

Late Eocene to Early Miocene depositional environments of the Mesohellenic Basin, North-Central Greece: Implications for hydrocarbon potential

A. Zelilidis, N. Kontopoulos, P. Avramidis, D. Bouzos

Department of Geology, University of Patras, 26110 Patras, Greece
Fax (30) 61-991-900; E-mail a.zelilidis@upatras.gr

(Submitted: 12.12. 1995; accepted for publication: 29.02 1996)

А. Зелилидис, Н. Контопулос, П. Аврамидис, Д. Бузос — Позднеоценовые-раннемиоценовые условия осадконакопления в Мезохеленическом бассейне, Северная—Центральная Греция: Приложение для оценки углеводородного потенциала. Позднеоценовые-раннемиоценовые отложения Мезохеленического бассейна накапливались в тектонически контролируемых условиях с неправильным и узким шельфом. Границы между эоцен-олигоценовыми Крания-Ептахори формациями и олигоцен-миоценовыми Ептахори-Пенталофос формациями маркируют глобальные понижения уровня моря во время соответствующих интервалов. Отложения всего Мезохеленического бассейна относятся к опущенным веерам без перекрытия береговыми осадками. Концепция распространения углеводородов считается применимой к Мезохеленическому бассейну, благодаря следующим характеристикам изучаемых отложений: (а) Песчаниковые выступы внешнего веера, классифицированные как суправеерные лбы, характеризуются стогами канальных тел песков с хорошими вертикальными и латеральными корреляциями. Эти особенности обуславливают хорошие коллекторские свойства пород. (б) Тонкозернистые осадки бахром лбов и бассейновых равнин изучаемых морских турбидитов могут выступать в качестве богатых материнских осадков или покрышек. (с) Геометрия лбов (стогов канальных тел песков) и внутренние несогласия (между четырьмя формациями) обуславливают наличие превосходных стратиграфических ловушек. (д) Синхронная эволюция этих отложений обеспечивает взаимные связи всех отмеченных факторов во времени. Так как изучаемые отложения соответствуют в основном осадкам западных бассейновых окраин, очень вероятно, что в сторону бассейна, в направлении проградации внутриканальные отложения обязаны перейти латерально в песчаные лбы внутреннего веера, окаймления лбов и отложения бассейновой равнины. Поэтому отложения внутренней части бассейна, до сих пор не обнаженные, по всей вероятности обладают благоприятными характеристиками единицы, перспективной в отношении нефтегазоносности.

Abstract. Late Eocene to Early Miocene Mesohellenic Basin deposits accumulated in a tectonically controlled basin with irregular and narrow shelves. The boundaries between the Eocene-Oligocene Krania-Eptachori Formations and the Oligocene-Miocene Eptachori-Pentalophos Formations record the global sea-level falling during the corresponding time intervals. The sediments of the Mesohellenic Basin have characteristics of lowstand fan deposits without coastal onlap. It is suggested that the concept of the hydrocarbon habitat is applicable to the Mesohellenic Basin due to the following characteristics of the studied deposits: (a) The outer fan sandstones lobes, classified in this work as suprafan lobes, are characterized by stacked channel sand bodies with good lateral and vertical communications. These features constitute excellent reservoir facies. (b) The fine-grained, lobe-fringe and basin-plain deposits of the studied marine turbidites may have operated as either fertile source rocks or topseals. (c) The geometry of the lobes (stacked channel sand bodies) and the internal unconformities (between the four formations) present excellent stratigraphic traps. (d) The synchronous evolution of these deposits assures the timely relationship among all factors listed above. Since the studied sediments correspond mostly to the western margin deposits it is very possible that basinwards, in the direction of the progradation, the interchannel deposits must laterally pass into, the outer fan sandstone lobe, lobe fringe and basin plain deposits. Therefore, sediments of the basin interior not presently exposed are very likely to support favourable conditions for petroleum play.

Zelilidis, A., Kontopoulos, N., Avramidis, P., Bouzos, D. 1997. Late Eocene to Early Miocene depositional environments of the Mesohellenic Basin, North-Central Greece: Implications for hydrocarbon potential. — *Geologica Balc.*, 27, 1-2; 45-55.

Key words: Eocene, Miocene; Depositional environment; Mesohellenic Basin; North-Central Greece; Hydrocarbon Potential

Introduction

Turbidite sediments of different types of facies, facies associations and geometry of sandstone bodies occur in a variety of sedimentary and tectonic settings.

Mutti (1985) classified turbidite deposits in three main type systems. Type I system corresponds mostly to elongate flysch basins of thrust belts. The sandstone bodies (lobes) in this system are characterized by lateral continuity and roughly tabular geometry over distances up to several tens of kilometers parallel to the current direction. Each lobe, 3-15 m thick, is thick bedded and grades in a downcurrent direction in thinner bedded and finer grained lobe-fringe deposits. Type II system displays depositional patterns that strongly resemble those of recent suprafans (after Normark, 1970). In Late Oligocene-Early Miocene submarine depressions of Tertiary Piedmont Basin, this type is associated with synsedimentary faulting. Sandstone bodies vary from very small (<4 km across, 10-30 m thick) to relatively large (width up to 20 km, several hundreds meters thick). Type III system is apparently the ancient expression of modern channel-levee complexes. The sandstone bodies are characteristic of small channel-fill deposits enclosed into predominantly muddy sequences.

The proportion of sandstone, volumetrically (thickness, geometry) decreases from system I to system II. Sand-richness depends also on shelves extent. Small setting with strong tectonic control, lack of extensive shelves and deltaic complexes produced sand-rich and small-volume turbidite systems (type II) that are fed by fan deltas or other types of coarse-grained alluvial fan and nearshore deposits.

Thin-bedded turbidite facies were classified by Mutti (1977) into three groups distinguished by a number of primary features which are palaeoenvironmental indicators by themselves. These are: (a) inner fan (with channel-margin, interchannel and channel-mouth facies), (b) outer fan (with lobe and lobe-fringe facies), and (c) basin plain, with basin plain facies.

Sandstone lobes generally form important hydrocarbon reservoirs (in terms of reservoir geometry) (e.g. Shanmugam, Moiola, 1988 for North Sea and California). The term "lobe" covers a wide spectrum of depositional facies associated with submarine fans. Seven lobe types

were recognized implying distinctly different reservoir properties; these are suprafan lobes, depositional lobes, fanlobes, pointed lobes, channelized lobes, levee-valley lobes and erosional lobes (Shanmugam, Moiola, 1991). The lobe type can be related to the depositional regime of a basin. For example, active margins exhibit high gradients, high sand/mud ratio, braided channels and small sand-rich fans, characterized by the development of channel-mouth lobes, classified as suprafan lobes. On the contrary, mature passive margins exhibit low gradients; low sand/mud ratio, sinuous channels with associated levee facies; and large mud-rich fans characterized by the lack of development of channel-mouth lobes, classified as fanlobes.

Geological setting

Sedimentation in the intramontane Mesohellenic Basin (Fig.1A,B) was the result of infilling of an elongated trough developed from late Eocene to late Miocene as a piggy-back basin (Doutsos et al., 1994; Robertson, 1994) along the eastern flanks of a giant pop-up structure, located at the contact between the Apulian and Pelagonian collided margins. The Apulian plate consists of a west-verging foreland prograding thrusts; whereas the Pelagonian plate consists of east-verging back thrusts. Ophiolitic rocks with lower Cretaceous melange (the Avdella melange) emplaced over the leading edge of the Apulian platform during compression, form the basement of the Mesohellenic Basin. Along the eastern margins of the basin, the ophiolites lie tectonically above the Pelagonian nappe pile.

The Greek sector of the Mesohellenic Basin (Fig.1B) is >130 km long and <40 km wide (the northern tip of the basin is situated in Albania), and is elongated NW-SE parallel to the isopic zones of the Hellenides.

According to Doutsos et al. (1994) the internal deformation of the basin varies along the basin axis due to the presence of two small indentors at the southern and northern ends of the basin, which induced a tectonic escape towards the central part of the basin until the Middle Miocene. The lowermost deposits in the basin, related with the Krania Thrust activity, are the late Eocene Krania Formation (Fig. 1C). During uppermost Eocene, the synchronous Krania and Apulia Thrust activity influenced the evolution

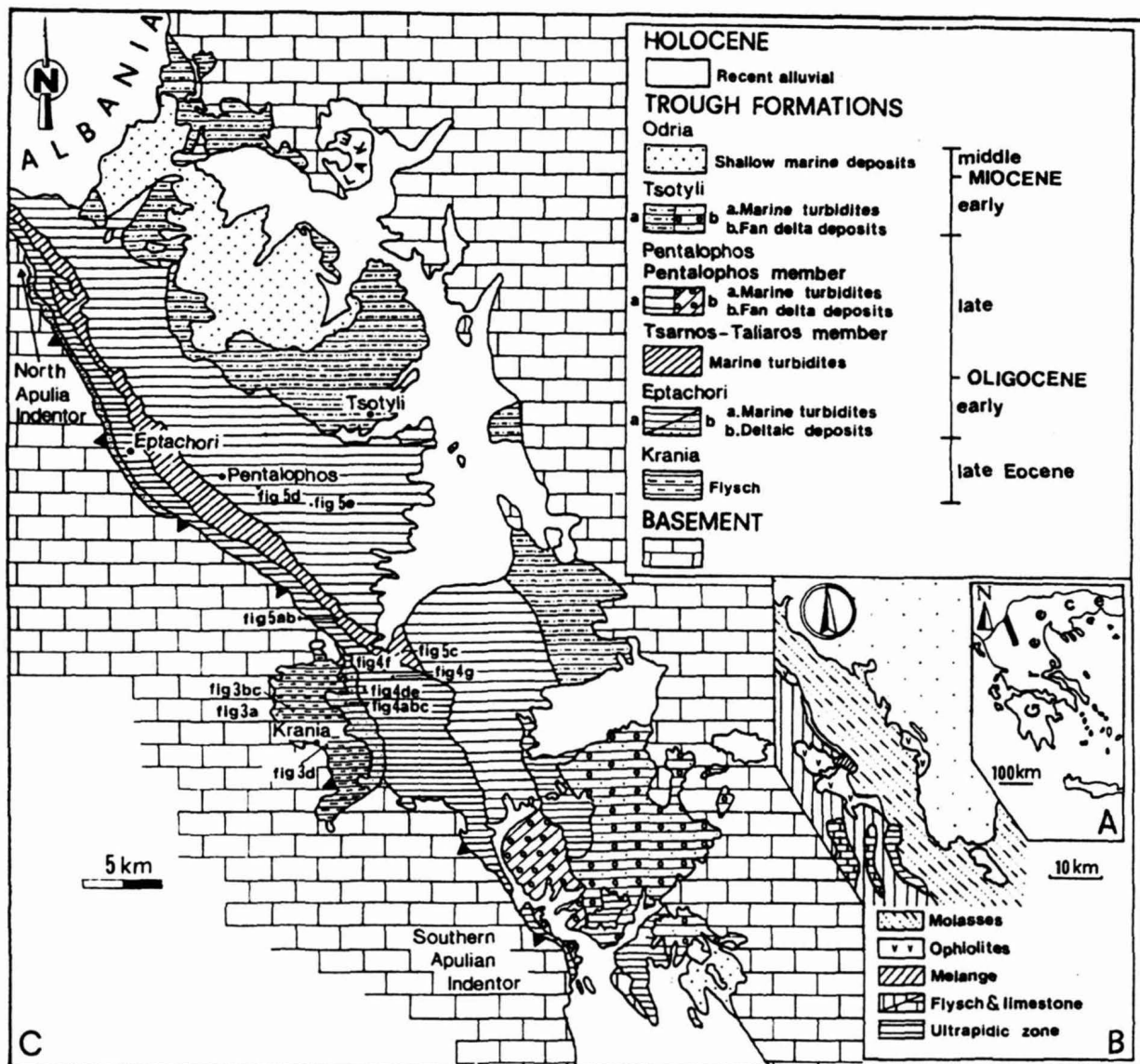


Fig.1. Geological setting. (A,B) Map of Greece showing the studied Mesohellenic Basin. (C) Geological map of the Mesohellenic Basin modified from Doutsos et al. (1994)

of the Krania Formation and formed a linked system with a piggy-back (westwards) and a foredeep (eastwards). Due to the Apulian Thrust activity, the Early Oligocene to Middle Oligocene sediments of Eptachori Formation, 800-1000 m thick, were deposited in a foredeep (Fig. 1C). The Eptachori Formation passes upwards into the Late Oligocene-Early Miocene Pentalophos Formation (Tsarnos-Taliaros member, up to 850 m thick; and Pentalophos Member, which is about 1500-2000 m thick)(Fig. 1C). The latter is overlain by the Early Miocene Tsotyli Formation, 500-1500 m thick (Fig. 1C). The northeastern and, in places, southeastern parts of the Mesohellenic Basin are occupied by the 20-450 m thick Late Miocene Ontria and Orlia Formations respectively.

The purpose of this paper is the hydrocarbon potential of the Mesohellenic Basin deposits, as indicated by the study of the depositional

environments in relation to the tectonic pattern within the basin; and by the way these depositional environments changed through the time along the basin axis. Description and interpretations of the turbidite facies, facies associations, depositional systems, types of submarine fan lobes, depositional processes and the development of large-scale cyclicity within the turbidites, are based on Mutti (1977, 1985); Shanmugam, Moiola (1991) and Piper, Stow (1991).

Tectonic elements and sedimentological data; depositional environments

Krania Formation

On a global scale, the Eocene is characterized by transgression conditions, and development of lowstand fan deposits is without coastal onlap (Vail et al., 1991). The Krania Formation deve-

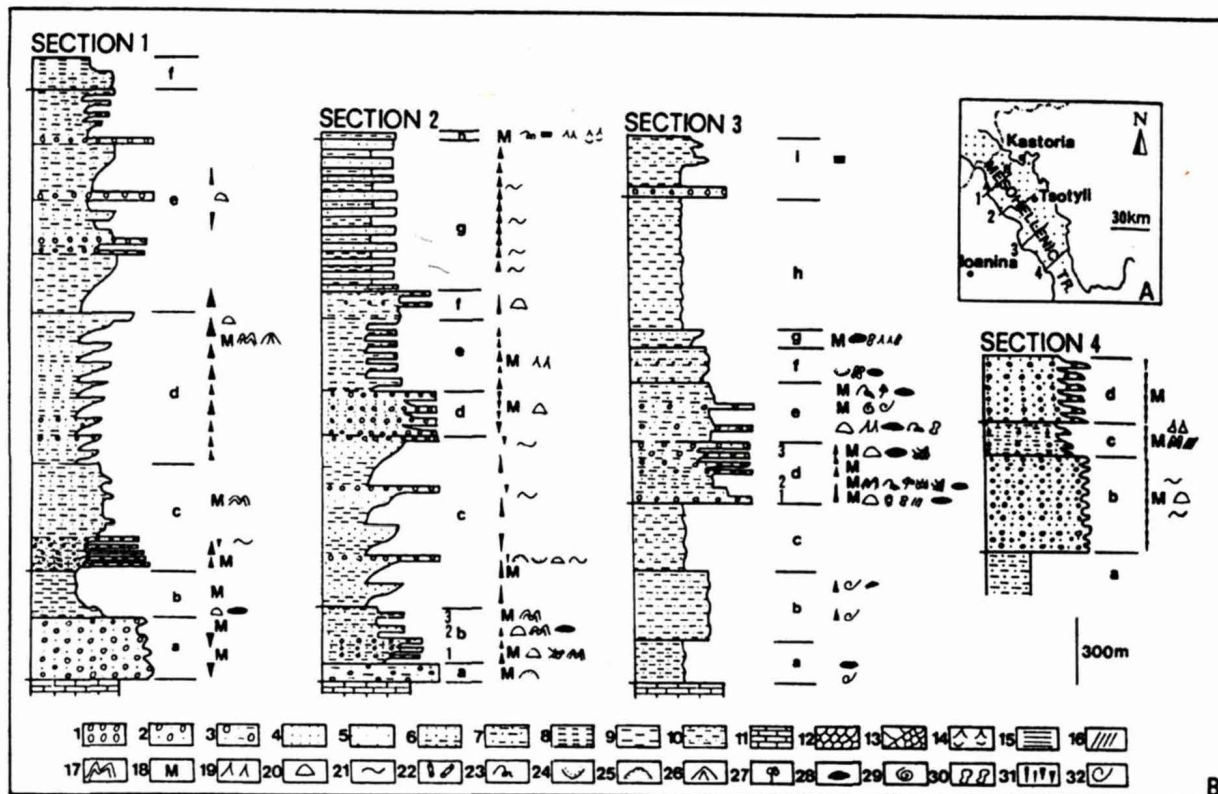


Fig. 2. (A) General geological map of Mesohellenic Basin showing the locations of the studied cross-sections. (B) Four synthetic stratigraphic columns of the four formations. Symbols: 1 — conglomerates; 2 — interbedded conglomerates/sandstones; 3 — interbedded conglomerates/sandstones/mudstones; 4 — sandstones; 5 — interbedded sandstones; 6 — sandstones with mudstone intercalations; 7 — interbedded sandstones/mudstones; 8 — mudstones; 9 — interbedded mudstones; 10 — mudstones with sandstone intercalations; 11 — basement; 12 — trough-cross stratification; 13 — micro-cross-bedding and small-scale trough-cross stratification; 14 — ripple cross-bedding; 15 — horizontal lamination; 16 — planar cross-stratification; 17 — fissile; 18 — massive; 19 — ripple laminae; 20 — lenticular bedding; 21 — erosional bounding surface or bedding plane; 22 — burrows; 23 — bioturbation; 24 — normal graded bedding; 25 — reverse graded; 26 — convolute bedding; 27 — leaves and plant fragments; 28 — coal fragments and lenses; 29 — shell fragments; 30 — fossils; 31 — coarsening upward sequence; 32 — slumps

developed during the late Eocene in a linked system composed by a piggy-back basin in the western margins of the Mesohellenic Basin and by a foredeep eastwards, formed due to the Krania and Apulian Thrusts activity (Doutsos et al., 1994, Fig.5, p. 263).

Cross-section 3 (Fig. 2A)

Description: Krania Formation sediments are constituted by three units. The lower unit consists of thin to medium interbedded, 200-600 m thick, sandstone (T_{uh} Bouma intervals) and mudstone beds and/or mudstone beds with sandstone intercalations (Fig. 2B: section 3a; Pl. I b, c) with abundant mica and coal fragments. Slumps are also present either adjacent to the basin margin (Pl. Ia) or basinwards (Pl. Id). Laterally, sediments of this unit pass to fan delta conglomerates deposited on the steep margin and composed by unstratified, matrix supported, massive greenish conglomerates, up to 40 m thick. The middle unit consists of thin to thick interbedded, up to 300 m thick, sandstone/

mudstone beds (ratio 1:1) (T_{abc} , T_{bcd} Bouma intervals in sandstones; Fig. 2B: section 3b). Sediments of this unit comprise several cycles, 30-40 m thick, with an upward thickening of sandstone beds (up to 6m thick). Within this unit slumps are also present (Pl. Ie). These slumps create channels, >50 m wide and up to 15 m thick. The upper stratigraphic unit, up to 300 m thick, consists of thin interbedded mudstones with rare (<1%) thin sandstone beds (Fig. 2B: section 3c).

The above described sediments of the Krania Formation represent the piggy-back basin deposits; sediments of the foredeep are covered by sediments of Eptachori Formation (seismic profile of DEP, personal communications).

Interpretation: The lower stratigraphic unit represents interchannel deposits. Conglomerates adjacent to the steep margins formed as debris flows in a fan delta. The middle unit represents outer fan sandstone lobe whereas slumps within this middle unit probably represent channel-fill deposits. The upper stratigraphic unit represents interchannel deposits.

Eptachori Formation

The Eptachori Formation was developed in a foredeep that formed due to Apulian Thrust activity. The basin is characterized by steep western margins and an eastward shallowing of basin depth. Apulian Thrust activity in relation to sedimentation rate influenced the basin evolution and produced an eastward progradation.

The western part of the Eptachori Formation consists, at its base, of basinal conglomerates which, to the east, pass upwards into marine turbidites, in the direction of the progradation. In the Eptachori Formation, laterally and over Krania Formation, and before the marine turbidites, instead of basinal conglomerates, deltaic sediments were accumulated (Fig. 1C)

Cross-section 1 (Fig. 2A), basinal conglomerates

Description: In this cross-section the conglomerates have the greatest thickness (300 m; Fig. 2B:section 1a). Over the ophiolitic basement, thick interbedded, up to 100 m thick, massive sandstone and fining upward, clast-supported, unstratified conglomeratic beds preserve mudstone lenses in their upper parts. Mean clast size of conglomeratic beds is 5-6 cm, whereas maximum clast size is less than 30 cm. Elsewhere in this cross-section, at higher altitudes also a 200 m thick sequence, mostly basinal conglomerates is observed; this sequence also contains medium to thick interbedded mudstone and conglomeratic beds. The mudstone beds, gray or reddish in colour, are massive, with sandstone lenses (2 m long and 10 cm thick) in the upper stratigraphic parts; and presence of coal lenses (1 m long and 5 cm thick). The conglomeratic beds are coarsening upwards; matrix- or clast-supported; mostly unstratified or with poorly reverse grading; and with low relief erosional bounding surfaces. Sandstone lenses are present in the lower stratigraphic parts (3 m long and 15 cm thick). Clast lithologies are 40-90% limestone, 0-40% chert and 10-20% ophiolitic. Clasts are well rounded and spherical with mean clast size 3-6 cm and maximum less than 15 cm.

Interpretation: Basinal conglomerates represent fan deltas deposits.

Marine turbidites in cross-section 1

Description: The turbidites consist of thin to medium interbedded mudstone beds, up to 250 m thick (Fig. 2B:section 1b), with rare lenticular sandstone lenses and coal nests.

Interpretation: These sediments probably represent interchannel deposits.

Cross-section 2 (Fig. 2A), basinal conglomerates

Description: The conglomerates, up to 100 m thick (Fig. 2B:section 2a), are composed of thin to thick interbedded reddish massive mudstone and matrix supported, polymodal, mostly pebbly conglomeratic beds with reverse grading, presence of small sandstone lenses and bar cross stratified structures.

Interpretation: Basinal conglomerates represent fan deltas deposits.

Marine turbidites in cross-section 2

Description: Sediments in this cross-section, have up to 250 m exposed thickness (Fig. 2B:section 2b). They are composed from the bottom to top by four distinct sequences: Sequence a, up to 130 m thick, consists of eight (8) coarsening upward cycles, 15-20 m thick. Each cycle is mostly massive or fissile mudstone. However, the upper 3-4 m of each cycle are mainly lenticular sandstones (sheets) and less pebbly-granule conglomeratic lenticular lenses; with medium scale trough cross-stratification and internal sandstone slumps. Sequence b is composed of thin interbedded fissile-laminated mudstone beds (T₁ Bouma intervals), up to 80 m thick, with rare lenticular sandstone lenses (T₂ Bouma intervals; 60-70 m long and 0.6-1 m thick), mica abundance and coal nests. Sequence c is composed of thin to medium interbedded mudstone and sandstone (T₃ Bouma intervals) beds, up to 20 m thick. Sequence d, up to 20 m thick, consists of fissile or massive mudstone beds, up to 20 m thick. A transitional zone occurs between Eptachori Formation and the overlain Pentalophos Formation which consists of superposed lenticular mudstone, sandstone and conglomerate lenses (Pl. IIa, b).

Interpretation: Sequence a formed in the proximal area of a sub-marine fan and represents channel-fill deposits. Sequence b sediments formed as distal interchannel or lobe-fringe. Sequences c and d represent proximal marine channel-mouth bar deposits (Mutti, 1977). The transitional zone from Eptachori Formation to overlain Pentalophos Formation represents channel-fill deposits.

Deltaic sediments in cross-section 3 (Fig. 2A)

Description: To the east, in the direction of the thrust movement, the Krania Formation passes laterally into the Eptachori Formation. The latter is composed at its base, of delta plain deposits (delta front and pro-delta deposits, not exposed, probably underlie the marine turbidites). These

sediments consist of three cycles. Cycle a, up to 30 m thick (Fig. 2B: section 3d1), consists of big lenticular channelized yellowish orange massive sandstones (channels up to 40 m long and 0.3-4 m thick); black gray mudstone; and, at the lower 6m, clast-supported, mostly limestone pebbly-granule, reddish conglomerates, with planar cross-stratification, lenticular lenses of coal and transported fossils as clasts. Cycle b (Fig. 2B: section 3d2) consists, at the lower 85 m, of thin to medium interbedded massive mudstone beds, with channelized sandstone lenses [presence of reworked fossils in mudstone beds, vertical burrows in sandstone lenses (Pl. IIa) and crystallized coal lenses]. The massive mudstone beds pass upwards into thin to thick interbedded muddy sandstone, sandstone and conglomeratic beds, up to 15 m thick (Pl. IIb). The muddy sandstones are massive, fissile, friable with a lot of bioturbation and abundant coal fragments. Sandstone beds are mostly massive, in places with normal grading and contain fossils and abundant concretions. Tabular or low angle trough cross-stratification, micro-cross stratification, and thick lamination are observed. The contact between mudstone and sandstone beds is abrupt. The conglomerates are clast-supported with trough cross-stratification. Cycle c, up to 120 m thick (Fig. 2B: section 3d3), it composed of three coarsening upward subcycles (29, 64 and 27 m in thick, respectively). The lower part, of each subcycle, consists of massive mudstone with rare fossils and caliche. The colour of beds changes laterally from grayish to yellowish orange and in places to reddish. The upper part of the subcycles consists of thin to thick interbedded clast-supported, trough-cross stratified, pebbly conglomerates; and massive channelled sandstone beds. The latter include muddy sandstone lenses and coal nests.

At the top of this sequence, below the overlying marine turbidites, a conquina formed (Pl. IIc).

Interpretation: The cycle a represents alluvial fan sedimentation at the western margins of the delta-plain, unconformably over Krania Formation. Coarsening upward cycles b and c, characterized by the absence of Bouma intervals, represent a deltaic sedimentation. Especially, the lower 85 m of cycle b represent offshore sedimentation; the rest of cycle b and all of cycle c represent lower to upper shoreface sedimentation.

In the third cycle, the lateral change of colour is probably due to varying oxidation conditions (subaerial and sebaqueous conditions along the same bed) as a result of block tilting.

Marine turbidites in cross-section 3

Description: The turbidites are composed of two units. The lower unit, up to 200 m thick (Fig. 2B: section 3e), consists of thin to thick upward interbedded mudstone and sandstone beds (T_a/T_c Bouma intervals; Pl. II d,f) with subordinate conglomeratic beds (Pl. II e). The mudstones are massive, bioturbated (mostly vertical burrows) with crystallized coal nests. Some beds are laminated with abundant plant fragments and lenticular lenses (7 m long and 15-20 cm thick); these beds in some places are amalgamate. The sandstone beds, thickening upwards in the section, from 0.5 to 2 m, are mostly massive interbedded occasionally with matrix-supported conglomeratic lenses (6 m long and 10 cm thick); occasionally, they show irregular bedding, lamination, coal lenses (15 cm long and 5 cm thick), fossils and bioturbation. The conglomeratic beds are channelized (30 m long and 4 m thick), poorly sorted, matrix- or in places clast-supported (matrix is a coarse-grained sand), polymodal, with well rounded clasts and fossil fragments (<1%). Locally, the conglomerates are fining or coarsening upwards with rare imbrication. There are many transported fossils.

There is a transitional zone with slumps and small channel mouths between marine turbidites and deltaic deposits up to 17 m thick; this zone is composed of black gray massive shales with fossils and massive sandstone beds.

The upper unit, up to 820 m thick, is composed of three differently coloured facies.

The stratigraphically lower grayish blue facies, up to 150 m thick (Fig. 2B: section 3f), consists of graded bedded sandstone units. Each of them is up to 60 cm thick commonly changing in the upper 15 cm from sandy to marly; the latter with poorly preserved fossils (<1%) and coal fragments. Bouma T_a and T_{ab} intervals were recognized. Poorly sorted, matrix-supported conglomerate layers are occasionally present at the base of the sandstone units. Clasts are well rounded and spherical. However, very angular sandstone clasts (a-axis as 50 cm) are also present.

The intermediate stratigraphically yellowish gray facies, up to 70 m thick (Fig. 2B: section 3g), is composed of repeated 6-8 m thick cycles. Each cycle consists of thin to thick interbedded massive mudstone beds at its base, with vertical burrows (10 cm high and 1 cm diameter), which pass upwards to thinly interbedded mudstone and sandstone beds (T_a/T_c Bouma intervals). The sandstone beds are characterized by ripple bedding (T_c Bouma interval; ripple index = 3.7); mudstone beds are massive with mica presence

and rare coal fragments. The uppermost part of each cycle consists of thinly to thickly interbedded massive sandstone beds (T_{uh} Bouma interval). Sandstone bed thickness increases upwards in each cycle; and decreases from the lowermost cycle upwards in the series (Pl. IIg).

The stratigraphically upper greyish facies, up to 600 m thick (Fig. 2B: section 3h), is poorly exposed and only small outcrops have been studied. In these outcrops this facies consists of thinly interbedded mudstone and sandstone beds (mudstone/sandstone proportion is 9/1) or thinly interbedded mudstone beds with <1% sandstone intercalations.

Interpretation: Thinly interbedded sandstone/mudstone beds (T_u/T_c Bouma intervals) at the base of the coarsening upward lower unit represent interchannel deposits; the thick interbedded sandstone/mudstone beds, with amalgamation in the sandstones and presence of conglomerate, indicate channel-mouth bar deposits. In the sequence of the upper unit, the lower stratigraphic facies represents channel-mouth deposits; the intermediate stratigraphic facies represents outer fan sandstone lobe deposits; the upper stratigraphic facies probably represents lobe-fringe or basin plain deposits.

Sediments of the transitional zone, at the base of the marine turbidites, represent delta mouth deposits.

Marine turbidites in cross-section 4 (Fig. 2A)

Description: The turbidites have an exposed thickness 200 m (Fig. 2B: section 4a). They consist of thin to thick interbedded, mudstone and sandstone beds (T_u/T_{uh} Bouma intervals). The mudstone/sandstone proportion changes upwards from 1/9 to 9/1. Conglomeratic lenses are present at the base of the sequence. Fossils (1%) and coal nests are present within the whole section.

Interpretation: These sediments represent channel-mouth bar (thick interbedded) and interchannel (thin interbedded) deposits.

Pentalophos Formation

The Late Oligocene-Early Miocene Pentalophos Formation overlies unconformably the Eptachori Formation. It consists of two members; the Tsarnos-Taliaros Member; and the Pentalophos Member (Fig. 1C).

During sedimentation of the Pentalophos Formation, near the southern indenter, the pre-existing foredeep basin was subdivided into two smaller sub-basins due to an upthrust (the Theotokos Thrust); these sub-basins underwent different depositional processes. At the same time period, the central part of the Mesohellenic

Basin was affected by transtensional structures producing north-east trending grabens (Doutsos et al., 1994).

a. Tsarnos-Taliaros Member

Cross-section 1 (Fig. 2A)

Description: This section consists of two parts. The lower part, up to 150 m thick (Fig. 2B: section 1c1), consists of six (6) coarsening upward stacked cycles. Each cycle is characterized by massive mudstone at the lower parts, passing upwards to massive or channelized sandstone (T_{uh} Bouma intervals), and finally to thin to thick interbedded mudstone and sandstone beds. In the uppermost part of each cycle polymodal, clast- or matrix-supported fining upward conglomerates, with low-scale erosive bases, were formed. Mean clast size, of the conglomerates, is 5-10 cm, with maximum of 40 cm. Generally the clast size of coarse lithology decreases upwards from the lower to the upper cycle.

The upper part, up to 350 m (Fig. 2B: section 1c2), is composed of thin to thick interbedded massive or fissile mudstone and sandstone beds (T_{uh} Bouma intervals). Mudstone/sandstone proportion varies from 9/1 to 1/1 to 1/2 to 1/9. In the mudstone beds, sandstone lenses (30 m long and 80 cm thick) are present.

Interpretation: The lower part of cross-section 1 represents inner fan deposits (channel-fill or channel-mouth bars); the upper part represents either inner fan (interchannel) or outer fan (lobe-fringe) deposits.

Cross-section 2 (Fig. 2A)

Description: In this section, the Tsarnos-Taliaros Member, up to 840 m thick (Fig. 2B: section 2c), is composed of five coarsening upward cycles (100, 150, 140, 200 and 250 m thick). Each cycle consists of thin to thick interbedded massive mudstone and medium to thick sandstone beds. Mudstone/sandstone proportion is 9/1 in the lower parts, changing upwards to 1/1. The medium-thickness sandstone beds are lenticular and characterized by Bouma T_{ub} intervals; thick sandstones are channelized. In some places sandstones change upwards to calcareous sandstones. The top parts of cycles 2, 4 and 5 consist of clast- or matrix-supported, poorly sorted and weakly normal or reverse graded, poorly sorted sandy conglomeratic lenses (up to 150 m thick, in the upper cycle; Fig. 2B: section 2c).

Interpretation: The above cycles are interpreted to represent lobe deposits; the conglomeratic lenses are channel-fill deposits.

Cross-section 3 (Fig. 2A)

Description: In this section, the Tsarnos-Taliaros Member has 300 m exposed thickness (Fig. 2B: section 3i). At its base there is a conglomeratic bed, up to 30 m thick. This bed is composed of channels with matrix supported conglomerates. Clasts mostly ophiolites, are well rounded, poorly sorted with 10% boulders, 20% cobbles and 70% pebbles. This conglomeratic bed is overlain by thin to medium interbedded mudstone and sandstone beds. Mudstone/sandstone proportion is 9/1. The mudstone is very thinly bedded with lamination. The sandstone is massive with lower contact slightly erosional.

In the upper parts of this section, near the contact with the Pentalophos Member, the thin to medium interbedded mudstone and sandstone beds, contain sandstone bed intercalations up to 1m thick (Pl. IIIc).

Interpretation: The interbedded mudstone and sandstone beds probably represent inter-channel deposits; the conglomeratic bed and the sandstone intercalations represent channel-fill deposits.

b. Pentalophos Member

Two different depositional systems are recognized in this member.

The first depositional system occurs in the central and northern parts of the Pentalophos member, overlain unconformably the Tsarnos-Taliaros member (cross-sections 1 and 2). The second depositional system (cross-section 4) is observed in the southern part of the Pentalophos Member, along the periphery of the southern indenter where it overlies unconformably the Eptachori Formation and Ulapindic basement.

Cross-section 1 (Fig. 2A)

Description: In this section, the Pentalophos Member, up to 1900 m thick, was studied in two localities A & B (Fig. 2A). In section 1A, the sequence is up to 720 m thick and overlies conformably the Tsarnos Member (Fig. 2B: section 1d). The sequence in section 1B is up to 1180 m thick (Fig. 2A; Fig. 2B: section 1e).

Section 1A: The sedimentary sequence characterized by repeated coarsening upward cycles (20-170 m thick). Each cycle consists of either massive or fissile mudstone beds. Convolute bedding and lenticular sandstone lenses (T_{bul} Bouma interval, 100 m long and 50 cm thick) are common. At the top-most parts of each cycle the mudstone beds pass into thinly to thickly interbedded mudstone and sandstone beds (T_a/T_c Bouma intervals). The mudstone/sandstone proportion is 1/1 and changes upwards in the

cycles to 9/1. In the lower part of the sequence slumps with pebbly conglomerates are present.

Section 1B: The sedimentary sequence consists of two parts. The lower part, up to 320 m thick, consists of thinly bedded mudstones (Te Bouma intervals) which pass upwards into thin to medium interbedded mudstone and sandstone beds, in 1/1 proportion. The upper part, up to 860 m thick, consists, from bottom to top, of a slump horizon, up to 45 m thick. The base of this horizon consists of conglomeratic lenses (200 m long and 30 m thick) which pass upwards into sandstone (10 m thick) and finally into mudstone (5 m thick) beds. This is followed upwards of a second slump horizon consisting of conglomeratic lenses up to 25 m thick, overlain by thinly to thickly interbedded mudstone and sandstone beds, up to 200 m thick. The proportion of these interbeds changes from 1/9 (in the lower 50 m) to 1/1 (in the upper 150 m). Over them there is a third slump horizon with conglomeratic lenses up to 30 m thick. The latter pass upwards into thinly to thickly interbedded mudstone and sandstone beds up to 280 m thick. Following upwards, three cycles of equal thickness, up to 280 m total thickness, are observed. Each cycle consists of thickly interbedded mudstone and sandstone beds, in a proportion varying from 1/1 in the lower parts to 1/9 in the uppermost 50 m.

Interpretation: The sediments of section 1A represent outer fan sandstone lobe and interlobe/lobe-fringe deposits. The sediments of section 1B represent channel-fill and interchannel deposits.

Cross-section 2 (Fig. 2A)

Description: The Pentalophos Member is up to 1500 m thick and is composed of two fining upward cyclothems. The lower cyclothem, up to 580 m thick, consists of two sequences. The lower sequence, up to 280 m thick (Fig. 2B: section 2d), consists of four (4) equal cycles. Each cycle consists of lenticular conglomeratic lenses (60-80 m long and 10-20 m thick), deposited in slumps. The fourth cycle passes upwards into turbidite sandstones. The upper sequence, up to 300 m thick (Fig. 2B: section 2e), consists of eight (8), equal cycles. Each cycle is coarsening upwards and consists of turbidite mudstones, at the lower part, which pass into the middle and the upper part to thin turbidite silts alternating with calcareous hemipelagic normal graded sediments and rare sandstone beds (T_{ad}/T_e Bouma intervals). In the uppermost part of each cycle sandstone beds are abundant. Mudstone/sandstone proportion changes upwards, within each cycle, from 9/1 to 1/9. The

PLATE I

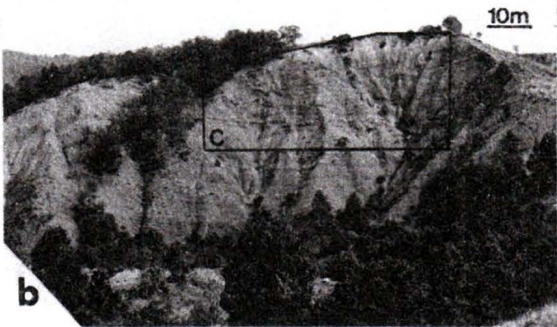
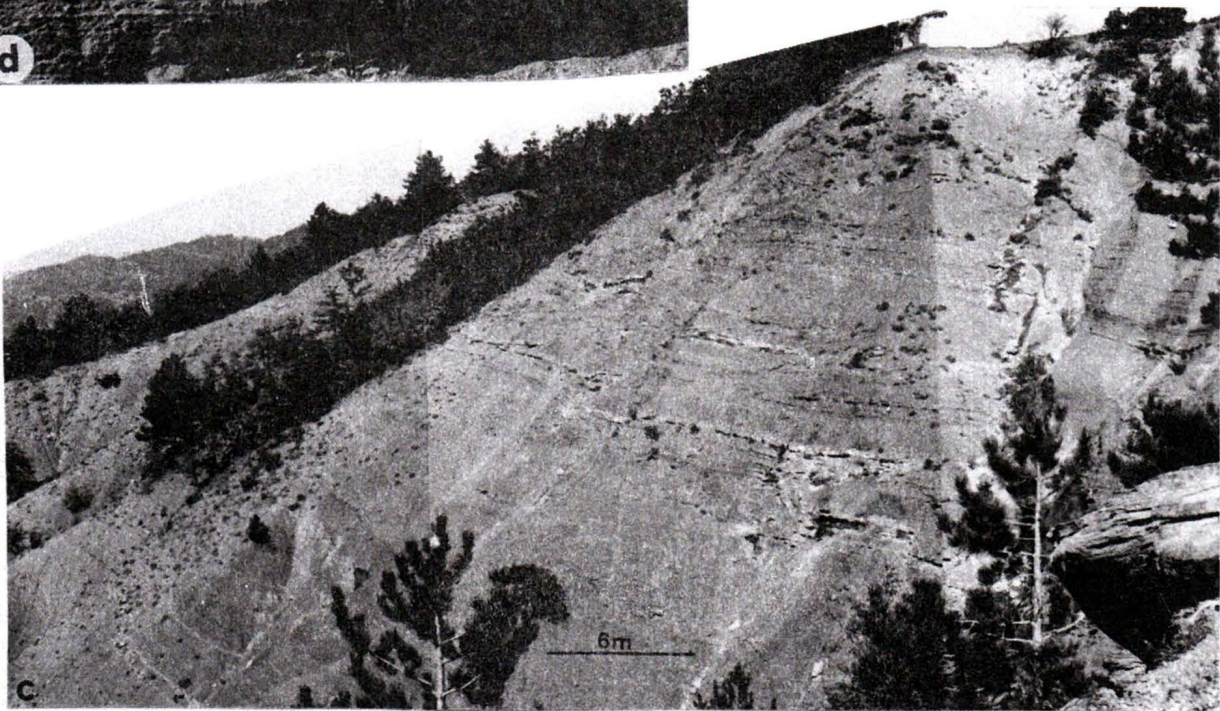


PLATE II

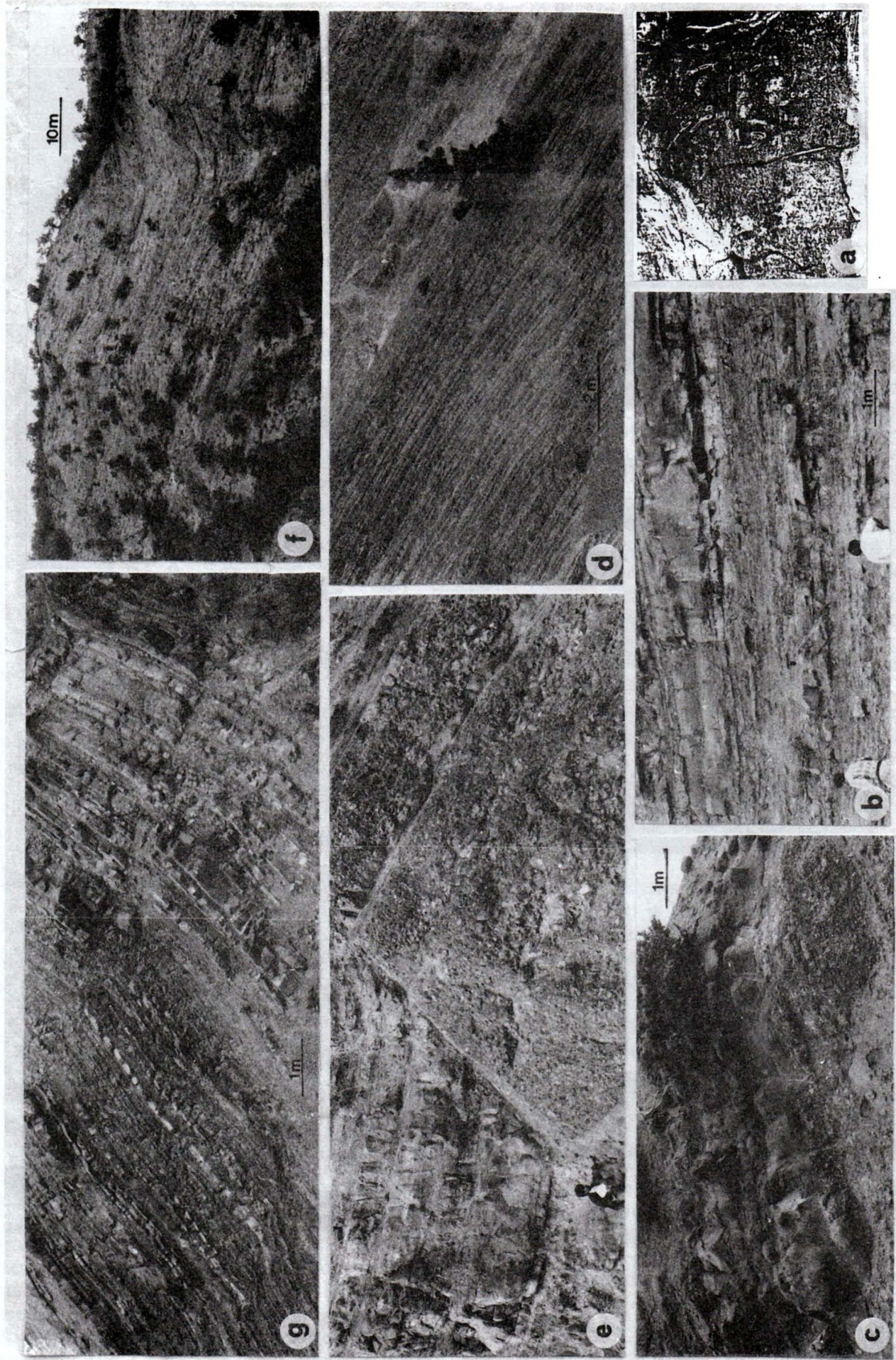


PLATE III

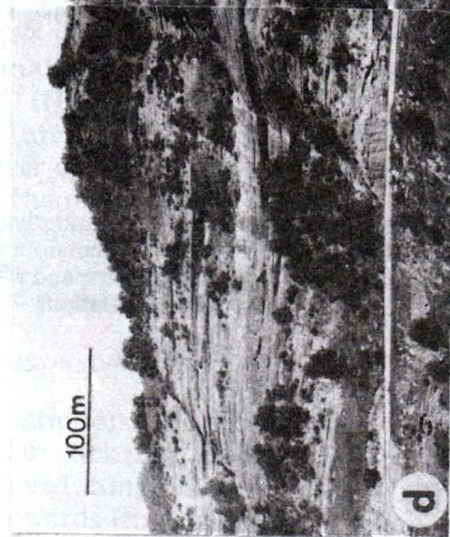
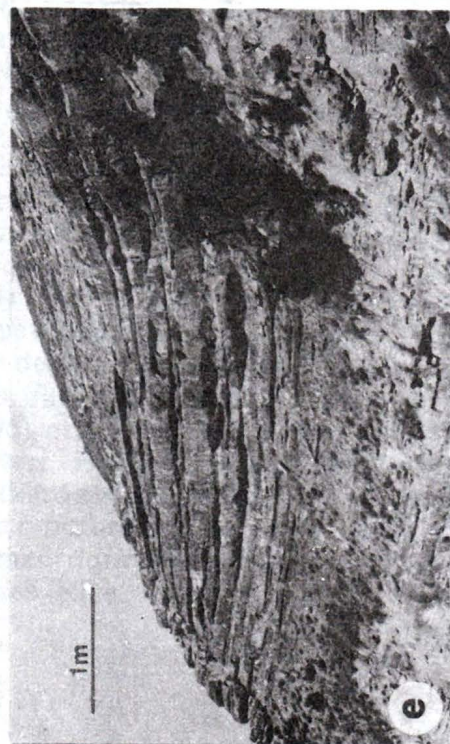


PLATE I

Photographs from the Krania Formation

- (a) slumps adjacent the basin margins;
 - (b, c) thin interbedded mudstones with sandstone intercalations, with small slump horizons;
 - (d) slumps within the thin to medium interbedded mudstone and sandstone beds;
 - (e) slumps within the middle unit of the Krania Formation;
- Photographs a, b, c and d correspond to the lower unit of Krania Formation

PLATE II

Photographs from the Eptachori Formation

- (a) burrows within sandstone lenses in the deltaic deposits;
- (b) interbedded mudstone and sandstone beds in the deltaic deposits;
- (c) conquina at the top of the deltaic deposits;
- (d) thin interbedded mudstone and sandstone beds in the marine turbidites;
- (e) conglomerates at the base of the marine turbidites;
- (f) thick interbedded mudstone and sandstone beds with conglomeratic lenses in the marine turbidites;
- (g) thin to thick interbedded mudstone and sandstone beds with the sandstone content and bed thickness to increase upwards

PLATE III

Photographs from the Pentalophos Formation

- (a, b) lenticular sandstone lenses at the base of the Pentalophos Member and at the contact with the underlying Eptachori Formation;
- (c) thin to medium interbedded mudstone and sandstone beds near the top of the Pentalophos Member sequence;
- (d) coarsening upward cycles with thin to thick interbedded mudstone and sandstone beds and with the sandstone presence and bed thickness to increase upwards;
- (e) Sandstone beds with mudstone intercalations

upper cyclothem, up to 920 m thick, is composed of two sequences. The lower sequence is coarsening upwards, is up to 140 m thick (Fig.2B: section 2f); it consists of bedded turbidite mudstone and sandstone beds, characterized by Bouma T_{abcd} intervals and in places with great lenticularity (100 m long and 4m thick), and by channelized, clast-supported, conglomeratic lenses (150 m long and 4m thick), deposited as slumps. The upper sequence, up to 780 m thick (Fig.2B:section 2g), consists of ten (10) coarsening upward cycles 40-70 m thick (Fig. 5d). Each cycle consists of turbidite blue grey mudstones (20-30 m thick), with sandstone intercalations (T_{abc} Bouma intervals), which pass laterally and upward into thinly to thickly interbedded, brownish mudstone and sandstone channels with no erosional bounding surfaces and, into the uppermost part (8-15 m), to sandstones (Pl. IIIe).

Interpretation: The lower sequence of the lower cyclothem represents channel-fill and interchannel deposits; the upper sequence represents lobe-fringe and/or basin plain deposits. The upper cyclothem represents outer fan sandstone lobe and lobe-fringe deposits.

Cross-section 4 (Fig. 2A)

Description: The Pentalophos Member, up to 350 m thick (Fig.2B:section 4b), consists of fining upward conglomeratic cycles dipping as 30° westwards (foresets). Each cycle consists, from bottom to top, of well-sorted massive sandstone-granule and imbricated fining upwards conglomeratic beds. Clasts are aligned parallel to the slope direction and dip upslope. Mudstone-sandstone lenses (3m long and 10 cm thick) are present, within each cycle, in the conglomeratic uppermost parts. Within these foreset deposits some intraformational unconformities have been recognized.

Interpretation: Textures and structures of these sediments suggest fan delta deposits. These fan delta deposits developed as a trapezoidal-type fan delta (after Zelilidis, Kontopoulos, 1996) or as Gilbert-type fan deltas (after Ori, Roveri, 1987). The source area of the cross-section 4 sediments was the basement in the east. The intraformational unconformities may have formed during minor compressional tectonic pulses (Riba, 1976).

Tsotyli Formation

The early Miocene Tsotyli Formation overlies unconformably the Pentalophos Formation. As in the case of the Pentalophos Member, two different depositional systems are recognized in this formation.

Cross-section 1 (Fig. 2A)

Description: At an outcrop west of the village of Nestorio, the Tsotyli Formation rests unconformably over the Pentalophos Formation, with a thickness of up to 80 m, which is the minimum thickness of the formation. It consists of thinly to thickly interbedded mudstone and sandstone beds (Tae Bouma intervals). The mudstone to sandstone proportion changes from 9/1 to 1/9 in the upper 20 m.

At a second outcrop east of the village of Nestorio, the Tsotyli Formation is up to 150 m thick (Fig. 2B:section 1f). The lower part of this outcrop, 80-100 m thick, is similar to that of the western outcrop above, and passes upwards into mudstone beds, 50-80 m thick.

Interpretation: The sediments of these two small exposures probably represent interchannel deposits.

Cross-section 2 (Fig. 2A)

Description: In this section, exposures of the Tsotyli Formation are poor owing to horizontal bedding and weak tectonic activity.

On the eastern end of the section, the uppermost part (20 m thick) of the formation (Fig. 2 B: section 2h), consists of thickly interbedded gray mudstone and brown sandstone beds. Mudstone beds are thickly laminated, thinly bedded or rippled and/or bioturbated. The sandstone beds are horizontal bedded or thinly laminated ($l = 7$ cm, $h = 1$ cm), micaceous; they contain either lenticular channels or medium to thick gray mudstone intercalations.

To the west, the Tsotyli Formation overlies the Pentalophos Formation and consists of black coloured, bioturbated, rippled, thickly laminated or thinly bedded, locally calcareous, mudstone beds (up to 4m thick); these in turn pass upwards to medium to thickly interbedded mudstone and sandstone beds (up to 4m thick). The latter, in the uppermost part of the sequence, pass with an erosional surface contact, to thinly inter-

bedded massive and locally lenticular channelized (15 m long and 70 cm thick) sandstones (up to 3 m thick) with mudstone intercalations. The frequency and thickness of the sandstones increase upwards.

Interpretation: This facies represents a small part of the Tsotyli Formation; it is interpreted as an either channel-mouth bar or outer fan sandstone lobe deposits.

Cross-section 4 (Fig. 2A)

Description: The Tsotyli Formation in this section, up to 450 m thick, is composed of two parts. The lower part, up to 150 m thick (Fig. 2B: section 4c), consists of three (3) repeated, fining upward, cycles. Each cycle consists of thinly to thickly interbedded mudstone-sandstone and conglomeratic beds. The proportion of the mudstone-sandstone to conglomerate changes upward from 1/9 to 1/1. The mudstone-sandstone beds are interbedded, and in proportion 9/1. The mudstones, brownish in colour, are fissile with cross-bedding and sandstone lenses (5 m long and 1 m thick). The sandstones are massive. The conglomerates, reddish orange in colour, are well sorted, fining upward, mostly clast-supported and in minor matrix-supported. Planar cross-bedding is present. Clasts are well rounded and discoidal. Mean clast size is 5-7 cm, with maximum of 25 cm. Clast lithologies are 90% ophiolitic, 5% limestone and 5% chert. The upper part, up to 300 m thick (Fig. 2B: section 4d), consists of six (6) repeated fining upward cycles. Each cycle consists of conglomerates at the base, up to 5 m thick, which pass upwards to yellowish grey massive sandstones.

Interpretation: Textures and structures suggest fan delta deposits (? Gilbert- type).

Implications for the petroleum play

The geological factors capable of providing the essential ingredients of the petroleum play are a reservoir unit; a petroleum charge system; a regional topseal or caprock; petroleum traps; and the timely relationship of the above four ingredients (Allen & Allen, 1990).

Organic matter content in source rocks; rates of heating of kerogen; burial depth of source rocks, reservoirs and topseals; porosity and permeability of reservoirs, appear to be critical in petroleum generation.

In the case of the Mesohellenic Basin, the following characteristics bear on the hydrocarbon potential of the basin: (a) Outer fan sandstone lobes classified in this work as suprafan lobes

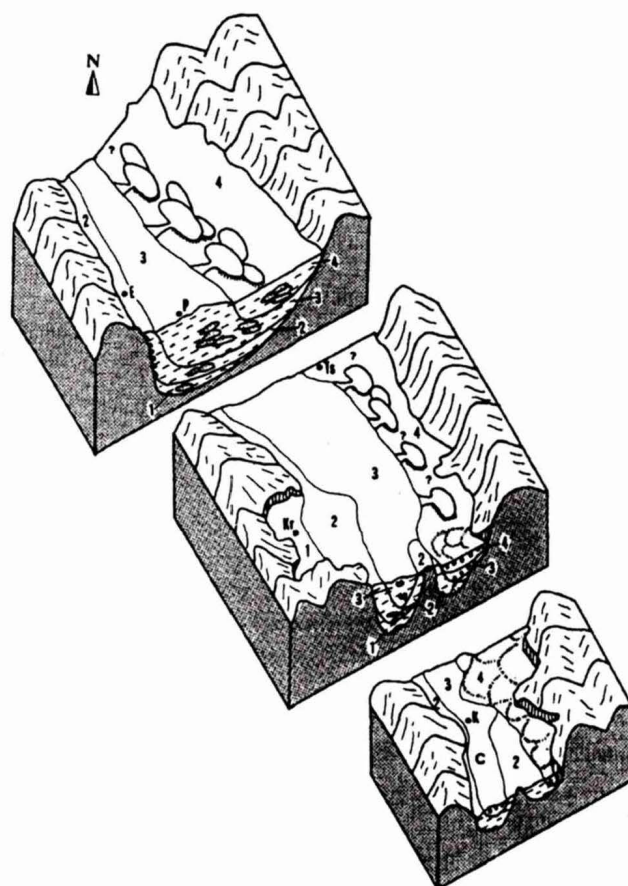


Fig. 3. Schematic block diagram of the Mesohellenic Basin during the sedimentation of Tsotyli Formation. Marine turbidites (channel-fill, interchannel, lobe, lobe-fringe and basin plain) deposits were accumulated in the central and northern parts of the basin; whereas fan deltas were accumulated southwards.

Numbers: 1, 2, 3, 4 correspond to Krania, Eptachori, Pentalophos and Tsotyli Formations respectively. Location of villages: Kr - Krania; E - Eptachori; P - Pentalophos; Ts - Tsotyli; K - Kalabaka

(Shanmugam, Moiola, 1991), are characterized by stacked channel sand bodies with good lateral and vertical communication (Fig. 3). These features constitute excellent reservoir facies (Shanmugam, Moiola, 1991). (b) The fine-grained lobe-fringe and basin-plain deposits of the studied marine turbidites may have operated as either fertile source rocks or topseals. (c) The geometry of the lobes (stacked channel sand bodies) and the internal unconformities (between the four formations) present excellent stratigraphic traps (either depositional or unconformity). (d) The synchronous evolution of these deposits assures the timely relationship among all factors listed above. Therefore, it is suggested that the concept of the hydrocarbon habitat is applicable to the Mesohellenic Basin.

Since the studied sediments correspond mostly to the western margin deposits it is very pos-

sible that basinwards, in the direction of the progradation, the interchannel deposits must laterally pass into, the outer fan sandstone lobe, lobe fringe and basin plain deposits (Fig. 3). Therefore, sediments of the basin interior not presently exposed are very likely to support favourable conditions for the petroleum play.

Concluding remarks

During the four stages of development* (four formations), the Mesohellenic Basin was bounded from the west by active margins characterized by the lack of regular extensive shelves. The Mesohellenic Basin deposits appear to belong to turbidite system II of Mutti (1985), in which (1) the basin is small and tectonically controlled; (2) relatively in small volumes of coarse-grained sediments, chiefly fan-delta deposits, were accumulated along the narrow and irregular shelves and, (3) the different turbidite stages within the same formation indicate a rapid lowering of sea level, followed by a gradual reestablishment of shelf deposition.

Regarding the depositional regime of the basin the lobe deposits studied in this work are likely to represent to suprafan lobes (classification of Shanmugam, Moiola, 1991).

The boundaries between the Eocene-Oligocene Krania-Eptachori Formations and the Oligocene-Miocene Eptachori-Pentalophos Formations record the global sea-level falling during the corresponding time intervals. The Mesohellenic Basin sediments have characteristics of lowstand fan deposits without coastal onlap. The two fining upward cyclothems of the Pentalophos Member, interpreted as allocyclic (Piper, Stow, 1991), represent sea-level fluctuations (Shanmugam, Moiola, 1988) related to regression and transgression events (Vail et al., 1991; Haq, 1991). On the other hand, the coarsening upward cycles of the studied sandstone fan lobes suggest basinward progradations of lobes (Walker, Mutti, 1973; Mutti, Ricci Lucchi, 1975).

More work on sedimentation rates; vertical and lateral facies distribution-geometry of lobes; organic matter content and origin; porosity and permeability of lobes; and seismic profiles for the determination of the burial depth, will enable assessment of the hydrocarbon potential of the Mesohellenic Basin.

References

- Allen, P.A., Allen, J.R. 1990. *Basin Analysis: Principles and Applications*. Blackwell Scientific Publications; 451p.
- Doutsos, T., Koukouvelas, I., Zelilidis, A., Kontopoulos, N. 1994. Intracontinental wedging and post-orogenic collapse in the Mesohellenic Trough. — *Geologische Rundschau*, 83; 257-275.
- Haq, B.U. 1991. Sequence Stratigraphy, sea-level change, and significance for the deep sea. — *Spec. Publ. Int. Assoc. Sediment.*, 12; 3-39.
- Mutti, E. 1977. Distinctive thin-bedded turbidite facies and related depositional environments in the Eocene Hecho Group (South-central Pyrenees, Spain). — *Sedimentology*, 24; 107-131.
- Mutti, E. 1985. Turbidite systems and their relations to depositional sequences. In: Zuffa, G.G. (ed.), *Provenance of arenites*, Dordrecht. D. Reidel; 65-93.
- Mutti, E., Ricci Lucchi, F. 1975. Turbidite facies and facies associations. — In: *Examples of turbidite facies and facies associations from selected formations of the northern Apennines*, International Association of Sedimentologists Fieldtrip Guidebook A-11, International Sedimentologic Congress IX; 21-36.
- Normark, W.R. 1970. Growth patterns of deep sea fans. — *AAPG Bulletin*, 58; 2170-2195.
- Ori, G.G., Roveri, M. 1987. Geometries of Gilbert-type deltas and large channels in the Meteora Conglomerate, Meso-Hellenic basin (Oligocene-Miocene) central Greece. — *Sedimentology*, 34; 845-859.
- Piper, D.J.W., Stow, D.A.V. 1991. Fine-grained turbidites. — In: Einsele, G., Ricken, W. & Seilacher, A. (eds), *Cycles and Events in Stratigraphy*. — Springer-Verlag, Berlin; 360-376.
- Riba, O. 1976. Syntectonic unconformities of the Alto Cardener, Spanish Pyrenees: a genetic interpretation. — *Sedim. Geol.*, 15; 213-233.
- Robertson, A.H.F. 1994. Role of the tectonic facies concept in orogenic analysis and its application to Tethys in the Eastern Mediterranean region. — *Earth-Science Reviews*, 37; 139-213.
- Shanmugam, G., Moiola, R.J. 1988. Submarine fans: characteristics, models, classification, and reservoir potential. — *Earth-Science Reviews*, 24; 383-428.
- Shanmugam, G., Moiola, R.J. 1991. Types of submarine Fan Lobes: Models and Implications. — *AAPG Bulletin*, 75; 156-179.
- Vail, P.R., Audemard, F., Bowman, S.A., Einsele, G., Perez-Gruz, G. 1991. The stratigraphic signatures of tectonics, eustasy and sedimentation. — In: Einsele, G., Ricken, W. & Seilacher, A. (eds), *Cycles and Events in Stratigraphy*. Springer-Verlag, Berlin; 617-659.
- Walker, R.G., Mutti, E. 1973. Turbidite facies and facies associations. — In: Middleton, G.V. & Bouma, A.H. (eds), *Turbidites and Deep-water Sedimentation. Pacific section. Soc. Econ. Min. Paleo., Short Course*; 119-157.
- Zelilidis, A., Kontopoulos, N. 1996. Significance of fan deltas without toe-sets within rift and piggy-back basins: examples from the Corinth graben and the Mesohellenic trough, Central Greece. — *Sedimentology*, 43; 253-262.

