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North Aegean sedimentary basin evolution during the Late Eocene to Early Oligocene based on sedimentological studies on Lemnos Island (NE Greece)

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Abstract: From the Late Eocene to Early Oligocene (NP18–NP21), submarine fan deposits and shelf deposits were accumulated on Lemnos Island, Greece. These sediments, with shelf deposits overlying the submarine fans, were deposited in a broad basin, which, in this time interval was gradually restricted in space. Colour, texture, thickness, grain size and sedimentary structures were used for the detailed sedimentological analysis of the turbidite deposits, in order to identify the sub-environments and the processes which control the growth of the submarine fan. This analysis demonstrates the classification of the sediments as a sand-rich submarine fan, which was constructed under the simultaneous interaction of progradation and aggradation and shows a main paleocurrent direction from SSW to NNE. The flow types that control the depositional processes of the submarine fans were grain flows, debris flows and low, medium- and high-density turbidity currents. The evolution of depositional environments outlined above indicates a progressive relative sea-level fall, and in relation to the lowstand conditions, during this time space (NP18–NP21), with no significant sea-level fluctuations, it could establish a theory that the studied area was mostly influenced by regional tectonic activity and less by eustatic sea-level changes.

Key words: Lemnos Island, sand-rich, submarine fan, currents, turbidites.

Introduction

An increasing emphasis in the oil industry on the exploration for turbidite-hosted reservoirs has been the driving force behind the growing research on turbidite systems (e.g. Shanmugan & Moiola 1991; Hickson & Lowe 2002). Outcrop studies of turbidite deposits allow a precise documentation of their internal structures, thicknesses, grain-size, sorting and composition. Turbidite deposits vary in facies architecture and geometry as a result of variations in the delivery system, grain-size availability, slope profile, and basin floor topography (e.g. Bouma 1962; Mutti & Ricci Lucchi 1972; Piper & Stow 1991; Reading & Richards 1994; Galloway 1998; Mulder & Alexander 2001). A great opportunity to examine some of the attributes mentioned above is offered by the Upper Eocene to Lower Oligocene turbidite deposits on Lemnos Island, NE Greece. They consist of conglomerates, sandstones and mudstones. These deposits underlie Lower Oligocene shelf deposits. The primary aim of this paper is the detailed description of the deep-water deposits in the Lemnos Basin, the recognition of the depositional processes and the sub-environments of deposition and reconstruction of the paleogeographical evolution of Lemnos Island.

Geological setting

The study area is located in the NE Aegean (Fig. 1A). The sedimentological evolution of the island of Lemnos is based on the geological mapping that was carried out by Roussos (1982) (Fig. 1B). The oldest sediments, Late Eocene to Early Oligocene in age, consist of conglomerates, sandstones and claystones and have been characterized as deep water in origin (Units 1 to 3 in Fig. 1B). Above them, during Early Oligocene, shelf deposits have been conformably accumulated. During the Late Miocene, the island of Lemnos was the site of volcanic activity. The Miocene ends with the deposition of conglomerates, marls and marly sandstones. Local Pleistocene porous calcareous and locally oolitic limestones and Holocene alluvial, coastal deposits and dunes are found.

Methodology

Sixteen outcrops of deep-water sediments of Late Eocene to Early Oligocene age were selected for study in Lemnos Island (Fig. 1B). Due to the scarcity of the outcrops, the studied outcrops were restricted to road cuts and beaches. The lithological units were described in terms of colour, texture, thickness, grain size and sedimentary structures. The paleocurrents were mainly derived from sole marks, as they provide the best estimate of the mean flow directions, although additional data were collected from ripples. In amalgamated sandstone strata, the only available paleocurrent indicators were cross-lamination foresets. The terminology of Pickering et al. (1986) has been used for the general description of sedimentary facies. Walker (1965, 1967), Hubert (1967), Nardin et al. (1979), Lowe

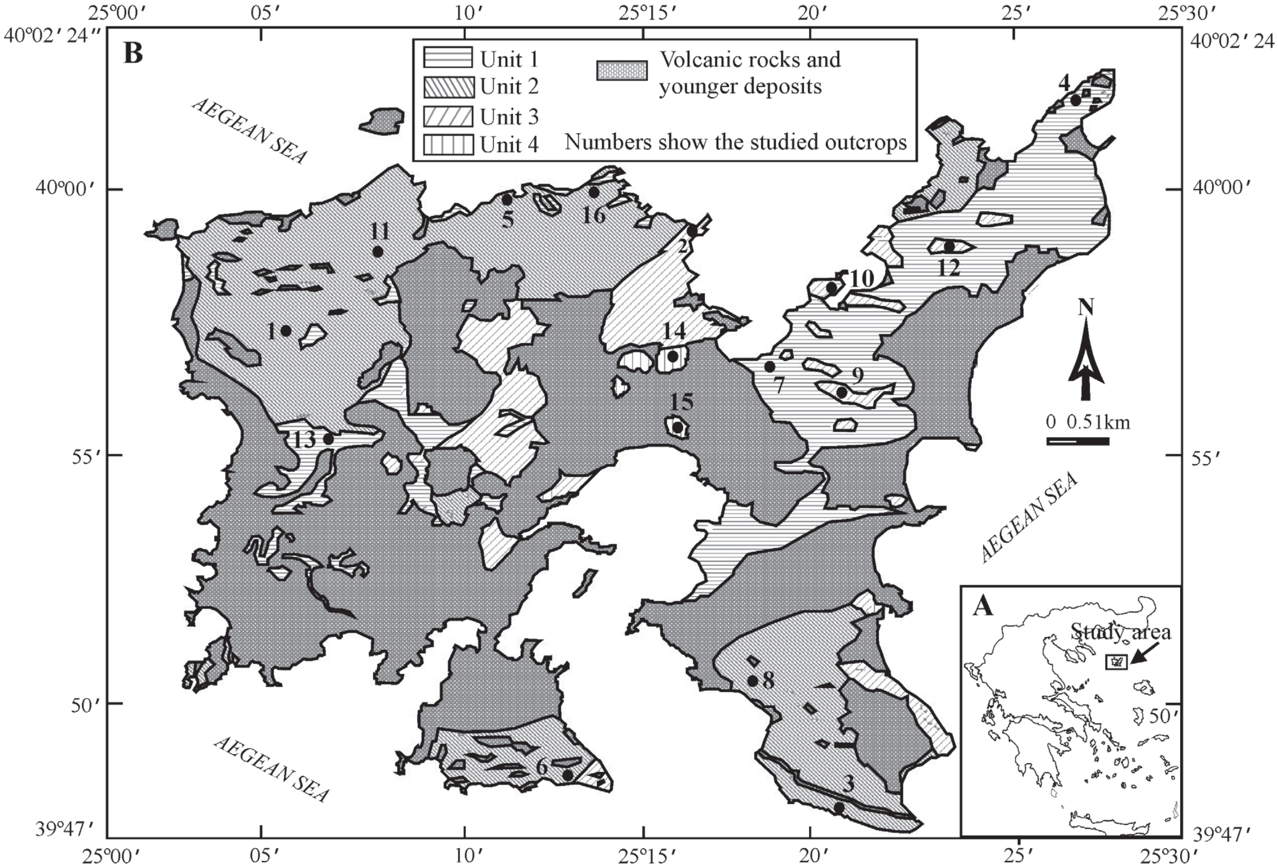

Fig. 1. A — Geological map of Greece showing Lemnos Island. **B** — Detailed geological map modified from Roussos (1982) of Lemnos Island where the four stratigraphic units were mapped.

(1982), Piper et al. (1985), Postma (1986), Shanmugam (2000), Stow & Johansson (2000) works are used to infer the flow types during the deposition.

Sedimentary facies and environments

The sedimentary succession in Lemnos Island is divided into four units (Fig. 2). The lower three units correspond to submarine fan deposits whereas the upper one corresponds to shelf deposits, according to Roussos's (1982) classification, which are from the lower to the upper:

Unit 1

Description: This unit, with up to 100 m total thickness, was studied at outcrops 1, 2, 3 and 4 (Fig. 1B), and is characterized by light brown to light green, fine- to medium-grained sandstone, grading upwards, to very fine-grained sandstone, interbedded with hemipelagic claystones (Fig. 3C). It often exhibits parallel lamination; cross-laminations and/or climbing ripples, defining sequence Tb and Tc of Bouma (1962) sub-divisions (Fig. 3A). The cross-lamination is commonly overlain by convolute lamination. The sandstone beds have flat bases and very good lateral continuity (at least a hundred meters). The claystone facies are brownish and typically lack internal structure, although beds with silt lamina, with an upward decrease in lamina thickness, have been recognized.

Trace fossils are very common in the fine- to medium-grained sandstones. These traces (e.g. *Lorenzinia*, *Paleodictyon* and *Cosmorhaphae*) have great propagation and at the base of some sandstone beds these species are of significant size. Flute and groove marks are of great importance, especially groove marks, which are abundant. The groove marks typically have lengths of 15–25 cm while the flute marks have lengths of 6–10 cm and widths of 2–4 cm.

Turbidites at outcrops 1 and 2, show a distinct upward increase of the sandstone/claystone ratio up to 9:1 (Fig. 3B) in contrast to the turbidites at the outcrops 3 and 4 which lack well-defined trends in bed thickness (Fig. 4A,B). The sandstone thickness varies from 1 to 200 cm, at the outcrops 1 and 2, and from 1 to 40 cm, at the outcrops 3 and 4.

Interpretation: The characteristic features demonstrate deposition from both low and high-density turbidity currents. The sandstone and claystones beds are classified as sedimentary facies C2.1, C2.2 and C2.3 and D2.2 in the Pickering et al. (1986) nomenclature. The common occurrence of convolute and climbing ripples clearly

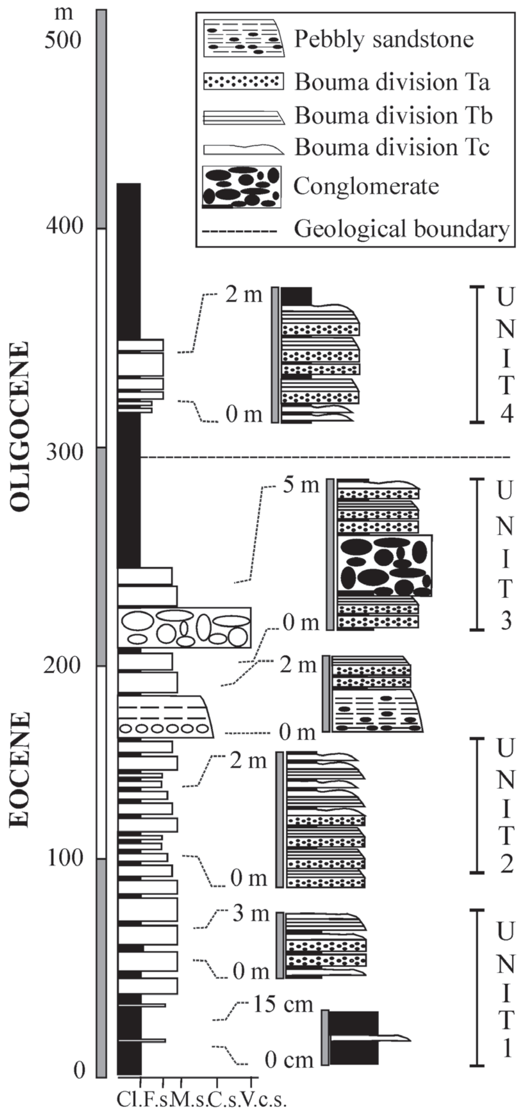

Fig. 2. Stratigraphy of Upper Eocene–Lower Oligocene deposits in the Lemnos area.

indicates rapid deposition of sediments from suspension. Such rapid deposition is related to the dilution of flow associated with the transition from confined, channelized conditions, with high gradients, to unconfined, lateral spreading across more gently sloping depositional lobe areas (Mutti & Normark 1987).

The presence of distinct, small-scale, thickening-upward cycles within major thickening-upward cycles, at the outcrops 1 and 2, indicates a lobe sequence (Mutti et al. 1978). These minor thickening-upward cycles are considered to represent compensation features or "compensation cycles" produced by progressive smoothing out of the depositional relief as a result of lobe upbuilding or aggradation (Mutti & Sonnino 1981). Both, aggradation and progradation, are responsible for lobe development. At the bedform scale the system is aggradational, however, the entire lobe package is a result of progradation (Shanmugan & Moiola 1988).

The lack of well-defined trends in bed thickness in the turbiditic succession, of the outcrops 3 and 4, indicate that these outer fan deposits are constructed by vertical aggradation, rather than basinward progradation (Hiscott 1981). The turbiditic succession, of the outcrops 3 and 4, could also suggest levee deposits (especially away from the levee crests). However, their very good lateral continuity, the lack of slump features, resulting from levee failure, and the absence of evidence for channel-fill deposits, preclude this suggestion.

From the above interpretations a basin floor environment is indicated for this unit.

Unit 2

Description: This unit, with a total thickness up to 50 m, was studied at outcrops 5, 6, 7, and 8 (Fig. 1B), and is constituted by light brown to light green, thin- to thick-bedded (beds 4–250 cm), fine- to coarse-grained sandstones, interbedded with hemipelagic claystones (Fig. 5A,C).

In the lower part of this unit sandstones, mostly massive and less with normal grading, are thick-bedded and the sandstone to claystone ratio ranges from 7:1 to 9:1. Sandstones commonly show sharp, irregular and sometimes erosional bases, forming amalgamated beds up to 300 cm thick (Fig. 5B), and with very low lateral continuity. The upper parts of beds with normal grading show parallel lamination and/or ripple cross-lamination (Tb and/or Tc of Bouma (1962) sub-divisions).

In the upper parts of this unit, turbidites show a distinct fining and thinning trend. Thus thick-bedded, coarse-grained sandstones fine upward and/or laterally pinch out to thin-bedded, fine-grained sandstones interbedded with hemipelagic claystone. The sandstone to claystone ratio, in this upper part, ranges from 3:1 to 6:1. The majority of the thin-bedded sandstones show parallel lamination and/or ripple cross-lamination (Tb and/or Tc of Bouma (1962) sub-divisions) while a few massive beds occur.

Interpretation: The sharp, irregular and sometimes erosional base in association with the laterally discontinuous geometry of the thick-bedded sandstones indicates infill of submarine fan channels, from turbidity currents with erosive ability, such as high-density turbidity currents. The thick-bedded, normally graded sandstones with parallel lamination and/or ripple cross-lamination are classified as deposits from waning turbidity currents in a submarine channel environment. The sandstones and claystones are classified as sedimentary phases C1, C2.1 and D2.3 in the Pickering et al. (1986) nomenclature. The thin-bedded sandstones with the parallel lamination and/or ripple cross-lamination have been interpreted as channel-related overbank deposits. These deposits were deposited by turbidity currents emanating from within the confines of an adjacent channel and are classified as facies C2.2 and C2.3 in the Pickering et al. (1986) nomenclature.

The overall interpretation suggests slope fan deposits (Posamentier & Allen 1993).

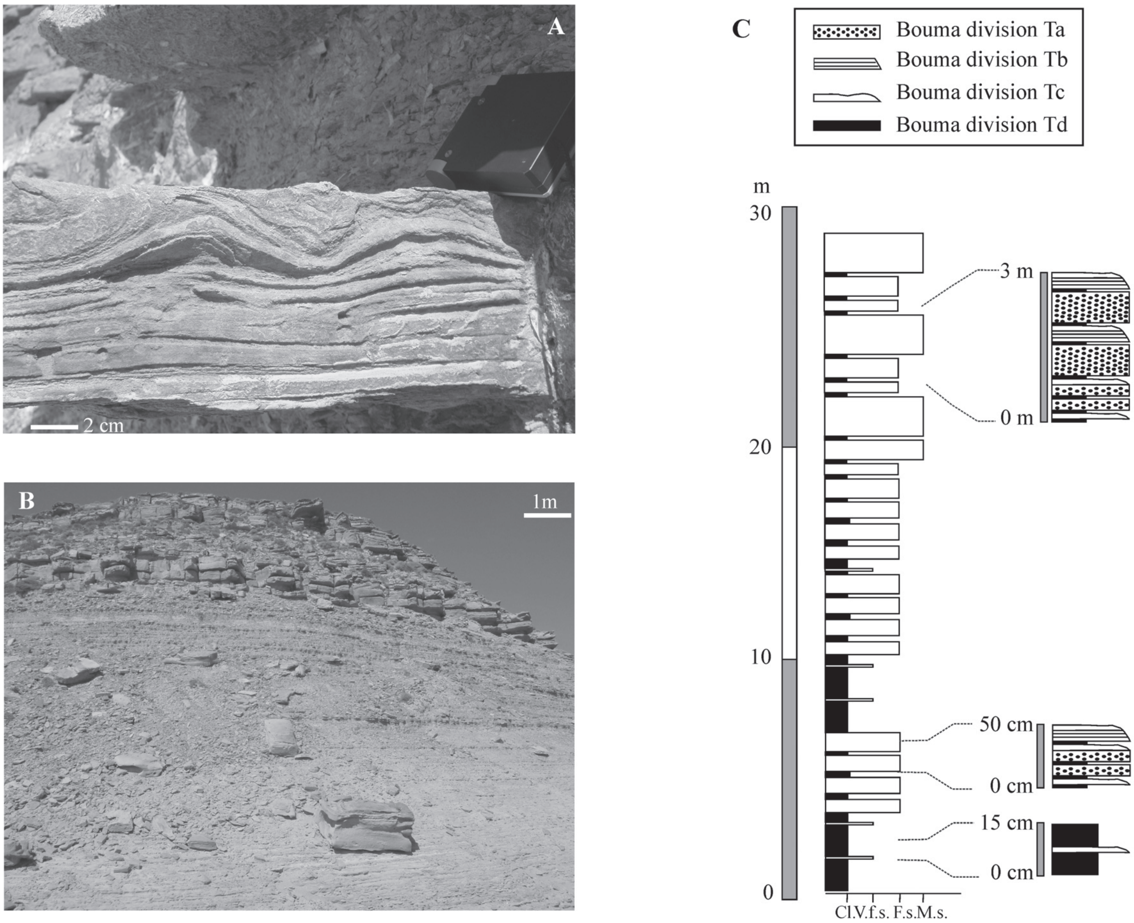

Fig. 3. **A** — Outcrop of sandstones defining sequence Tb and Tc divisions of Bouma. **B** — Outcrop from Unit 1. Note the upward change of the sandstone to claystone ratio. **C** — Stratigraphic log of Unit 1.

Unit 3

Description: This unit, with a total thickness up to 50 m, was studied at outcrops 9, 10, 11 and 12 (Fig. 1B), with a distinct fining and thinning upwards trend (Fig. 6C). Sediments consist of thin- to very thick-bedded sandstones (beds 3–400 cm thick), which are locally associated with pebbly sandstones and conglomerates, interbedded with hemipelagic claystones (Fig. 6A). Sandstones are light brown to light green, fine- to very coarse-grained and with very low lateral continuity. Conglomerates are often disorganized although locally inverse to normal grading is present. The conglomerates are polymictic and consist of radiolaritic, calcareous, arenaceous, gneissic schists, quartzitic cobbles and of arenaceous cement. The claystone facies are brownish and typically lack internal structure although beds with silt laminae have been recognized.

In detail, the very thick- to thick-bedded, very coarse- to medium-grained sandstones, associated with pebbly sandstones and conglomerates (sandstone to claystone ratio ranges from 8:1 to 9:1), fine upward and/or laterally evolve into thin-bedded, fine- to medium-grained sandstones (sandstone to claystone ratio ranges from 1:3 to 1:1), interbedded with hemipelagic claystones.

The thick-bedded sandstones commonly show sharp, irregular and often erosional bases and form amalgamated beds up to 350 cm thick. The sandstone is generally massive and in some places normal grading is also present. The upper parts of normally graded beds show parallel lamination and/or ripple cross-lamination (Tb and/or Tc of Bouma (1962) sub-divisions). The thin-bedded sandstones show parallel lamination and/or ripple cross-lamination (Tb and/or Tc of Bouma (1962) sub-divisions). Laterally, these thin-bedded sandstones evolve into a slump unit of fine sandstone and claystone interbeds. The sandstone beds have lenticular geometry and exhibit mostly cross-lamination (Fig. 6B).

Moreover, in the central part of outcrop 13, brownish, thin-bedded claystones are present and typically lack internal structure (Fig. 7A,B). Sandstone beds within claystones, are unusual, but when they occur they are very thin-bedded and fine-grained.

Interpretation: Conglomerates, pebbly sandstones, sandstones and claystones are classified as facies A1.1, A2.2, A2.3, B1.1, C2.1, C2.2, C2.3 and D2.2 in the Pickering et al. (1986) nomenclature. Conglomerates and pebbly sandstones were deposited from traction-carpet beneath high concentration currents, non-cohesive sandy debris flows or grain flows. The massive, thick-bedded sandstones demonstrate deposition from turbidity currents with erosive ability, such as high-density turbidity currents. Both thick- and thin-bedded, normally graded sandstones with parallel lamination and/or ripple cross-lamination are classified as a deposit from waning turbidity currents in a submarine channel environment. The slumped thin-bedded sandstones with mostly cross-lamination were deposited by turbidity currents emanating from within the confines of an adjacent channel and are interpreted as overbank deposits, while slump may have developed in response to failure of aggraded overbank deposits (Walker 1978).

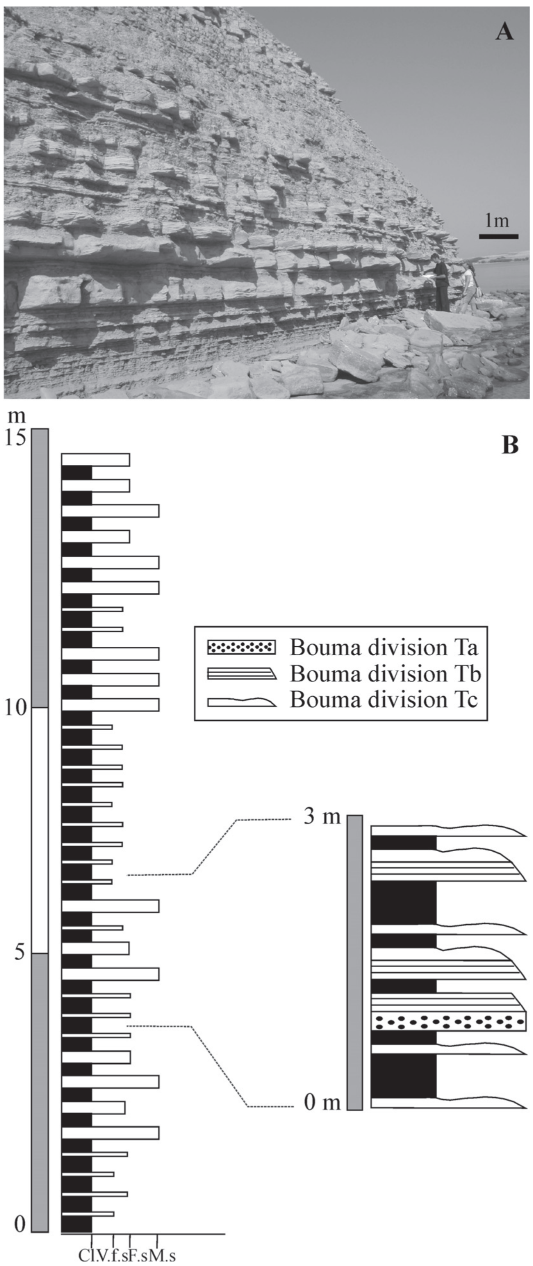

Fig. 4. A — Outcrop from Unit 1. Note the lack of well-defined trends in bed thickness in the turbidite packets. **B** — Stratigraphic log of Unit 1.

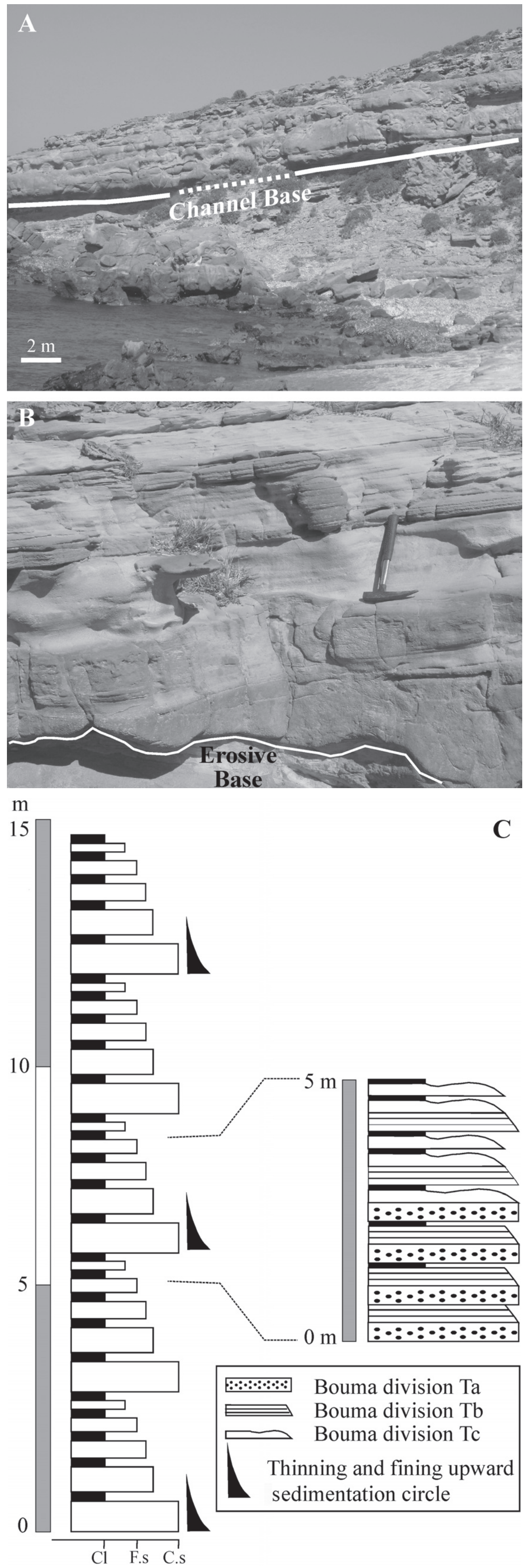

Fig. 5. A — Outcrop photograph of Unit 2. **B** — Outcrop of sandstones showing erosive base. **C** — Stratigraphic log of Unit 2. Note the thinning and fining upward cycles.

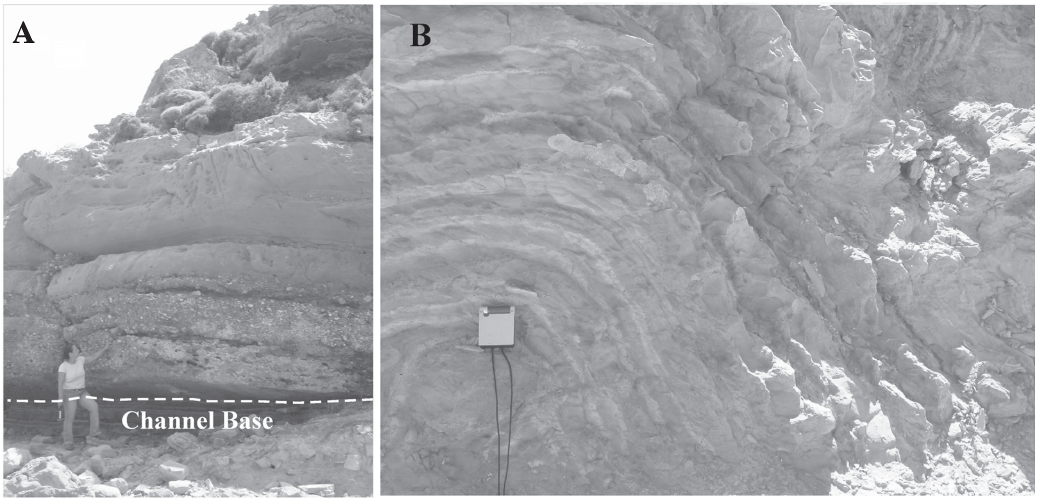

Fig. 6. A — Outcrop of Unit 3. Note the abrupt upward decrease in grain size within the channel-fill succession. **B** — Slump unit of fine sandstone and claystone interbeds.

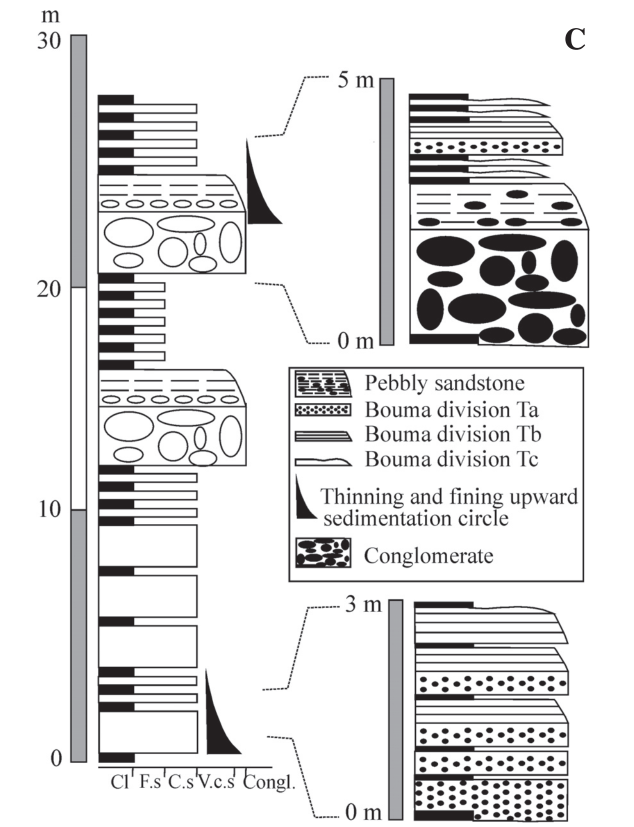

Fig. 6. C — Sedimentological log of Unit 3 at outcrop 9. Note the thinning and fining upward sedimentation cycles.

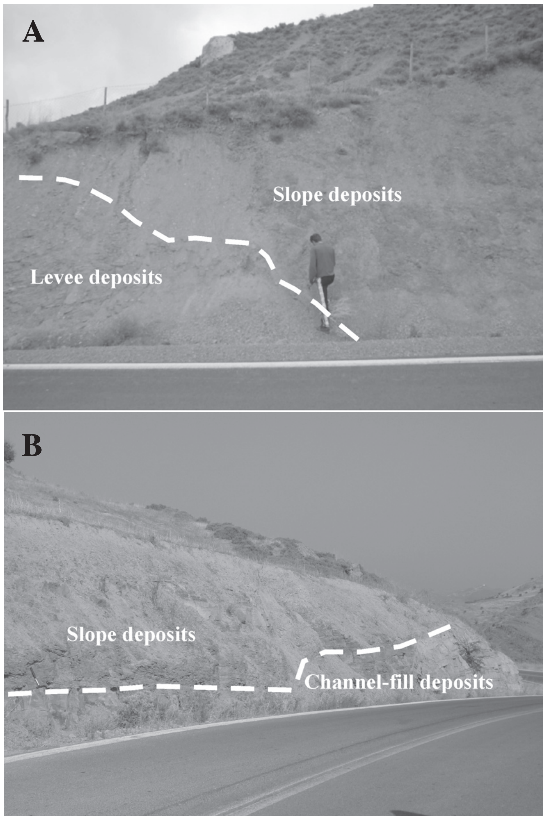

Fig. 7. Outcrop 13 where slope deposits cross-cut levee in the eastern part of the section (photo **A**) and channel-fill deposits in the western part of the section (photo **B**).

This unit, as Unit 2, represents slope fan deposits, but sedimentation took place in the upper parts of a submarine fan and represents the infill of a relatively deep, leveed channel. The influence of the erosion during deposition was greater indicating more restricted basin topography in a position more proximal to the source area in terms of Unit 2.

The thin-bedded claystones in the central part of outcrop 13 are interpreted as slope deposits that cross-cut channel or levee deposits.

Unit 4

Description: This unit, with a total thickness up to 250 m, was studied at outcrops 14 and 15 (Fig. 1B). The base of this unit consists almost entirely of sandstones, in beds up to 60 cm thick, which are interbedded with very thin claystone beds (Fig. 8C,E). Many soles of sandstone beds appear featureless but others show grooves and tool marks. Internal structures are dominated by prominent parallel lamination. The sandstone beds show,

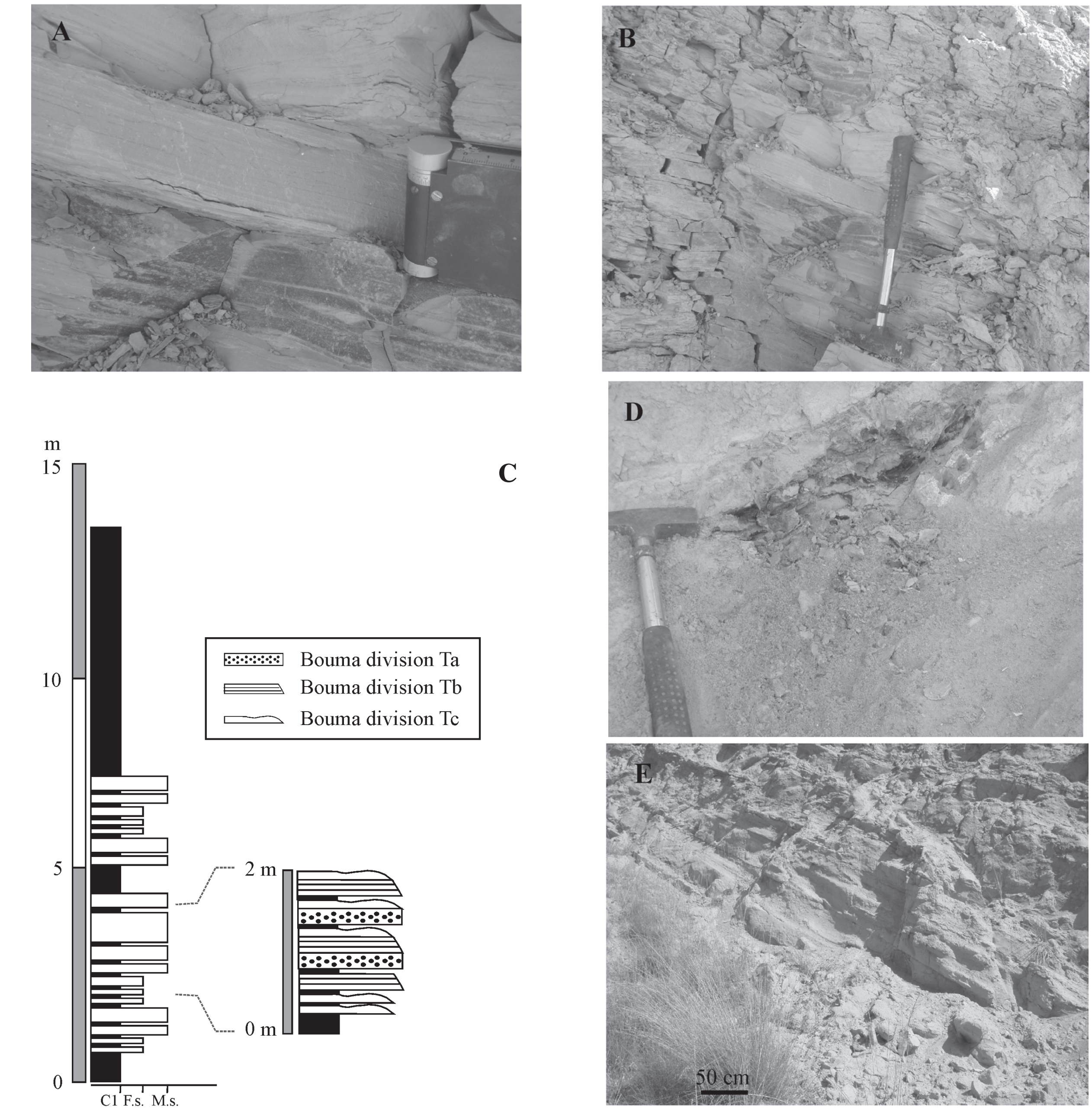

Fig. 8. A, B — Thin-bedded claystones from the lower part of Unit 4. **C** — Sedimentological log of Unit 4. **D** — Coal nests at the base of the un-cohesive sandstones. **E** — Un-cohesive sandstones in the upper part of Unit 4 where Bouma sub-divisions are absent.

generally a single set of ripple cross-laminae at the top. The claystone interbeds commonly contain a high amount of coal debris (Fig. 8D). Upwards, this unit grades from a sand-dominant to an almost completely clay-dominant sequence, which consists of massive, homogeneous green or green-grey claystones (Fig. 8A,B).

Interpretation: The sandstones of this unit do not resemble any of the turbidity facies described by Mutti & Ricci Lucchi (1975). Similar sandstones are described by Hamblin & Walker (1979) and interpreted as storm-surge deposits on the deeper parts of shelves. The overall fining-upward trend has been attributed to turbidity currents (Hamblin & Walker 1979) and, to shelf storm currents (Aigner & Reineck 1983).

Paleocurrent analyses

In order to estimate the paleoflow direction, paleocurrent data were collected from six outcrops (see locations 3, 5, 7, 8, 9 and 16 in Fig. 1B) and the flute and groove marks were measured. The number of measurements from each outcrop ranges from 10 to 15 and there were plotted in rose diagrams (Fig. 9), showing that the main paleocurrent direction has a NNE trend. Rose diagrams that comprised a consistency ratio less than 0.7 were not taken into consideration during interpretation of the results.

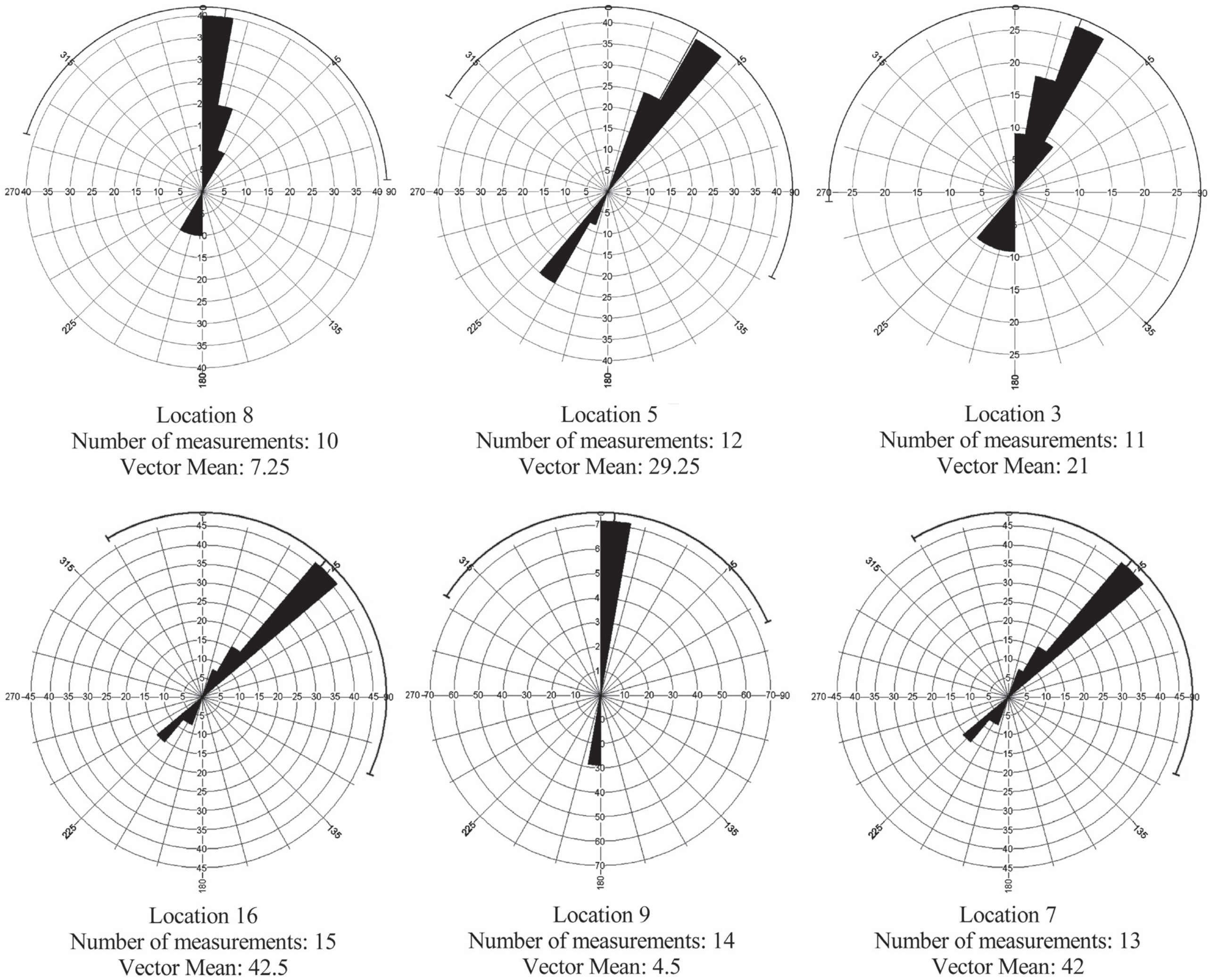

Fig. 9. Rose diagrams from six outcrops (for location see Fig. 1B), showing the main N-E trend of the paleocurrent direction.

Discussion and conclusions

From the Late Eocene to Early Oligocene in Lemnos Island, Greece submarine fan and shelf deposits were accumulated. Submarine fans underlie shelf deposits. The sediments accumulated in a broad basin, which, in this time interval, was gradually restricted in space.

The flow types that controlled the depositional processes of the submarine fans were grain flows, debris flows and low-, medium- and high-density turbidity currents (Walker 1965, 1967; Hubert 1967; Nardin et al. 1979; Lowe 1982; Piper et al. 1985; Postma 1986; Shanmugam 2000; Stow & Johansson 2000).

The submarine fan is characterized by the presence of distinct, small-scale, thickening-upward cycles within major thickening-upward cycles at the outcrops 1 and 2 (Unit 1), the lack of well-defined trends in bed thickness in the turbiditic succession, of the outcrops 3 and 4 (Unit 1), and by the covering of distal fan deposits (Unit 1), by proximal fan deposits (Unit 2), at the location 16 (Fig. 10). These features indicate a simultaneous interaction of progradation and aggradation for the submarine fan development (Shanmugan & Moiola 1988).

The facts that: 1. the sandstone to claystone ratio within the entire submarine fan deposits is up to 70 % approximately, 2. typical lobes are well preserved and, 3. the presence of attached lobes in outcrop 16, demonstrates the classification of the deep water deposits as a sand/rich submarine fan (Shanmugan & Moiola 1988; Reading & Richards 1994). Unit 1 can be characterized as basin floor fan deposits while Units 2 and 3 are slope fan deposits (Posamentier & Allen 1993).

The above described evolution of turbidites in the three lower units, show the active supply of coarse-grained siliciclastic sediments to the deep water environments and could be related to a prodeltaic setting on a prograding delta to turbidite slope (Piper et al. 1985). Thus, the sedimentological evolution of turbidites related to the fact that during the Early Oligocene shelf deposits were deposited conformably over submarine fan deposits, a progressive relative sea-level fall is indicated for the period between the Late Eocene and Early Oli-

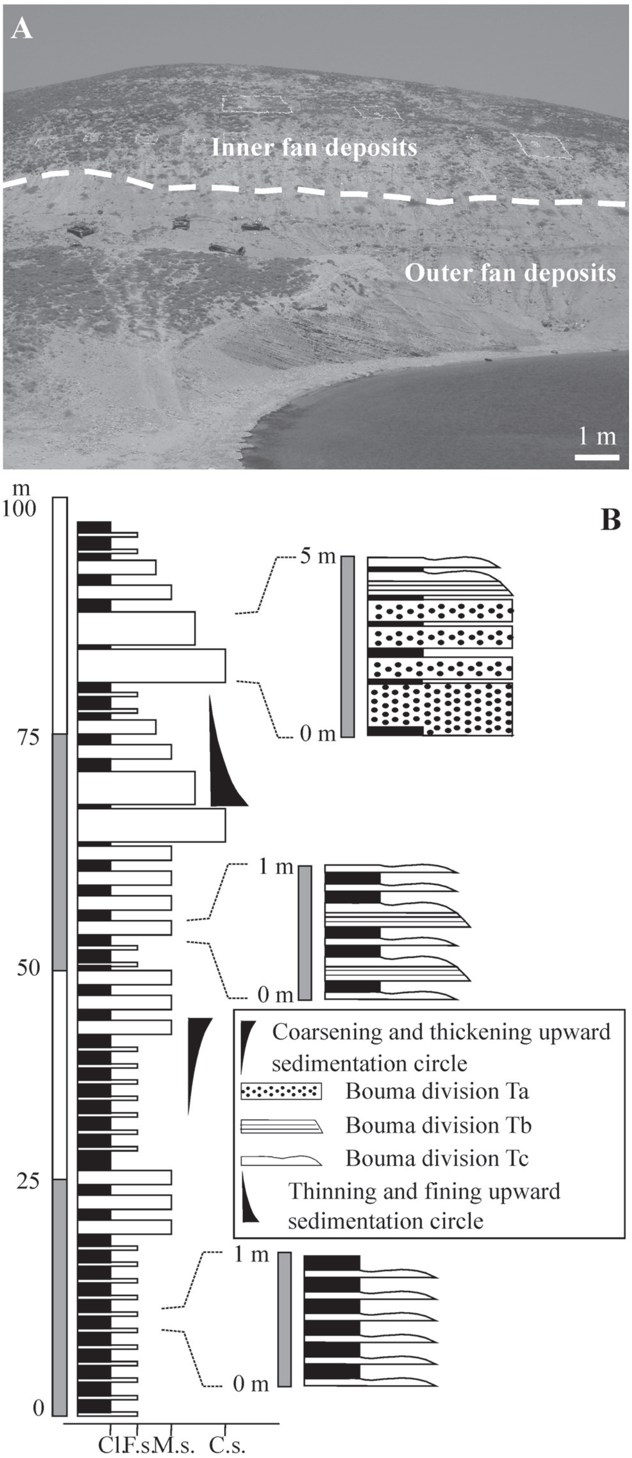

Fig. 10. A — Sediment succession in outcrop 16. Note that inner fan deposits have overlain the outer fan deposits. **B** — Sedimentological log of outcrop 16. The lower part of the sequence consists of thickening and coarsening upward sedimentary cycles, while the upper part consists of thinning and fining upward sedimentary cycles.

gocene (Ricci Lucchi & Valmori 1980; Mutti 1985; Posamentier & Vail 1988).

The biostratigraphy of calcareous nannofossils show that sedimentation took place between the NP18 to NP21 Biozones (Martini 1971). According to Haq et al. (1987) this time interval is characterized by lowstand conditions with no significant sea-level changes. Thus, it could be suggested that the studied area was mostly influenced by regional tectonic activity rather than by eustatic sea-level changes.

Considering that the main paleocurrent direction is NNE and the fact that the conglomerates consist of metamorphic and pyroclastic clasts a proximal source for the fan should be located SSW.

The proposed style of a sand rich fan could be applied in the direction of hydrocarbon field development, given the abundance of sand within the sequence, which is very critical for reservoirs in the N–NE Aegean region.

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