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Porosity-Permeability and Textural Parameters of the Palaeogene Forearc Sedimentary Fill on Lemnos Island, NE Greece

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Abstract: The Palaeogene forearc sedimentary fill on Lemnos Island, NE Greece, was examined to determine reservoir characteristics and textural parameters. During this time interval the studied area was the site of accumulation of submarine fans that underlie shelf deposits, with tectonic activity responsible for the shallowing upward trend. Turbidites were deposited in both inner (slope fan facies) and outer parts (basin floor fan facies) of the submarine fan system and consist of alternating sandstone and mudstone beds. Sandstones occur in both complete and incomplete Bouma sequences while shelf deposits have been interpreted as storm-surge deposits on the deeper parts of shelves. The 'Mercury Porosimetry Technique' was carried out on 20 sandstone samples, while 30 sandstone samples were examined under a polarizing microscope for grain-size analysis. This porosity-permeability study suggests that these rocks can be considered as both oil and gas reservoirs. 'Slope' fan facies generally reveal the most efficient values, making them the most promising sub-environment for further hydrocarbon research. Most samples display two pore-size distributions suggesting major textural heterogeneity. Textural parameter analysis reveals that sorting was of great importance during sedimentation. Rocks are generally well to very well-sorted while samples with moderate sorting are also present. This fact can be both attributed to the restricted grain-size range and their possible great distance from the source area. This generally well-sorted sequence argues well for further hydrocarbon research in the Northeast Aegean Sea, since the higher the sorting the higher the porosity. Selected samples are generally very fine to fine grained, whereas medium-grained sandstones are extremely rare and mostly seen on 'slope' fan facies. The finest grained sandstones are the best sorted.

Key Words: porosity, permeability, textural parameters, grain-size, Lemnos Island, NE Greece

Lemnos Adası Paleojen Hendek-önü Tortul Dolgunun Gözeneklilik-Geçirimlilik ve Dokusal Öğeleri, KD Yunanistan

Özet: KD Yunanistan'da Lemnos adası Paleojen hendek-önü tortul dolgusu, hazne özelliklerinin ve dokusal öğelerini belirlemek üzere çalışılmıştır. Bu zaman aralığında çalışma sahası, tektonik etkinlik denetiminde üste doğru sığlaşan ve şelf tortulları ile üzerlenen denizaltı yelpazelerinin birikim alanı konumundaydı. Kumtaşı ve çamurtaşı tabakaları ile ardışımından kurulu türbiditler denizaltı yelpazesinin iç (yamaç yelpaze fasiyesi) ve dış (havza tabanı yelpaze fasiyesi) kesimlerinde depolanıyordu. Şelf tortulları, şelfin daha derin kesimlerindeki fırtına-kabarma tortulları olarak yorumlanırken kumtaşları ise tam veya eksikli Bouma istifi şeklindedir. 30 kumtaşı örneğinin tane boyu polarize mikroskopta belirlenmiş, 20 kumtaşı örneğinde ise Mercury gözenekliliği kullanılmıştır. Gözeneklilik-geçirimlilik çalışması bu tür kayaların petrol ve gaz haznesi olabileceğini göstermiştir. En verimli değerleri sunan yamaç yelpaze fasiyesi, ilerdeki hidrokarbon aramaları için en ümitli alt-ortamdır. Çoğu örnekler ana dokusal heterojenlik sunan iki boşluk-boyutu dağılımını sunar. Dokusal çalışmalar boylanmanın depolanma sırasında kazanılan önemli bir unsur olduğunu göstermiştir. Kayalar, orta derece boylanma ile birlikte genellikle iyi-çok iyi boylanmışlardır. Bu durum kısıtlı tane boyu aralığı ile birlikte olasılıkla kaynak alandan çok uzak mesafede oluşu gösterebilir. Genellikle iyi boylanmış istifler daha yüksek boylanma ve gözenekliliklerinden ötürü KD Ege Denizi'nde ilerde yapılacak hidrokarbon aramalarını gündeme getirir. Seçilmiş örnekler genellikle çok ince-ince taneli iken, orta-taneli kumtaşları oldukça nadirdir ve çoğunlukla yamaç yelpaze fasiyesinde görülürler. Öte yandan en ince taneli kumtaşları en iyi boylanmıştır.

Anahtar Sözcükler: gözeneklilik, geçirimlilik, dokusal öğeler, tane boyu, Lemnos Adası, KD Yunanistan

Introduction

Deep-water turbidite reservoirs are important exploration targets worldwide (Weimer & Link 1991). Most published work on such play targets is primarily focused on their spatial configurations and characteristics, sedimentary processes and distribution patterns, as well as slope and base of-slope fan systems and their effects on the distribution, quality, and reservoir architecture of submarine turbidite reservoirs. These reservoirs often have complex architectures and lithological variations. There is a wealth of literature on reservoir characterization, diagenetic cements, and reservoir heterogeneities (Prosser *et al.* 1995; Watson *et al.* 1995; Dutton *et al*. 2003).

Predicting subsurface porosity and permeability is a key challenge for hydrocarbon exploration and development when there is little subsurface data available. Samples from outcrops may provide an important source of data for the study of correlative reservoirs and provide the exploration geoscientists with the opportunity of observing sedimentary structures, lateral facies changes, and three-dimensional spatial relationships of correlative subsurface rocks. Outcrop-based samples also help geologists understand the burial history and the role of different diagenetic modifications on reservoir properties, which lead to prediction of porosity and permeability of subsurface reservoirs (Tobin 1997).

The exploration of turbidite sandstones is complicated since the quality of sandstone reservoirs in continental deposits is known to be affected by various geological processes, such as tectonic setting, depositional environment, mineral composition and basin fluid flow (Surdam *et al.* 1989; Gier 2000; Ketzer *et al.* 2002; Sachsenhofer *et al.* 2006). Although turbidite plays of the NE Aegean Sea (e.g., Lemnos) could serve as possible loci for hydrocarbon accumulation (Maravelis & Zelilidis 2010a); little is known about their reservoir quality and its controls on these Palaeogene sandstones. The objective of this study is to provide original sedimentological, porosity-permeability and textural parameter data to the study of these clastic sediments in order to define reservoir porosity.

Geological Setting

The study area lies in NE Aegean Sea, Greece. The plate configuration of the Aegean region (Figure 1) consists of the Aegean Plate to the south separated by a strike-slip boundary (McKenzie 1970; Papazachos *et al.* 1998) from the Eurasian Plate to the north, which encompasses the north Aegean, Rhodope and adjacent areas. The Aegean Plate is overriding the African Plate, accommodated by northeastward dipping subduction in the Hellenic Trench. The strike-slip boundary between the Aegean and the Eurasian plates (the north Aegean transform zone) consists of two major strike-slip faults, which are extensions of the North Anatolian Fault. Convergence between the Eurasian and African plates has played a key role in controlling magmatism in the Balkan Peninsula since the Late Cretaceous period. During this time, collision resulted in the formation of several sub-parallel southward migrating magmatic belts with the youngest one being the present-day Aegean Arc (Fyticas *et al.* 1984).

During the late Eocene–early Oligocene, magmatic activity, caused by the subduction of the African Plate beneath the Eurasian Plate, occurred in the Macedonian-Rhodope-North Aegean region (Harkovska *et al.* 1989; Marchev & Shanov 1991). The magmatic belt extends to the NW into Skopje and Serbia, crossing the Vardar Zone (Bonchev 1980; Cvetkovic *et al.* 1995) and continues to the SE in the Thracian Basin and Western Anatolia (Yılmaz & Polat 1998; Aldanmaz *et al.* 2000).

A subduction mechanism has been proposed to explain late Cretaceous magmatism in the Rhodope Zone (Dabovski 1991). High-precision U-Pb zircon and rutile age dating in the Central Rhodope area indicates a southward shift of this magmatism from 92 to 78 Ma (Peytcheva *et al.* 2002). The progressive southward migration of magmatic activity in the Aegean region (Fyticas *et al.* 1984) that commenced in the Rhodope in the Late Eocene (Yanev *et al.* 1998), has been confirmed by seismic tomography (Spakman *et al.* 1988), implying that present day north-vergent subduction in the Aegean region started at least 40 Ma ago.

It is generally believed that extension in the Greek part of the Rhodope Zone did not start

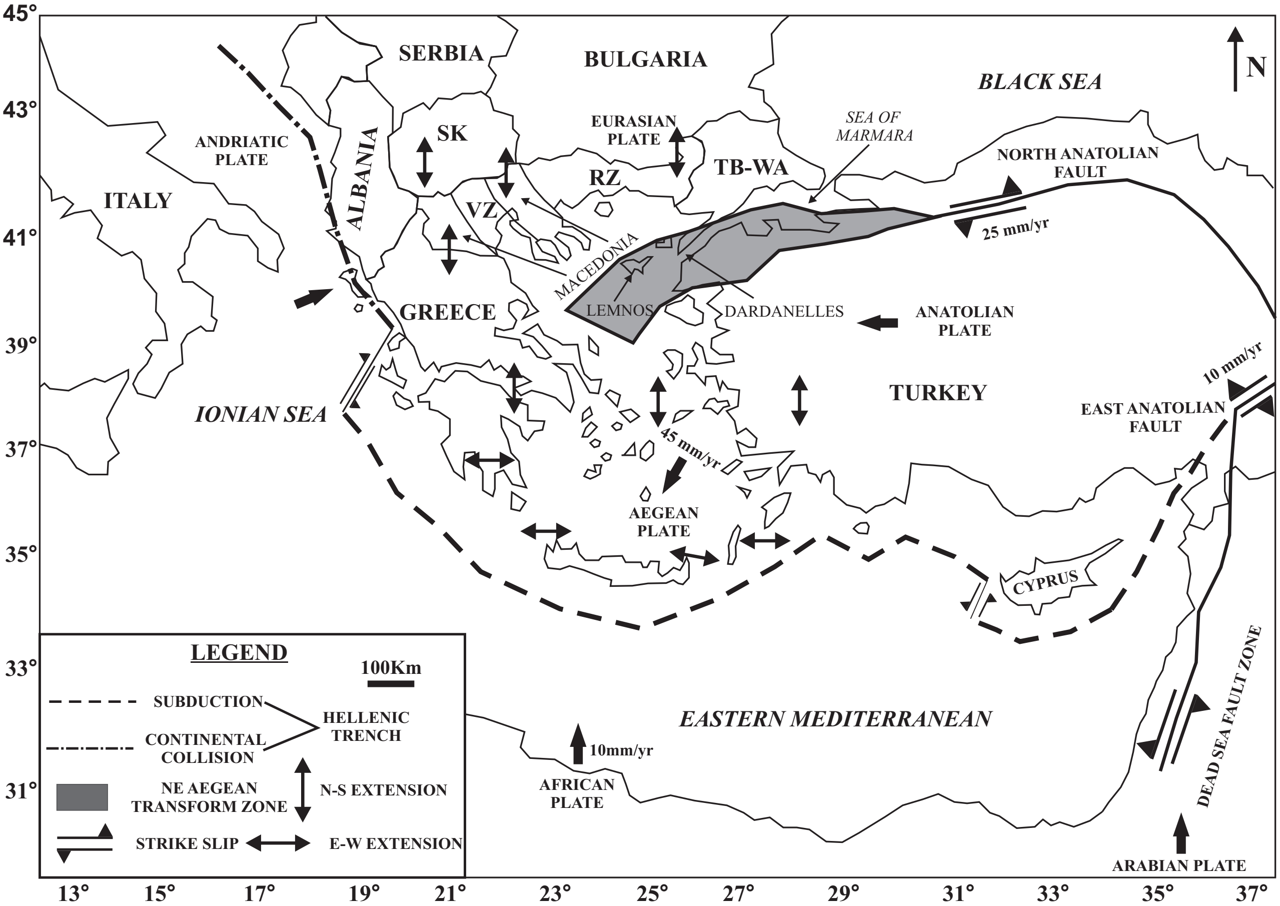

Figure 1. Plate tectonic configuration of the area around the Aegean (modified from Papazachos *et al.* 1998). SK– Skopje, RZ– Rhodope Zone, VR– Vardar Zone, TB-WA– Thrace Basin-Western Anatolia.

before the Early Miocene (Dinter & Royden 1993; Dinter 1994; Dinter *et al.* 1995). The Aegean region has experienced back-arc extension, related to the Hellenic subduction system, from the latest Oligocene to the present day (McKenzie 1978; Le Pichon & Angelier 1979; Meulenkamp *et al.* 1988), while back-arc extension in the Aegean area was (apparently) initiated between 15 and 20 Ma ago (Angelier *et al.* 1982; Jolivet *et al.* 1994). The extension started to be modified about 5 Ma ago, after the North Anatolian Fault had started to open the Sea of Marmara pull-apart basin and crossed the Dardanelles (Armijo *et al.* 1999). If so, the formation of sedimentary basins in the NE Aegean Sea (e.g., Lemnos) and Oligocene magmatic activity in the Rhodope area may be related to compression rather than extension. During the Late Eocene–Early Oligocene, Lemnos was a forearc basin of the 'contracted' type with the outer arc ridge (that often serves as a dam to pond sediments in the forearc region) as a major contributor of sediments into the forearc basin (Maravelis & Zelilidis 2010b) (Figure 2). This source, which delivered ultramafic, gabbro, basalt, chert and, possibly, some volcaniclastic detritus of variable grain size into the adjacent forearc basin (Lemnos), should be located south-southwest of Lemnos (Central Aegean region?). The source area was probably rugged, with vigorous and erosion, causing the ophiolitic bedrock to be incised deeply and rapidly, allowing a significant amount of coarse-grained material, from a rapidly uplifting source area, to be made available for sedimentation (Maravelis & Zelilidis 2010b).

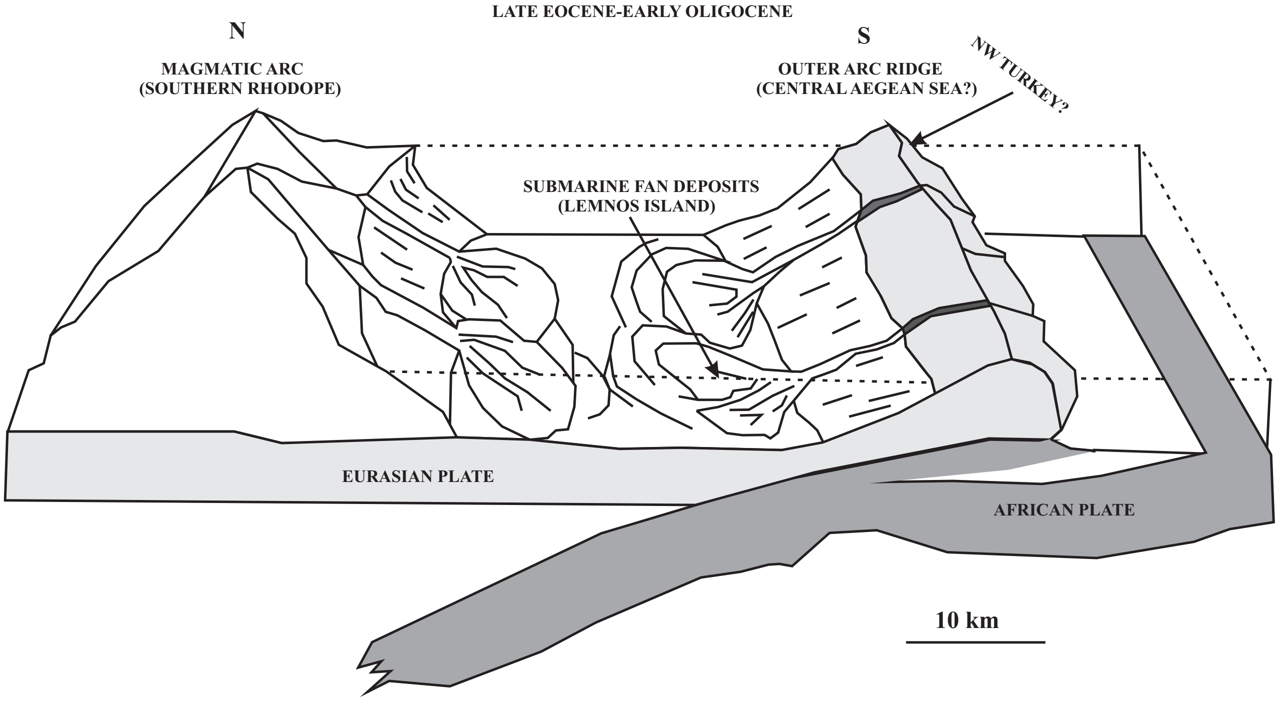

Figure 2. Schematic diagram illustrating the depositional setting of Lemnos (from Maravelis & Zelilidis 2010b).

Thus, the Palaeogene is characterized by deposition in a submarine fan system. Deep-water sediments at the base of the stratigraphic succession in Lemnos take the form of a conventional sand-rich submarine fan system made up of monotonous alternations of sandstone and mudstone. Sediments consist of very thin- to very thick-bedded sandstones and conglomerates, interbedded with hemipelagic mudstones. Sandstones are light brown to light green displaying both complete and incomplete sets of the Bouma sequence. Conglomerates are disorganized or have rare inverse to normal grading, are polimict, and consist of radiolarian, calcareous, arenaceous, gneissic schist, or quartzitic cobbles in an arenaceous cement. Mudstones are brownish and typically lack internal structure although beds with silt laminae have been observed (Maravelis *et al*. 2007).

The overlying shelf environment is characterized by a general fining upward trend. At its base are sandstones that are interbedded with very thin mudstone beds. Many sandstones appear featureless, although others show grooves and tool marks. Internal structures are dominated by a prominent parallel lamination. The sandstone beds show, generally a single set of ripple cross-laminae at the top. Mudstones commonly contain a high proportion of coal debris. Upwards, this unit grades from a sand-dominant to an almost completely mud-dominant sequence that consists of massive, homogeneous green or green-grey mudstones (Maravelis *et al*. 2007).

During the Miocene, Lemnos was the site of volcanic activity and magmatic rocks overlie the shelf deposits (Pe-Piper & Piper 2001). Magmatic rocks consisting of both plutonic and volcanic rocks, are principally trachyandesites and dacites, and cover a large part of the studied area. The igneous rocks are considered to belong to the one high-K province along the Aegean-Anatolian-Frontier, the Northern one, the 'Shoshonitic Province' of Pe-Piper *et al*. (2009) that includes the islands of Samothrace, Lemnos and Lesvos and runs 200 km into Western Anatolia and the Northern part of Chios and İzmir (Smyrna). These high-K rocks, mostly of intermediate composition, indicate ensuing calc-alkaline orogenic volcanism, emitted from large volcanic centres. Upwelling of asthenospheric mantle has been invoked to account for their genesis (Pe-Piper *et al.* 2009). The end of the Miocene is characterized by the deposition of conglomerates, marls and calcareous sandstones. Local Pleistocene porous calcareous and locally oolitic limestones and Holocene alluvial, coastal deposits and dunes are sparse in Lemnos (Figure 3).

Cenozoic	Holocene		alluvium coastal deposits dunes
	Pleistocene		porous, calcareous and oolitic limestones
	Pliocene	late	conglomerates, marls and calcareous sandstones
		early	
	Miocene	late	
		mid	volcanic rocks
		early	
	Oligocene	late	
		early	shelf sub-marine fans
	Eocene	late	

Figure 3. Generalized chart of the Late Eocene to Holocene stratigraphy of Lemnos, showing the position of the studied sediments.

Methodology

Samples were selected for both porosity-permeability and grain-size investigation with a view to investigate the entire stratigraphic succession of the studied area (Figure 4) and the lateral extent of the sedimentary units (Figure 5). Porosity-Permeability data were obtained using the 'Mercury Porosimetry Technique' as proposed by Ritter & Drake (1945) and Katz & Thompson (1986, 1987) on 20 sandstone samples. These analyses were undertaken at the Institute of Chemical Engineering and High Temperature Chemical Processes, Patras, Greece. Most of the selected samples are turbiditic sandstones, while one shelf-derived sample was selected for reservoir analysis (Figure 4).

In order to evaluate the grain-size, 30 sandstone samples (28 of turbititic origin and 2 of shelf-derived) were collected, prepared and examined under a polarizing microscope. Grain-size was determined using the method of Johnson (1994) and 300 detrital grains were counted in each sample. This number can provide accurate results even in medium-grained sandstones. By means of point counting the standard deviations were also calculated and were determined the grade of sorting of the selected sandstones. Johnson (1994) suggested that standard deviation of 0.45 φ or less characterize very well-sorted sandstones, standard deviations of 0.45 to 0.55 φ well-sorted sandstones, values of 0.55 to 0.70 moderately-sorted, 0.7 to 0.9 φ poorly-sorted while very poorly-sorted sandstones are designated by standard deviation values greater than 0.9 φ.

Reservoir Characteristics

Sedimentary Patterns

The study area largely comprises turbidites that have been interpreted as parts of a sand-rich submarine fan in a base of slope to basin floor environment, overlain by shelf deposits. The turbidity system is composed of a 'basin floor' fan underlying a 'slope' fan, and was constructed under the synchronous interaction of both progradation and aggradation processes. The 'basin floor' fan is the more distal and lower, unchannelized fan and is composed of lobe, lobe-fringe and fan-fringe deposits. The 'slope' fan consists of channel-overbank deposits, demonstrating greater proximity to the source area (Maravelis *et al.* 2007).

Bedding in the 'basin floor' fan is relatively simple, parallel, and regular, while the lateral bed continuity is relatively high. 'Slope' fans display a complicated bedding pattern with vertical and lateral random distribution of channel fills, axial erosion, and bed convergence towards the channel margins. The system presents an overall braided character to the fan surface with the formation of both sheet-like and lobate sand bodies, due to the low volume of fine-grained material within this system that prevents the development of confined and stable channels.

The CC (sensu Posamentier *et al.* 1988; Posamentier & Allen 1999) is not visible in the submarine fans of the study area; hence the change in strata stacking patterns from highstand normal regression to forced regression cannot be mapped. Thus, the studied sediments suggest deposition slightly after the onset of forced regression, passing through the two stages of forced regression until

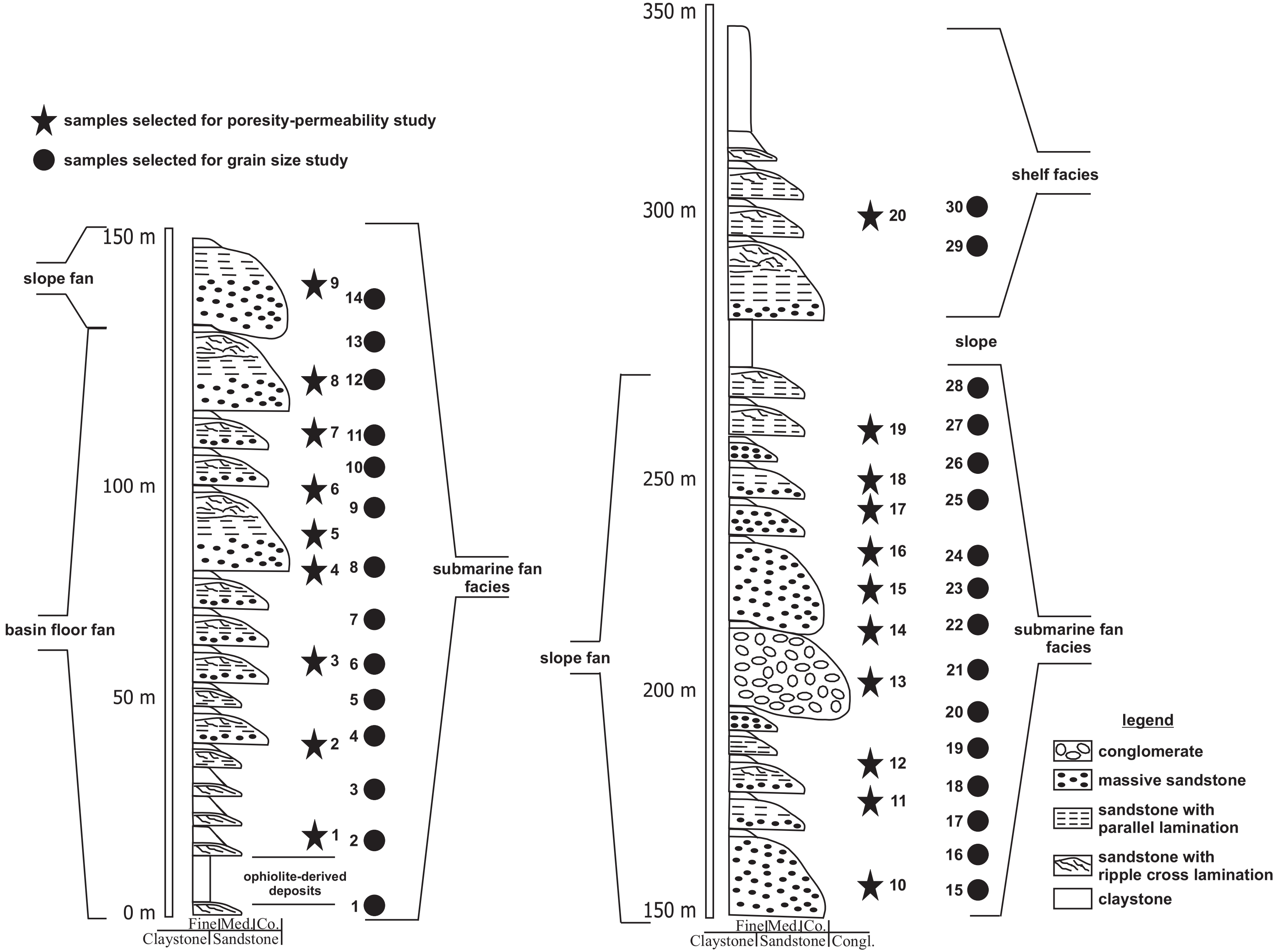

Figure 4. Synthetic stratigraphic succession of Lemnos during the Late Eocene–Early Oligocene. Cycles and stars mark the position of the samples selected for grain-size and porosity-permeability study (see Figure 5 for sample distribution on Lemnos).

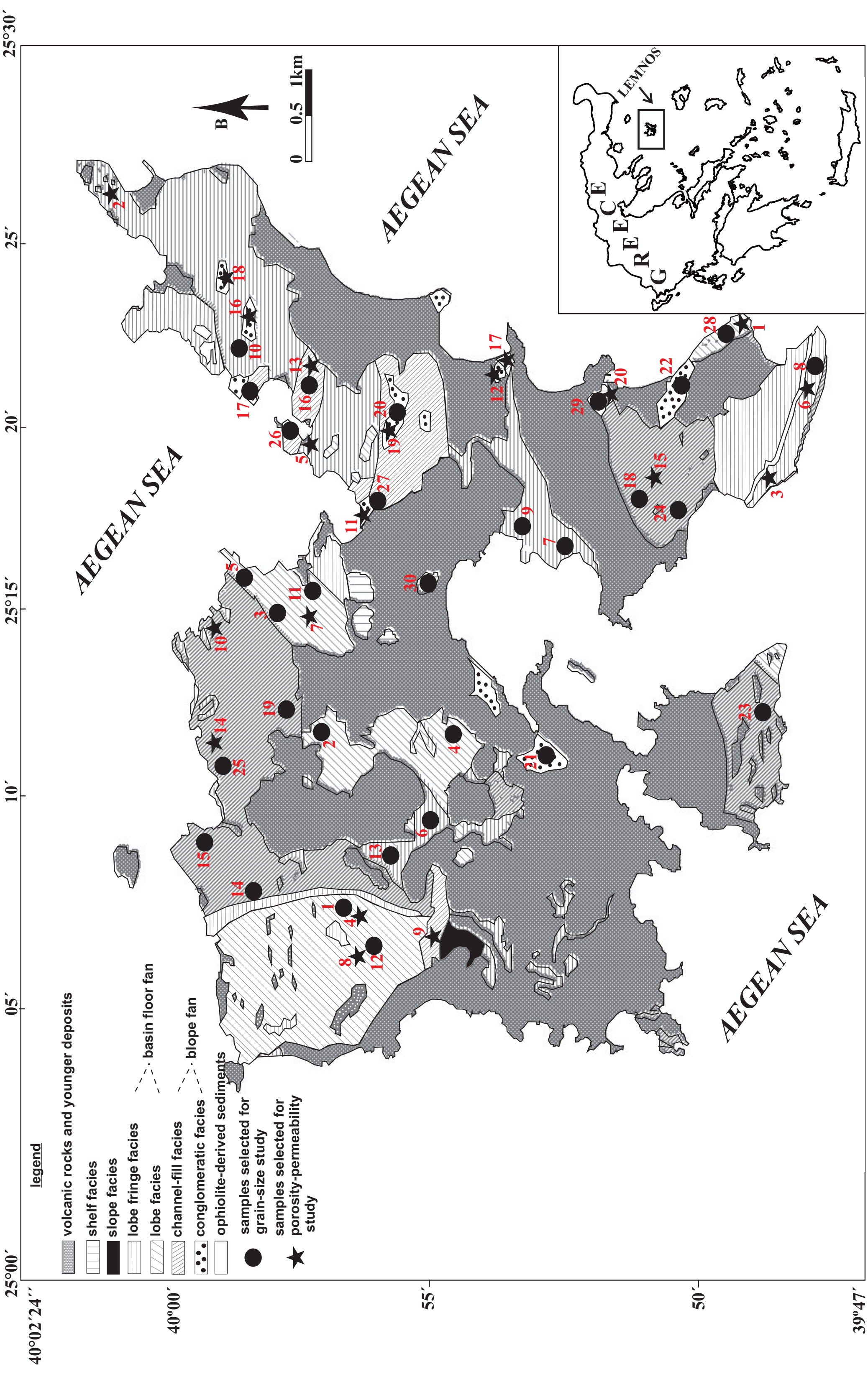

Figure 5. Geologic map of Lemnos , showing the distribution of the various sedimentary facies. Spots and stars mark the position of the samples selected for grain-size and porosity-permeability study (see Figure 4 for their exact location within the sedimentary succession).

the onset of lowstand normal regression (Maravelis & Zelilidis 2011). Organic-rich mudstone or shale is commonly interbedded with turbidites and these could serve as both source rocks and seals.

Porosity-Permeability of Outcrop Samples

Porosity is the void space in a rock. It is commonly measured as either a volume percentage or a fraction (expressed as a decimal). In this study the percentage form is used, revealing that the selected sandstones display porosity values that oscillate between 2.4% to 27% (Table 1). Permeability and reservoir quality are a function of how the pore spaces are connected, their type and distribution, and the pore throat sizes. The application of the 'Mercury Porosimetry Technique'on the Palaeogene sandstones of Lemnos indicate that the selected samples display a wide range of permeability values that oscillate between 0.0039 mD and 154 mD (Table 2). The application of Levorsen's (1967) classification suggests that, according to their porosity and permeability values, selected samples are of four types: non-reservoirs, with values 0-5% and <1 mD (samples 1 and 14); low-reservoir quality, with values 5–10% and<1 mD (samples 2, 3, 5, 7, 8, 10, 11, 13 and 16); moderate reservoirs, with values 10–15% and 1–10 mD (samples 6, 9, 17, 18 and 19); good reservoirs, with values 15–20% and 10–100 mD (samples 12 and 15) and very good quality reservoirs with values 20–25% and >100 mD (sample 4). Permeability value is a primary index to define the potential of the rocks to form oil or gas reservoirs. The exact value will depend upon the nature of the petroleum and the complexity of the reservoir. Permeability may exceed 10D in the best reservoirs, but in many reservoirs it may only be tens to hundreds of mD. At the lower end, gas may be produced from reservoirs of 0.1mD (samples 2, 3, 6, 9, 13, 16, 17 and 18). Gas reservoirs can still perform with a mean permeability of as little as 1 mD (samples 6, 9, 17, 18 and 19), while 10 mD is often accepted as the lower limit for light oil (samples 4, 12 and 15).

Pore-Throat Structure Probed by Mercury Porosimetry

Heterogeneities from the complex pore-throat structures of sandstone reservoirs in continental environments may yet be an important textural feature, playing a crucial role in the transport behaviour of reservoir liquids and prediction of the next-step strategies of petroleum exploration and exploitation (Chowdhury & Noble 1992; Sachsenhofer *et al.* 2006).

Mercury porosimetry is a powerful tool to effectively probe the pore structures at the meso-to macro-scales (4–400 mm). In mercury porosimetry

Table 1. Porosity (%) values and sedimentary facies of 20 selected outcrop samples from Lemnos sandstones (see figures 4 and 5 for their exact location within the sedimentary succession and for sample distribution on Lemnos respectively).

Sample No	Porosity (%)	Sedimentary facies	Sample No	Porosity (%)	Sedimentary facies
1	2.4	lobe-fringe	**11**	12	channel-fill
2	12.3	lobe-fringe	**12**	15.4	channel-fill
3	7.2	lobe-fringe	**13**	14.7	channel-fill
4	24.8	lobe	**14**	3.0	channel-fill
5	8.6	lobe	**15**	24.9	channel-fill
6	12.2	lobe	**16**	11	channel-fill
7	5.9	lobe	**17**	13.4	channel-fill
8	7.9	lobe	**18**	13.1	channel-fill
9	27	channel-fill	**19**	14.8	channel-fill
10	8.1	channel-fill	**20**	14	shelf

Table 2. Permeability (mD) values and sedimentary facies of 20 selected outcrop samples from Lemnos sandstones (see figures 4 and 5 for their exact location within the sedimentary succession and for sample distribution on Lemnos respectively).

Sample No	Permeability (mD)	Sedimentary facies	Sample No	Permeability (mD)	Sedimentary facies
1	0.0039	lobe-fringe	**11**	0.085	channel-fill
2	0.23	lobe-fringe	**12**	26.8	channel-fill
3	0.58	lobe-fringe	**13**	0.41	channel-fill
4	154.0	lobe	**14**	0.0054	channel-fill
5	0.021	lobe	**15**	12.7	channel-fill
6	6.3	lobe	**16**	0.13	channel-fill
7	0.0085	lobe	**17**	2.1	channel-fill
8	0.031	lobe	**18**	4.3	channel-fill
9	3.6	channel-fill	**19**	3.3	channel-fill
10	0.071	channel-fill	**20**	0.051	shelf

experiments, the volume of mercury penetrating into or receding from porous samples can be measured as a function of the applied hydraulic pressure. The obtained mercury intrusion and extrusion curves may be theoretically interpreted as pore size distributions in terms of the Washburn equation ($R= 2\gamma\cos\theta/P$), in which the applied hydraulic pressure, p, is related to the cross-sectional radius, R, of pore-throats accessible by the pressured mercury, together with two material-related thermodynamic parameters: surface tension of mercury, γ, and its contact angle, θ, with the sample material involved (Washburn 1921; Leon y Leon 1998).

Typical mercury intrusion curves, i.e. frequency versus pore throat diameter, are presented in Figure 6. They have similar profiles displaying two pore-size distributions, suggesting major textural heterogeneity (except sample 1). This feature could affect Lemnos reservoir quality by decreasing permeability. Even though sandstones display permeability values lower than their great porosity values (more than 10%), this feature was not of great importance since their permeability values are sufficient to consider these rocks as both oil and gas reservoirs.

Sandstone Texture and Composition

The studied sandstones are light brown to light green in hand specimen and are commonly interbedded with brownish mudstone (Maravelis *et al.* 2007). Compositionally they are lithic-arenites; point counting of thin-sections has shown that these rocks have stable clastic ingredients with the most common detrital grains being 40–58.4% quartz, 10–23% feldspar and 16.2–35.7% lithic fragments (Maravelis & Zelilidis 2010b). After quartz, lithic fragments are the most abundant component in the Lemnos sandstones. A wide variety of fragments has been observed in thin sections, including metamorphic (schist rock fragments), sedimentary (microcrystalline chert and sandstone rock fragments) and igneous (felsic plutonic granite and mafic volcaniclastic basalt fragments) lithic fragments Petrofacies analysis suggest that the metamorphic, sedimentary and plutonic igneous rocks, in a recycled orogenic environment, were the most important source rocks for the studied sediments (Maravelis & Zelilidis 2010b) (Figure 7).

Apart from these principal components, petrographic modal analysis revealed the presence

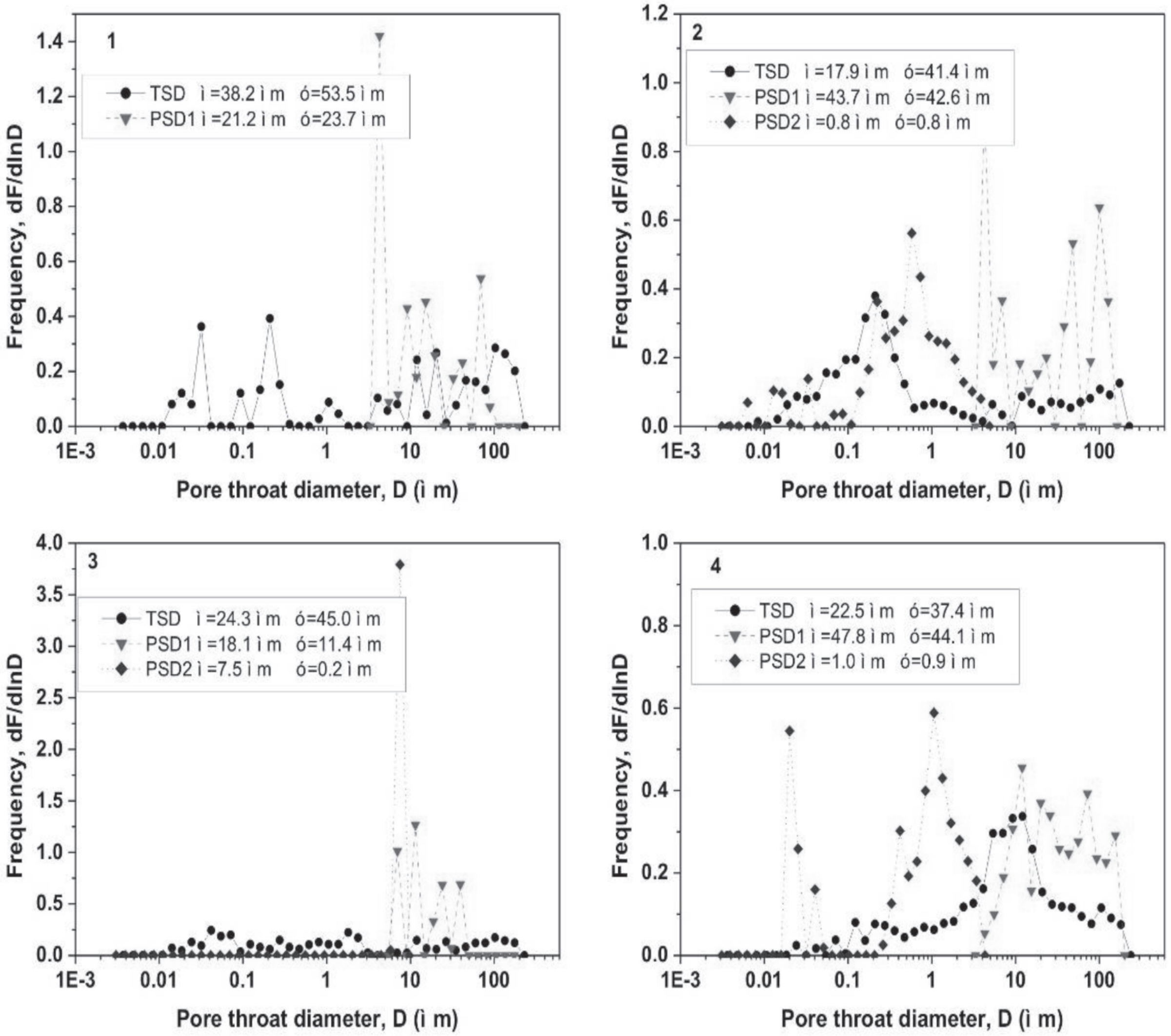

Figure 6. Typical mercury intrusion curves, frequency versus pore throat diameter. TSD– Throat-Diameter Distribution, PSD– Pore-size Distribution.

of a variety of heavy and accessory minerals, most commonly well-rounded, green/brown rutiles and tourmalines, while apatite, biotite, muscovite, chlorite and glauconite grains are the most important accessory minerals (Maravelis & Zelilidis 2010b).

Lithological features for each sample are summarized in Tables 3 and 4. The studied sandstones are classified as very fine grained to medium grained and comprise mostly moderately to very well-sorted lithic-arenites. There is no obvious relationship between sub-environments and textural parameters in these sediments, whereas the finer the sand grain-size, the better-sorted the sandstones. In general, textural parameters such as grain-size and sorting have effects on the porosity and permeability of reservoir facies. The amount of porosity lost will depend largely on how well-sorted the sand is. In a poorly-sorted sand, more porosity will be lost than in well-sorted sand, with the little grains filling in between the bigger ones (Vesic & Clough 1968). The finer the sand grain-size, the lower the permeability. The better-sorted sandstones tend to have higher porosity (Beard & Weyl 1973).

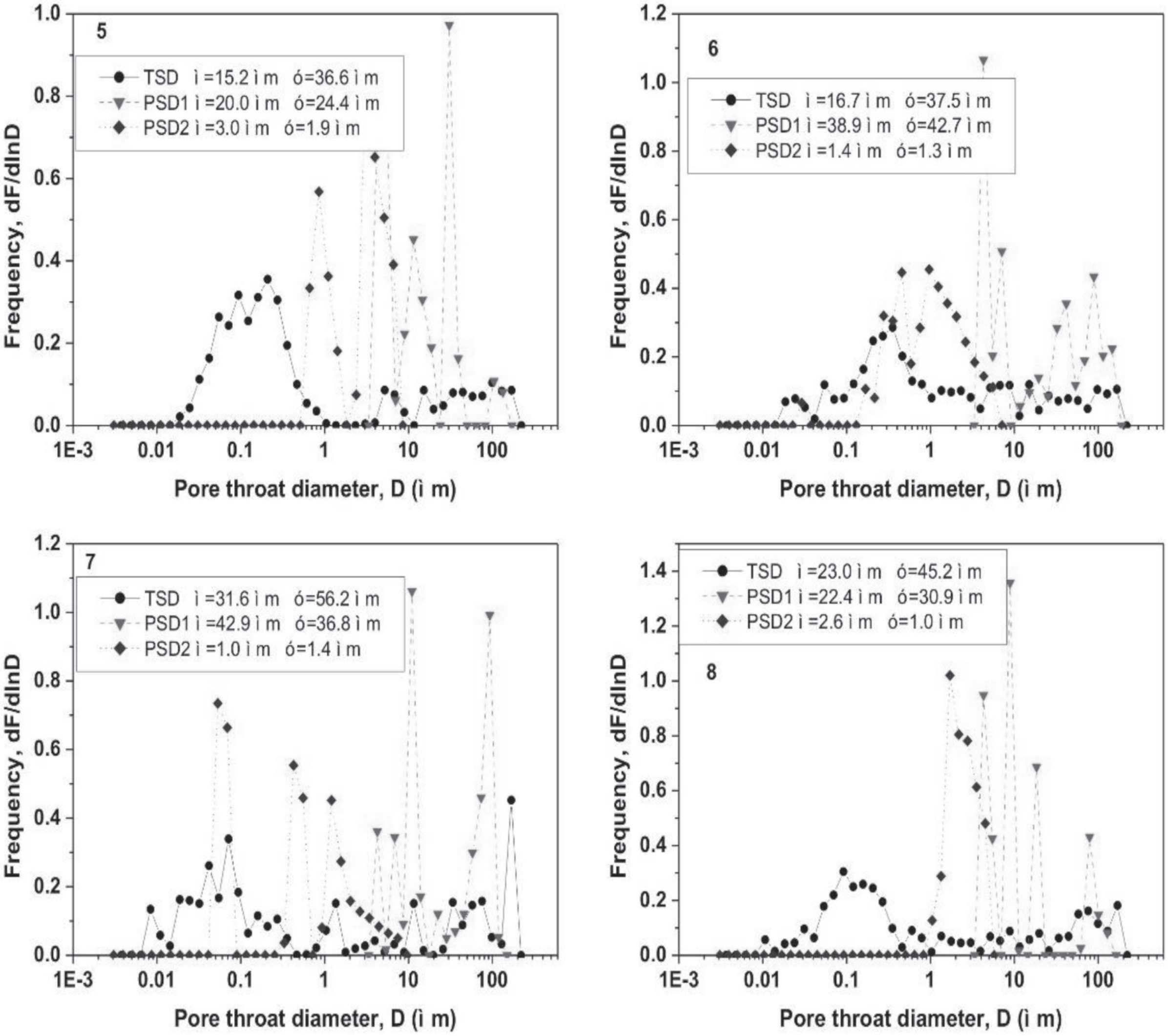

Figure 6. Continued.

Discussion

The NE Aegean Sea and surrounding areas have been the focus of hydrocarbon exploration during the last two decades of the 20th century. Many authors have described the oil and gas prospectivity of this tectonically active area, which is now considered to be a proven hydrocarbon province. The Thrace Basin, considered as a fore-arc basin by Görür & Okay (1996), provides a great example of the petroleum potential of the NE Aegean (Turgut *et al.* 1983). Exploration mainly targeted deep plays in Eocene sediments, resulting in several discoveries. Currently there are 14 commercial gas fields and 3 oil fields. A recent discovery has been made in shallower Oligocene sediments (http://www.amityoil.com.au). Similar hydrocarbon potential studies calculating the hydrocarbon potential have been performed in NW Anatolia by Kara Gülbay & Korkmaz (2008).

Given the proven hydrocarbon potential of the NE Aegean Sea and surrounding areas, this study

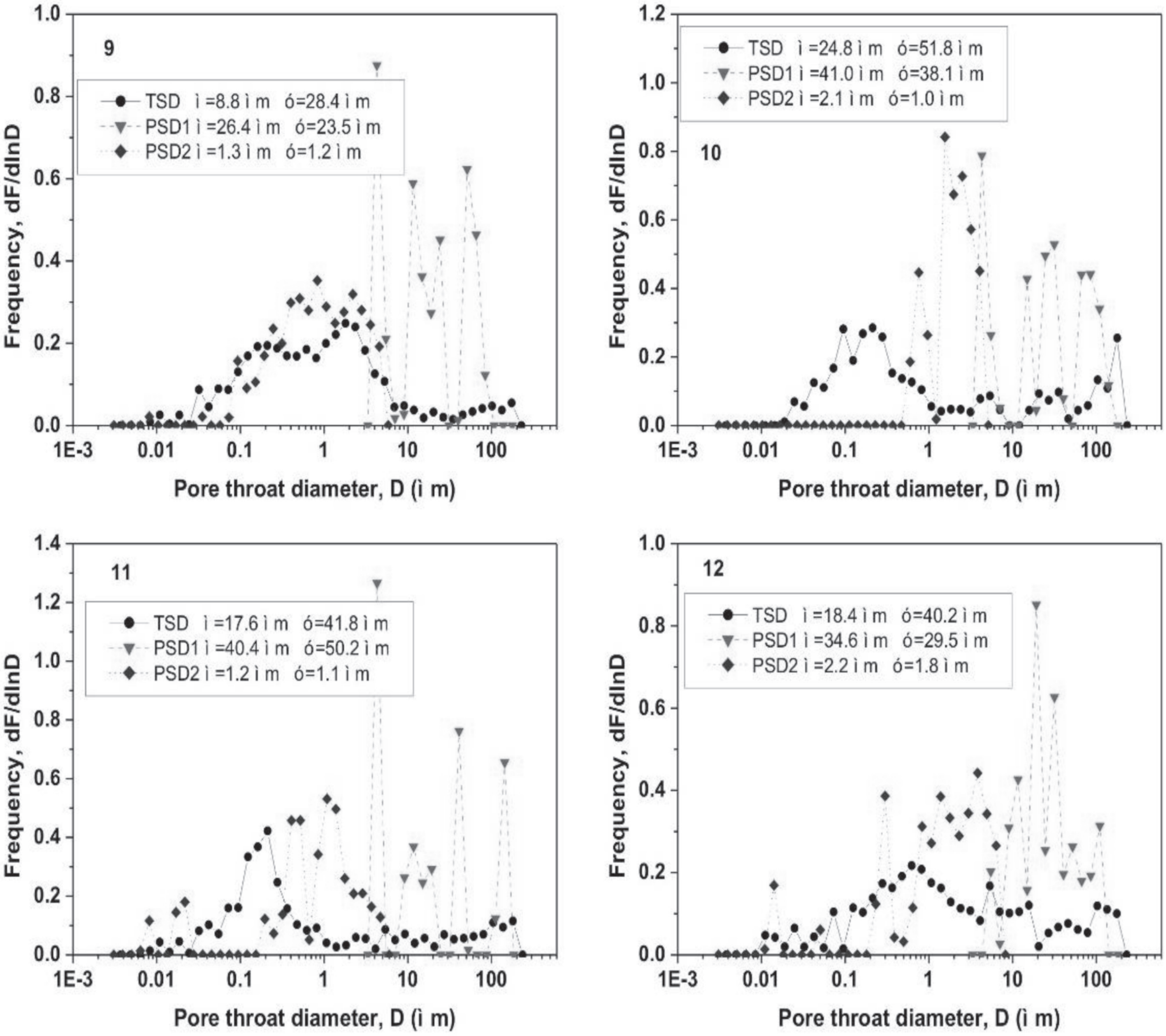

Figure 6. Continued.

attempts to add one more argument for further in-depth exploration by means of reservoir characteristic evaluation of similar to proven oil and gas field deposits.

Geochemical and petrographic data suggest that Lemnos sandstones were deposited in an active continental margin environment and represent the infill of a fore-arc basin of ‘contacted type’. The studied area, during the Palaeogene, lay between the active volcanic arc of the Rhodope Zone, and a structural high, located in the central Aegean Sea. As the sediments have an outer arc ridge-arc derivation, an alternative model of possible multiple sources for the rocks should be considered (Figure 2). This model does not correspond to the studied area and needs further examination, including the lateral correlation of these sediments with coeval submarine fan deposits in adjacent areas (e.g., NW Turkey) (Maravelis & Zelilidis 2010b).

The stratigraphic architecture of the sedimentary sequences within the studied area, characteristically exhibits a successive landward and northward

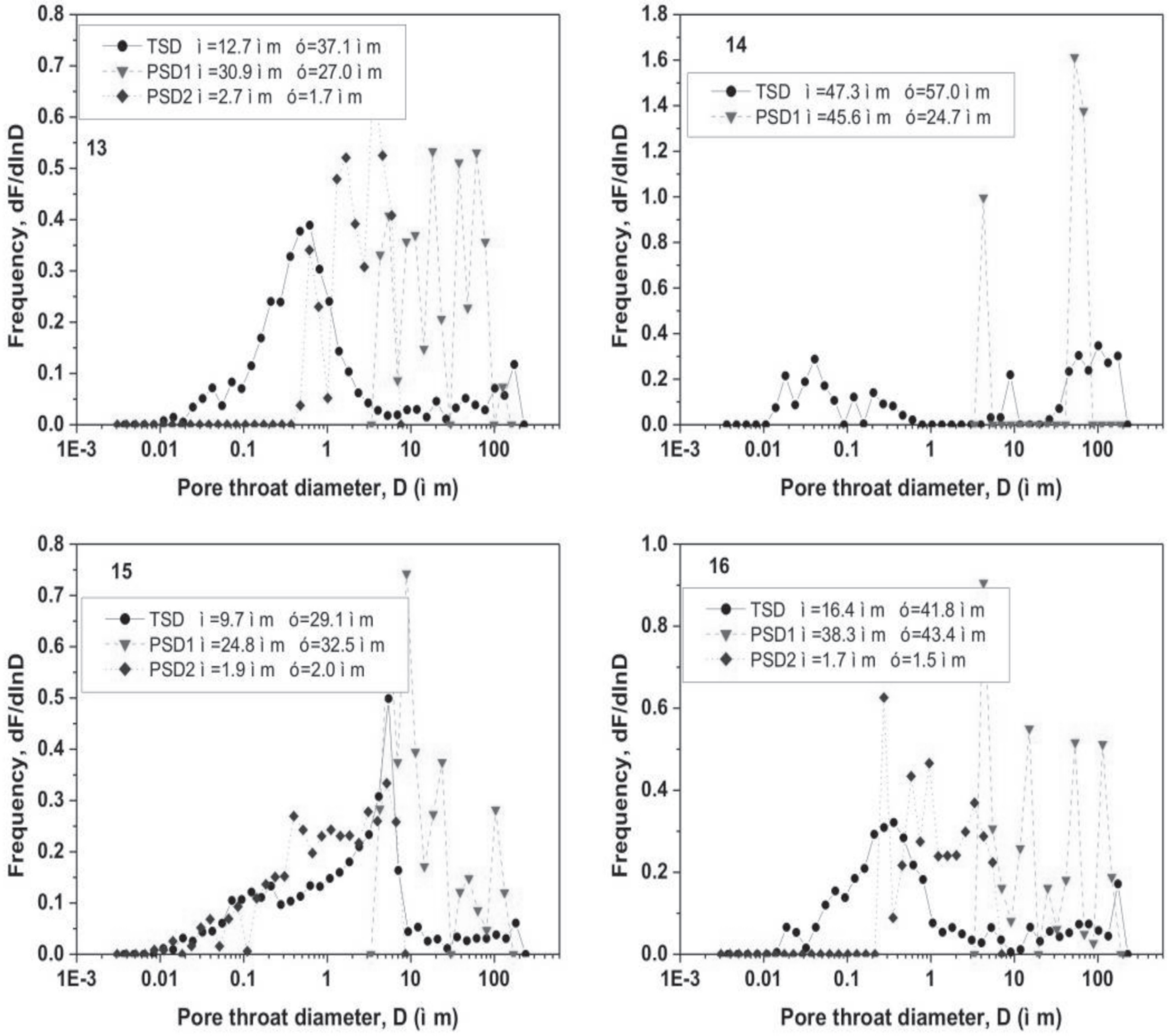

Figure 6. Continued.

migration of the basin depocentre, possibly because the accretionary structural high bounding the oceanward flank of the basin was forced upward and landward by continued accretion at the toe of the margin. The studied turbidity system comprises one outer and one inner fan approximately 300–350 m thick, and the outer fan deposits represent the greater part of the exposed sediments. In the relatively thick (up to 100 m) channelized fan area on Lemnos, only one sediment influx centre is present. The influx centre found in the field is a proximal distributary channel approximately in centre of the fan (Figures 8 & 9) and contains the coarsest sediment in the study area (Maravelis & Zelilidis 2011).

The regional parts of the study area consist mainly of basin floor fan facies (lobe, lobe fringe, and fan fringe facies), while slope fan facies (channel fill and levee facies) are restricted to the central parts. Thus, large regions in the SE and NE of the island consist of lobe deposits, and their laterally equivalent lobe

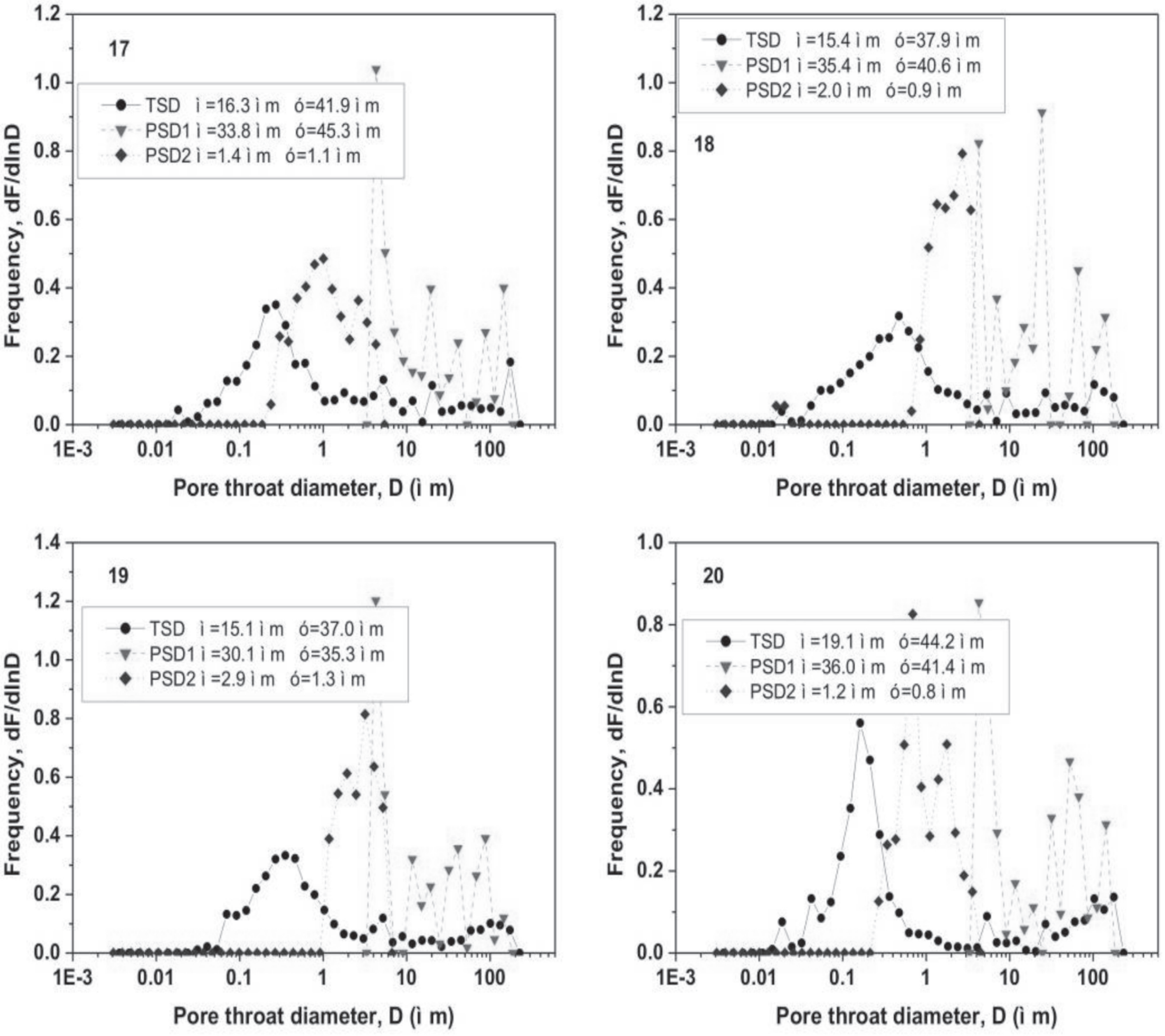

Figure 6. Continued.

fringe deposits (Figure 8 & 10). Lobe fringe facies are represented by underlying slope fan facies (Figure 8 & 11). Slope fan facies are restricted to central parts in both the northern and southern areas (Figure 8 & 12) while the entire stratigraphic succession is shown in figure 13 (Maravelis & Zelilidis 2011).

Generally, 'slope' fan facies, regarding their porosity/permeability values, provide the most promising sub-environment for further hydrocarbon research, in contrast to 'basin floor' fan facies. Nevertheless, 'basin floor' fan facies should also be the subject of further research, since lobe facies the greatest values of both porosity and permeability (Sample No 4). Apart from their reservoir characteristics, Palaeogene sandstones on Lemnos crop out extensively, making them important deposits for further hydrocarbon research. Both 'basin floor fan' facies, with their great lateral continuity, and 'slope fan' facies with their great thickness and lateral extent could serve as possible locations for hydrocarbon accumulation.

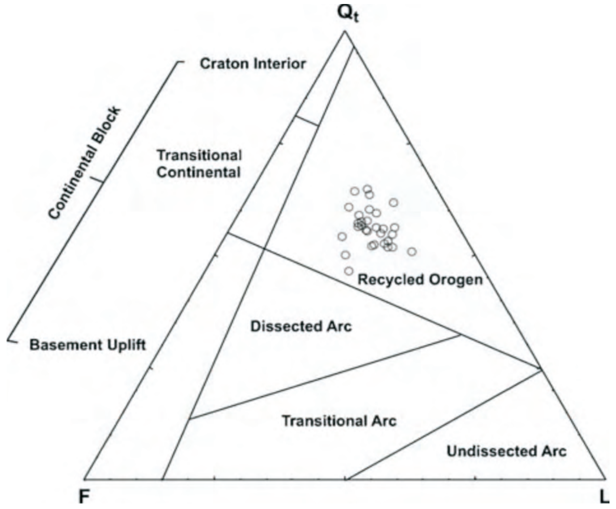

Figure 7. QFL diagram of the selected samples. All the sandstones fall in the Recycled Orogen provenance field (from Maravelis & Zelilidis 2010b).

Conclusions

Based on a comprehensive study of porosity-permeability evolution as well as sandstone textures, the following conclusions can be drawn for the study area that may provide important information about the reservoir quality of these rocks.

- They can be considered as both oil and gas reservoirs.
- Even though the greatest porosity and permeability values were obtained from a sample derived from a 'basin floor' fan (lobe facies), 'slope' fan facies generally display the most efficient values, making them the most promising sub-environment for further hydrocarbon research.
- Mostly they display two pore-size distributions, suggesting major textural heterogeneity.

Table 3. Lithological description for sandstone samples (see Figures 4 and 5 for their exact location within the sedimentary succession and for sample distribution on Lemnos respectively).

sample no	mean grain diameter	grain-size	sample no	mean grain diameter	grain-size
1	3.74 φ	very fine grained	**16**	3.3 φ	very fine grained
2	3,41 φ	very fine grained	**17**	3.39 φ	very fine grained
3	2.71 φ	fine grained	**18**	2.79 φ	fine grained
4	3.84 φ	very fine grained	**19**	1.9 φ	medium grained
5	1.96 φ	medium grained	**20**	2.72 φ	fine grained
6	3.41 φ	very fine grained	**21**	3.02 φ	very fine grained
7	3.14 φ	very fine grained	**22**	3.51 φ	very fine grained
8	1.64 φ	medium grained	**23**	3.46 φ	very fine grained
9	2.87 φ	fine grained	**24**	1.86 φ	medium grained
10	3.57 φ	very fine grained	**25**	1.87 φ	medium grained
11	2.9 φ	fine grained	**26**	1.88 φ	medium grained
12	2.62 φ	fine grained	**27**	3,37 φ	very fine grained
13	1.94 φ	medium grained	**28**	2.69 φ	fine grained
14	3.61 φ	very fine grained	**29**	3.42 φ	very fine grained
15	3.11 φ	very fine grained	**30**	3.5 φ	very fine grained

Table 4. Standard deviation values and grade of sorting for the studied sandstones (see Figures 4 and 5 for their exact location within the sedimentary succession and for sample distribution on Lemnos, respectively).

sample no	sorting	standard deviation	sample no	sorting	standard deviation
1	moderate	0.626 φ	**16**	moderate	0.629 φ
2	very well	0.441 φ	**17**	poor	0.759 φ
3	well	0.519 φ	**18**	well	0.454 φ
4	well	0.526 φ	**19**	moderate	0.546 φ
5	moderate	0.683 φ	**20**	moderate	0.513 φ
6	well	0.545 φ	**21**	well	0.63 φ
7	moderate	0.668 φ	**22**	well	0.456 φ
8	well	0.43 φ	**23**	well	0.455 φ
9	very well	0.474 φ	**24**	moderate	0.68 φ
10	well	0.51 φ	**25**	moderate	0.58 φ
11	well	0.542 φ	**26**	moderate	0.55 φ
12	moderate	0.594 φ	**27**	very well	0.44 φ
13	moderate	0.56 φ	**28**	moderate	0.562 φ
14	moderate	0.642 φ	**29**	well	0.508 φ
15	well	0.475 φ	**30**	moderate	0.556 φ

- Sorting was very important during sedimentation (studied samples are generally well to very well-sorted. Sandstones with moderate sorting do occur, while poor sorting was seen in only one sample).
- Selected lithic-arenites are generally very fine- to fine-grained, whereas medium-grained sandstones are extremely rare and mostly seen on ‘slope’ fan facies.
- The finer the sand grain-size, the better-sorted the sandstones.

Summarizing, the above study suggests that the Palaeogene forearc sedimentary fill on Lemnos, NE Greece should be the subject of further hydrocarbon research since the porosity-permeability values allow their consideration as both oil and gas reservoirs. These rocks consist of generally fine-grained and well-sorted sandstones.

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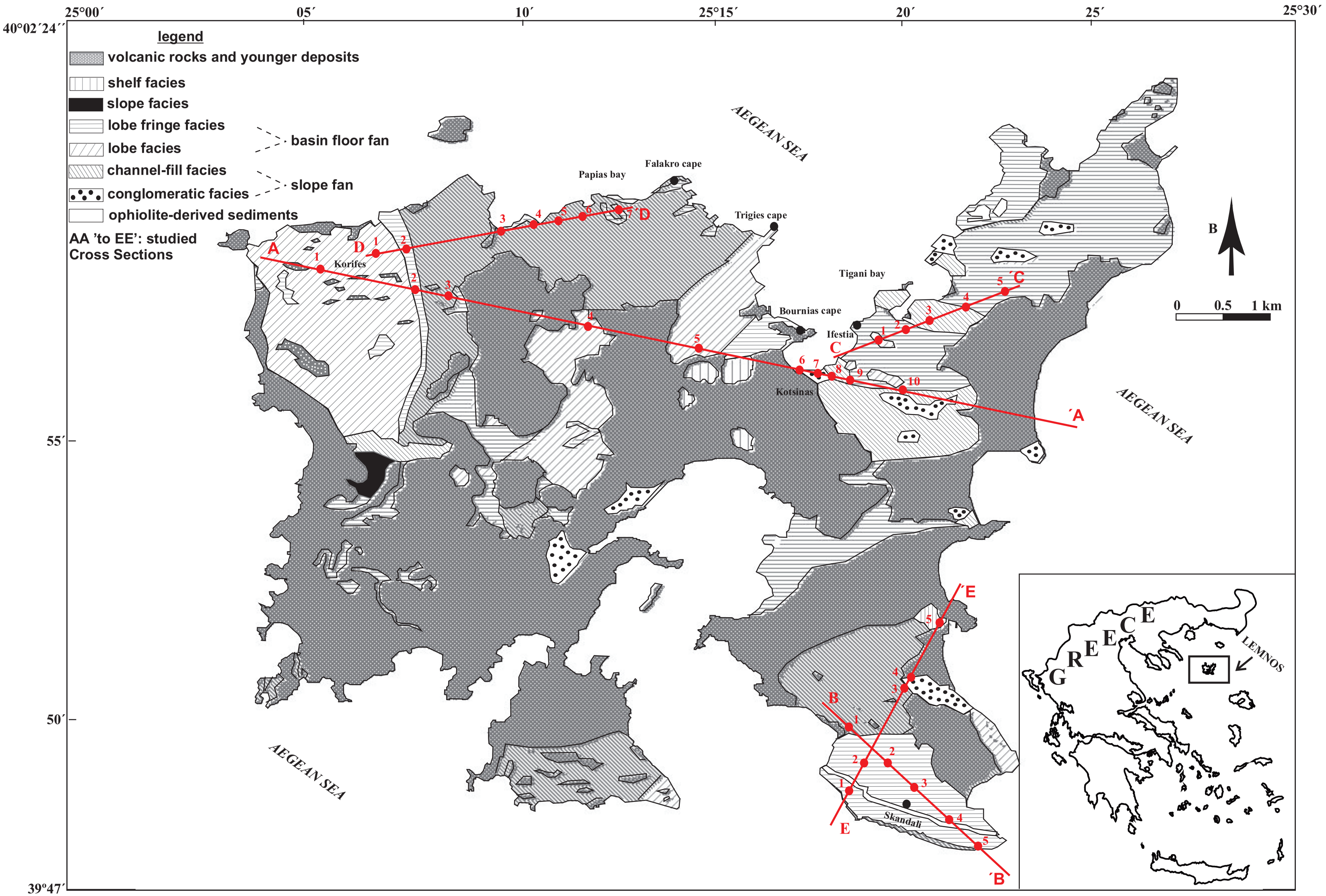

Figure 8. Geological map of Lemnos with selected cross-sections for better understanding of the sediment distribution (from Maravelis & Zelilidis 2011).

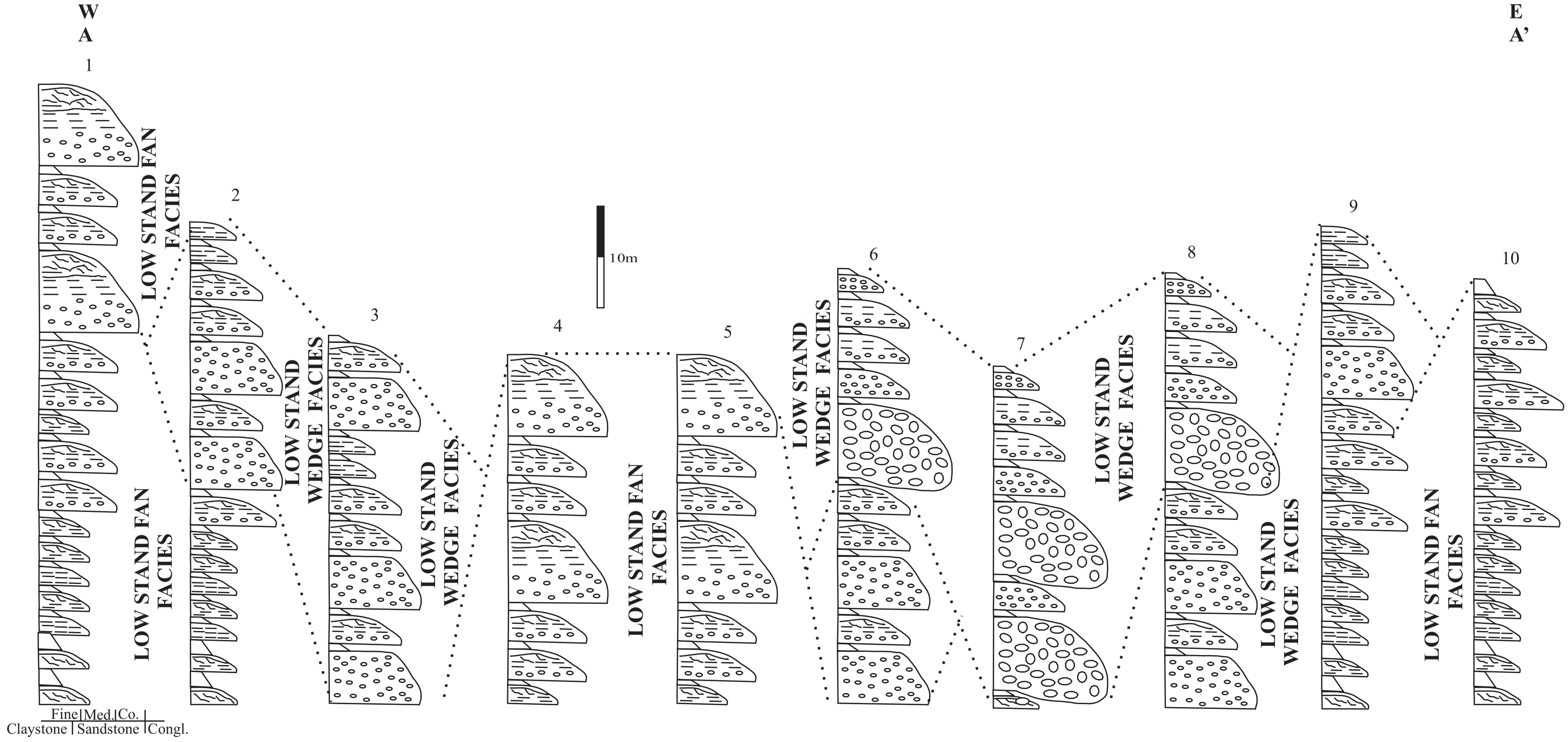

Figure 9. Constructed perpendicular to the main palaeocurrent regime displaying lateral evolution of the sedimentary facies (from Maravelis & Zelilidis 2011). Legend as in Figure 4.

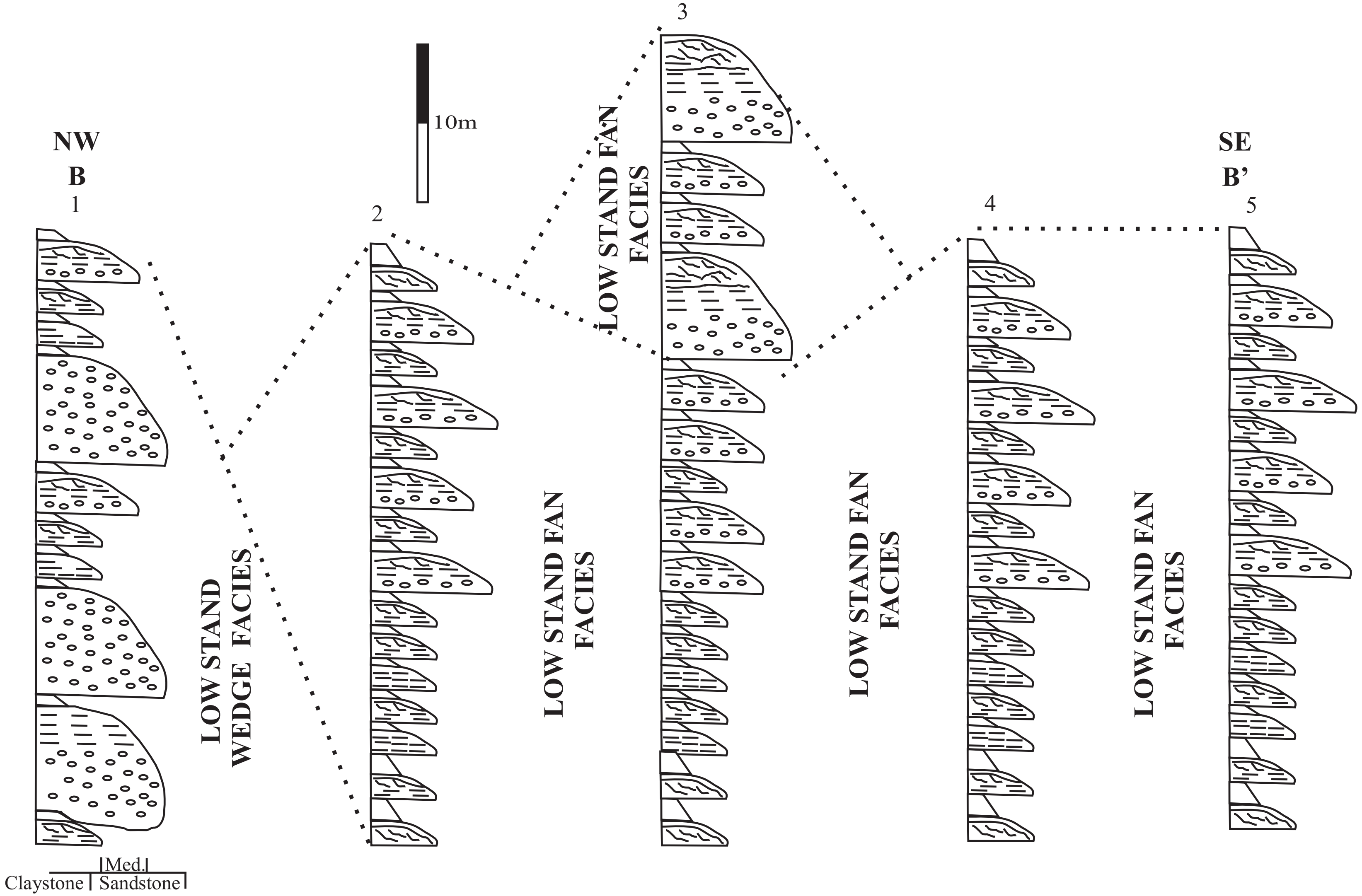

Figure 10. Constructed perpendicular to the main palaeocurent regime. Lobe deposits and their lateral equivalents lobe fringe deposits (from Maravelis & Zelilidis 2011). Legend as in Figure 4.

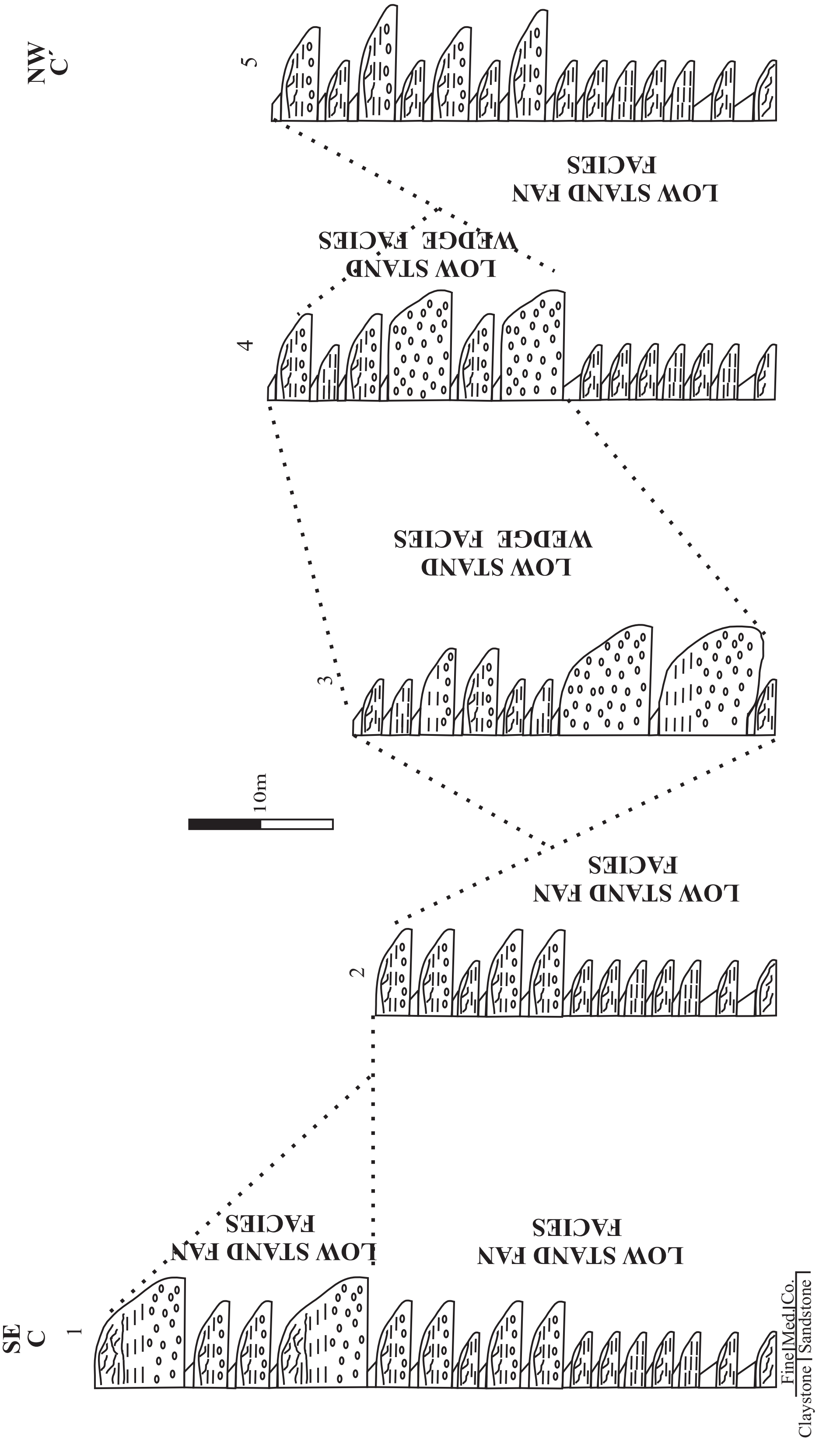

Figure 11. Lobe deposits and their laterally equivalent lobe fringe deposits (from Maravelis & Zelilidis 2011). Legend as in Figure 4.

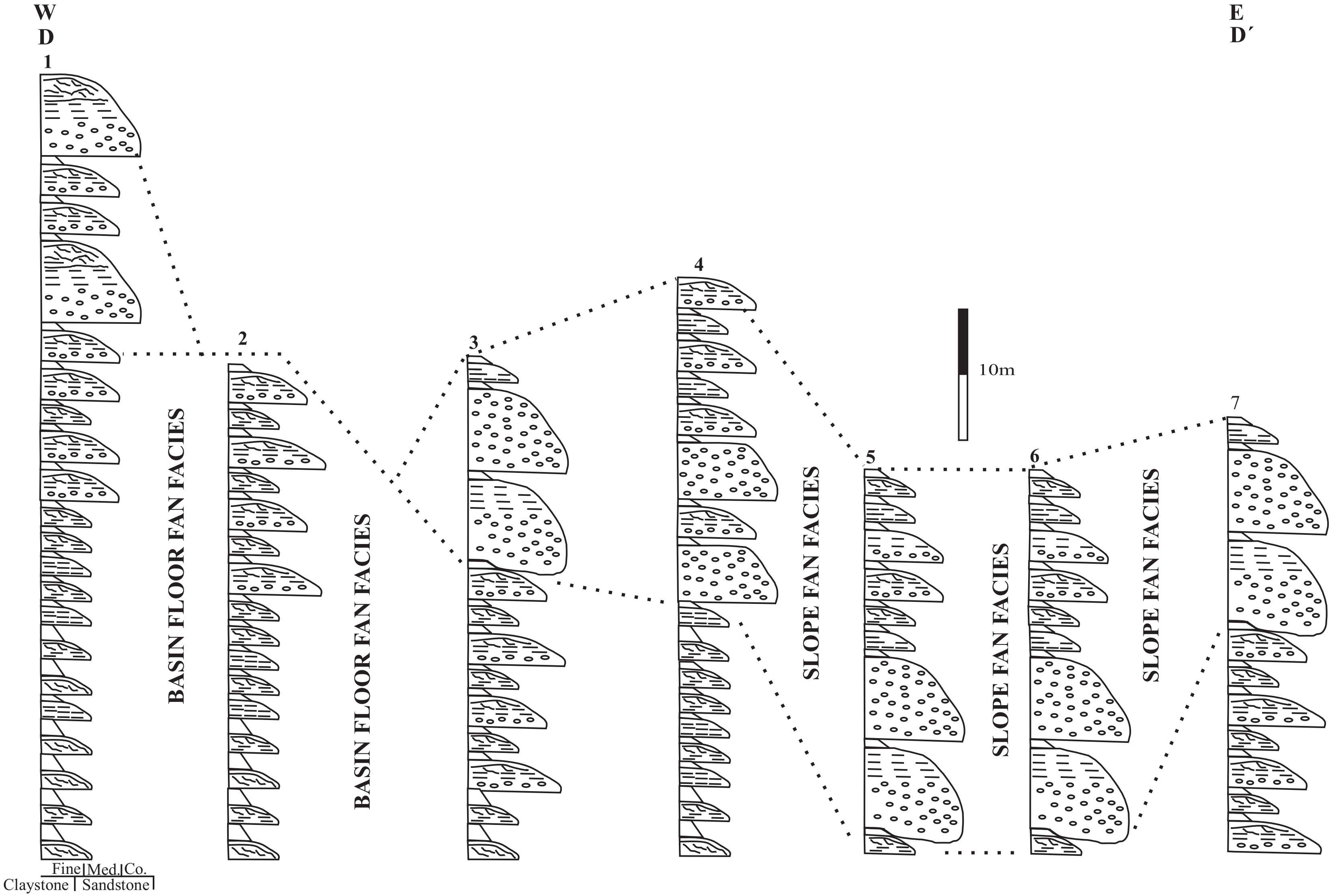

Figure 12. Limited lateral continuity of the channel fill facies. Note that lobe facies evolve laterally to lobe fringe facies that underlie channel deposits (from Maravelis & Zelilidis 2011). Legend as in Figure 4.

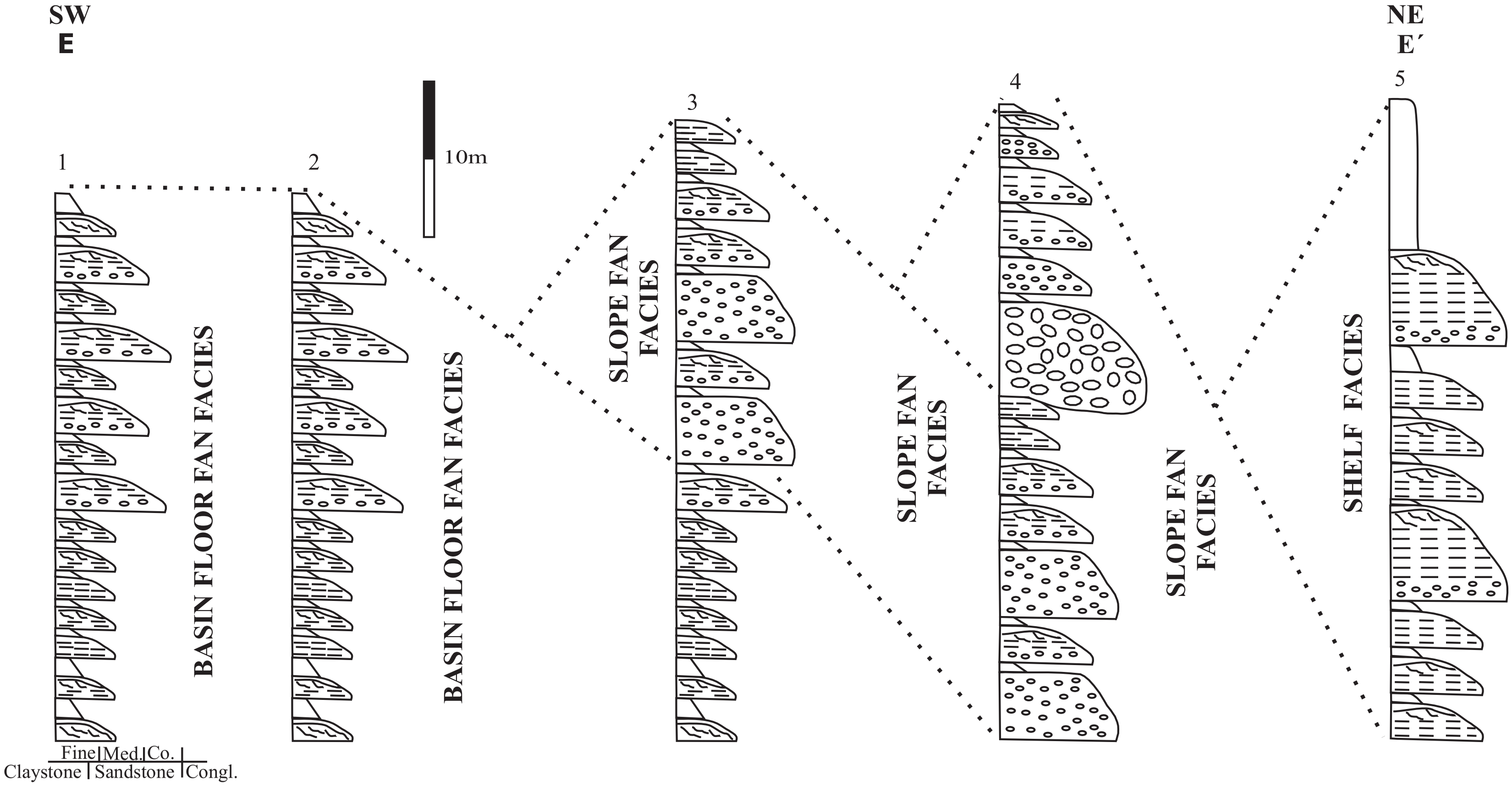

Figure 13. Representation of the sedimentary stratigraphy of the study area. Note the transition from basin floor fan to slope fan and finally to shelf deposits (from Maravelis & Zelilidis 2011). Legend as in Figure 4.

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