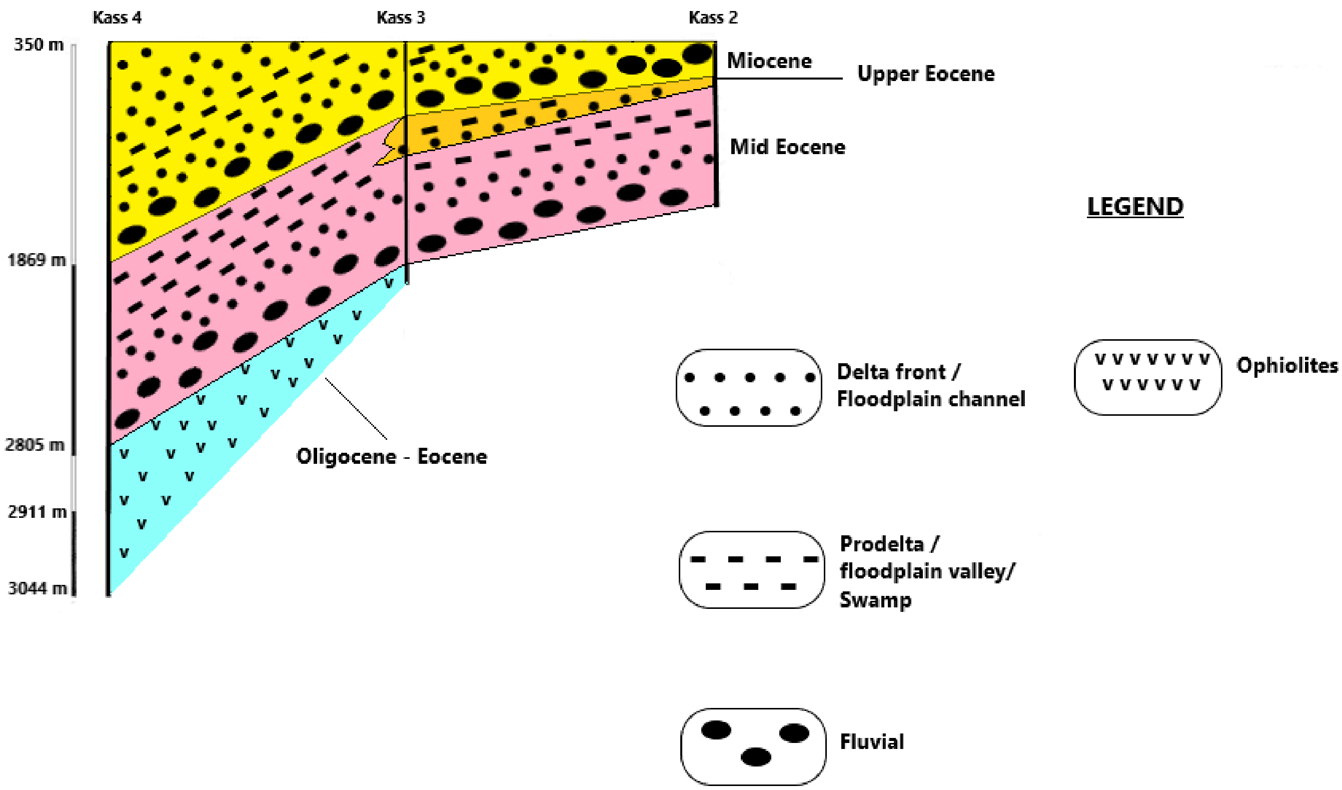

Figure 18: *Cross-section of the study area showing correlations between boreholes.*

7. Conclusions

The sedimentological investigation of the Kassandra Peninsula by using drill cores of the region, to attempt a more solid documentation of depositional environments and sub-environments, their stratigraphic evolution and the sedimentary succession, provided the conclusions below.

- The examined succession consists of eight facies and are grouped into six facies associations that consist in overbank and floodplain, tidally-influenced channalized, deltaic (prodelta and delta-front), fluvial, swampy, depositional environments.
- An Eocene to Miocene deepening-downward trend is detected in the KPB by the evolution of the deposition environments from delta front and to prodelta or from floodplain channel to floodplain valley setting.
- An Eocene to Miocene tidally-influenced, transgressive fluvio-deltaic depositional setting is indicated based on the: (1) Stratigraphic evolution that reveals a massive deepening-downward trend, from delta-front through prodelta deposits, to fluvial environments. (2) General coarsening-downward trend and (3) Absence of deepening-upward successions.
- This deltaic system presents an upward increase of the tidal influence, with an associated decrease in the fluvial energy. Sedimentary tidal-characteristic structures are abundant in the delta front deposits, become scarce in the prodelta sediments, and eventually become absent in the overlying fluvial setting.

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*****Kass 2: Kassandra 2 uncored drilling, Kass 3: Kassandra 3 cored drilling, Kass 3 uncored: Kassandra 3 uncored drilling, Kass 4: Kassandra 4 cored drilling.

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