3D modeling of biogenic gas-bearing Neogene deposits at Arkalochori region, Messara, Crete, Greece

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George Panagopoulos
Technical University of Crete

Ioannis Pyliotis
Technical University of Crete

Avraam Zelilidis
University of Patras

Emmanouil Manoutsoglou
Technical University of Crete

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George PANAGOPOULOS[1], Ioannis PYLIOTIS[2], Avraam ZELILIDIS[2], Evangelos SPYRIDONOS[3], Hamdan HAMDAM[1], Antonis VAFIDIS[1] & Emmanuil MANOUTSOGLOU[1]

[1] Tehnical University of Crete, Dept. of Mineral Resources Engineering, Chania, Greece
gpanagopoulos@isc.tuc.gr, emanout@mred.tuc.gr
[2] University of Patras, Department of Geology, Laboratory of Sedimentology, Patras, Greece
[3] PPCR SA, Geothermal Power Department, Athens, Greece

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Abstract

Numerous biogenic methane gas seepages in Arkalochori region of Central Crete were the motivation to explore the gas potential of the area. According to recent studies, the gases seem to be of biogenic rather than thermogenic origin. To quantify the size of the potential reservoir, the construction of a 3D model concerning the shallow Neogene sediments of the area became essential. The available data needed for the construction was scarce, so in order to enrich our data pseudo-boreholes were introduced. The resulting lithostratigraphic model honors the main structural characteristics and the spatial distribution of Neogene deposits, specifically those that belong to Tefelion Group. A 3D lithostratigraphic model in combination with sedimentological observations could assist in delineating possible locations of gas accumulation so that they could be examined thoroughly in the future.

1 Introduction

Potential areas for gas deposits in Neogene formations have been detected using existing geological, geochemical and geophysical information as well as new data collected during a demonstration project funded by the GSRT of Greece and the Alkalochori municipality. In an extended area (60 km^2) located in the central part of the island of Crete (Messara-Arkalochori region) (fig. 1), seepages were recorded during water drilling processes. Four wells were drilled in order for gases to be sampled for further geochemical analysis. The composition of the gases was defined to 90% methane and 10% nitrogen [vol.] that according to Pasadakis et al. (2009) indicates a possible biogenic origin. Consequently, the source rocks as well as the host rocks probably belong to the shallow Neogene deposits of the area. Gases are considered to accumulate in sandstone beds covered by marly/clayey layers. Such alterations are the main characteristic of Neogene sedimentary succession of the region.

The discovery of sufficient volumes of biogenic gas would be an asset to the agricultural development of the area, as they could be used for the heating of greenhouses. The construction of a 3D geological model would help us to define the location where gases are accumulated. Insufficient qualitative and quantitative data was the main problem we faced trying to construct a 3D lithostratigraphic model that honors sand deposits/reservoirs and potential gas traps. This paper presents the construction methodology of a 3D lithostratigraphic model based on the existing geological map (scale 1:50.000 [Vidakis et al., 1994]), data from geoelectrical survey (Vertical Electrical Soundings), drilling data and detailed field work. The model is the preliminary approach of the spatial distribution of the Neogene lithotypes observed in the study area and is the basis for the construction of new models dealing with properties such as porosity and organic-carbon content. The result, in combination with sedimentological and tectonic evidence, could be used in order to conclude on the most favorable places to host shallow methane gas.

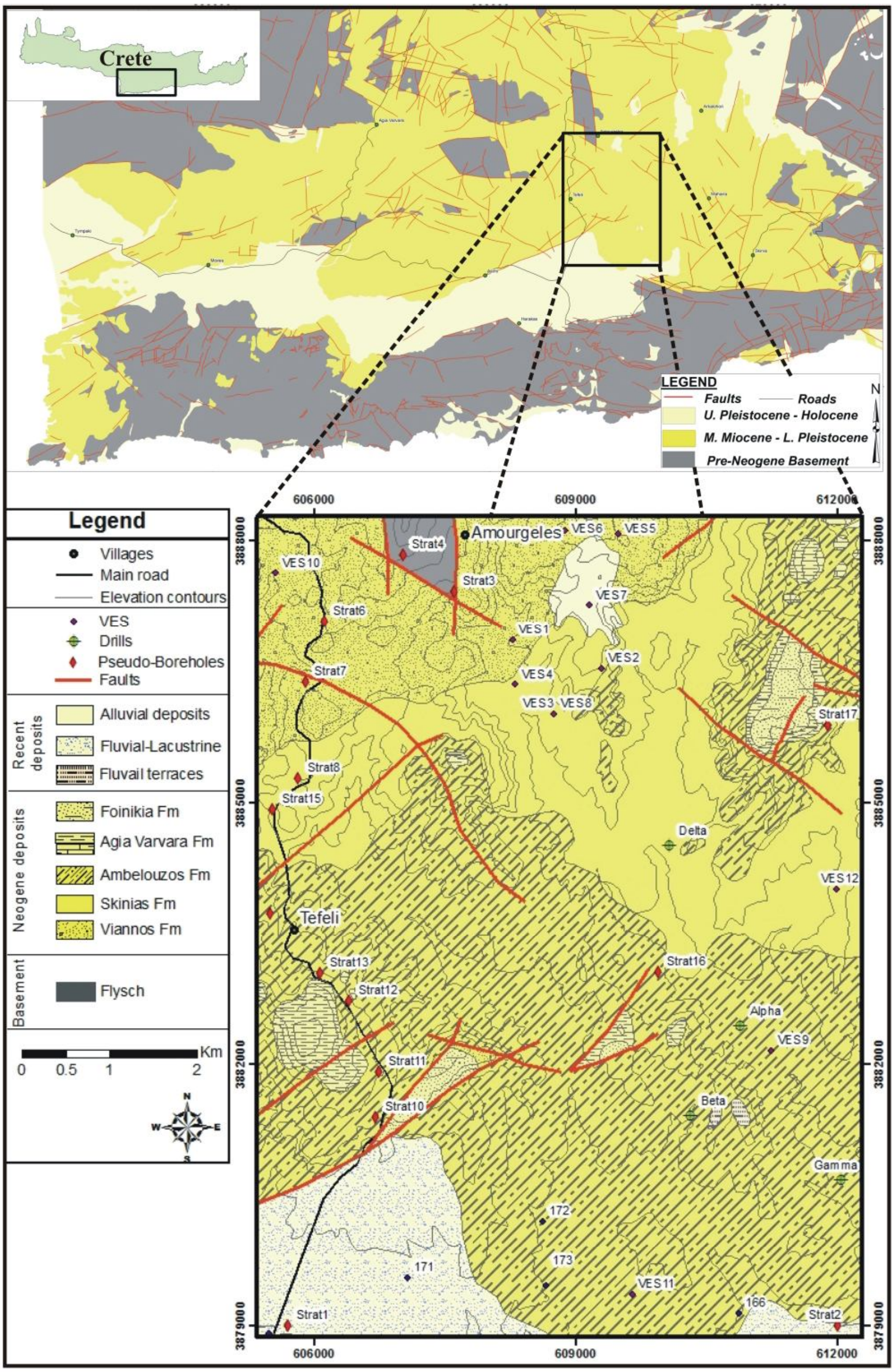

Figure 1: Geological map of Crete and the study area (modified after Vidakis et al., 1994) showing the location of the 4 boreholes, 15 pseudo-boreholes and 15 Vertical Electrical Soundings.

2 Geological framework

The island of Crete represents a prominent horst structure formed in the recent forearc of the still ongoing Hellenic subduction. The structure of Crete consists of a pile of nappes that contain rock units from various paleogeographic zones. The exhumation of the basement was accompanied by structural disintegration of the hanging wall, leading to formation of sedimentary basins on top of the nappe pile in the lower to middle Miocene. The Neogene history of Crete has therefore been object of intensive research. The tectonic regimes in the past and the evolution and the controlling mechanisms of the tectonic framework observed recently are still being debated (van Hinsbergen & Meulenkamp, 2008, Tortorici et al., 2010, Papanikolaou &Vasilakis, 2010).

The sedimentary characteristics of Neogene basins reflect the tectonic regime of the Hellenic fore arc at that time. Neogene deposits in Messara basin have undergone multidirectional extensional tectonic events with intervals of small, in duration and intensity, compressional events. The tectonic regime since 11Ma is explained by an arc-normal pull and a subsequent co-existence with transform resistance in the Pliny and Strabo trenches. That initially caused radial normal faulting and then additional activation of strike-slip and oblique faulting (ten Veen & Meijer, 1998).

Neogene sediments of Crete were subdivided by Meulenkamp (1979) into six lithostratigraphic groups, namely Prina, Tefelion, Vrysses, Hellenikon, Foinikia and Aghia Galini Groups. The study area comprises three of the six aforementioned Groups. Specifically, Tefelion is the main Group whereas Vrysses and Foinikia have minor extent, usually occupying tops of cliffs (fig. 1). Middle to Upper Miocene Tefelion Group consists of the Viannos, Skinias and Abelzouzos formations (table1):

Table 1: Description of the formations of the Tefelion Group

Formation	Age	Deposits	Depositional Environment	Thickness
Abelouzos	Tortonian	Sands, clays, siltstones, conglomerates	fluvio-lacustrine, marine	300m
Skinias	Serravallian-Tortonian	Clays, siltstones, sands	shallow marine	150m
Viannos	Serravallian	Sands, clays, siltstones, conglomerates	fluvio-lacustrine	600m

During field studies in several localities detailed geological mapping and sampling was carried out. Facies analyses helped to obtain information about the sedimentary processes leading to the formation of the basin fills. All three formations of Tefelion Group were studied at several naturally made slopes. The exposure height at these slopes locally ranges to considerably more than 10 m. Thus, the cuts provide a reasonable representation of the long-term sedimentary processes forming the deposits. To cover all variants of stratigraphy in the clastic wedges it was necessary to study an adequate number of outcrops.

All the three formations exhibit coarsening upward cycles, each up to 100m thick, with marls and clays at the base and sand layers at the top of each cycle (fig 2). Those alternations could act as potential stratigraphic traps. In addition, terrestrial floral relics were found in the upper clayey layers of Viannos and Abelouzos Formations.

Deposition of Viannos Formation took place in a large lake with boundaries that were defined by ENE-WSW striking faults. The grain size decreases southward and this is the reason to assume that the main source of sediments was from the North. The existence of synthetic and antithetic faults which were active during sedimentation resulted in a laterally constrained development of sand deposits, 200m-250m in width.

The domination of WNW-ESE striking faults in Middle Miocene contributed to the change of depositional environment into lagoonal, where Shinias Formation was deposited.

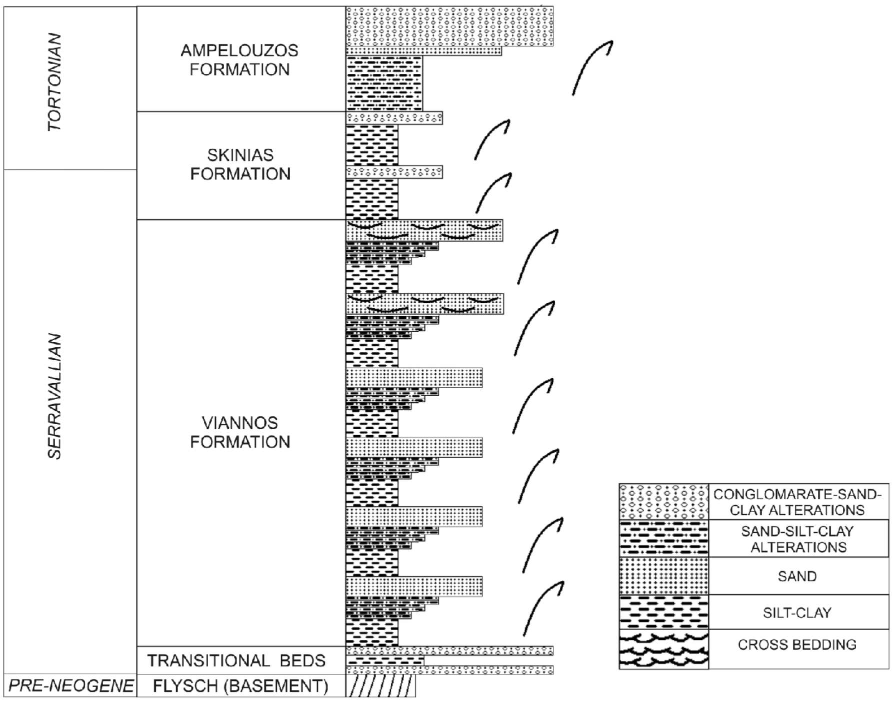

Figure 2: Sedimentary evolution of Tefelion Group.

Statistical parameters of the sediment which belong to Viannos and Shinias Formations, in combination with basin geometry lead us to the assumption that deeper parts of the basin are expected to be southward, where turbiditic currents transferred coarse-grained material to deeper parts composing submarine fans.

Lagoon retransformed into a lake just before salinity crisis. Following, the lake filled up with sediments and became a swamp (peat deposition).

The three formations of Tefelion Group dip southward. This fact is explained by assuming that the main fault which defined depositional conditions was the one located at the southern margin of the basin. Therefore, the age of these three formation decreases southward.

The biggest thickness of Neogene deposits is expected to be found in the southern part of the basin, where probably clayey layers of Viannos and Shinias Formations have maximum extent.

In case of generation of H/C gases, migration routes would be defined by the existence of several fault systems, as well as by the general dip angle of the layers. Specifically, the existence of syn-sedimentary faults contributed in the lateral restriction of sand deposits and in the establishment of vertical connection through faults, while the general dip to the south favours northward directed gas migration.

In addition, the development of submarine lobes in the deeper parts of the basin poses a question of whether even larger gas accumulations are trapped inside sand-lobe deposits in the southern section of the study area, or not.

3 Methodology

3.1 Data collection

In order to construct a 3D model we developed a GIS geological database (ArcGIS®) with all the available data, which was transferred in the geomodeler (Surpac®Vision) to be integrated into the 3D modelling process. The GIS package can achieve data integration in two dimensions, but it does not allow building complex surface or volumes such as geological folded and faulted structures (Kaufmann & Martin, 2008). Thus, the combined use of both types of software is desirable because it generates more complete and realistic models (Fallara et al., 2006).

Surface and downhole data were imported into the GIS geological database. Surface data comprise digitized geological and structural data which came from a geological map published by the Geological Survey of Greece (IGME) at a scale of 1:50.000 (fig. 1). The digitizing process presupposes the re-projection of all data in a common and synchronous coordinate system. In addition, a digital elevation model was constructed from point elevation data acquired over a regular grid of 20m x 20m cell's dimensions. The downhole data comprises 4 wells, 15 Vertical Electrical Soundings and 15 pseudo-boreholes with heterogeneous descriptions. Lithologic and stratigraphic values were assigned in every depth interval.

The heterogeneity of descriptions and interpretations in different data sets is a common problem in 3D geological modeling (Kaufmann & Martin, 2008). The information that was integrated during modeling process includes lithologic descriptions (drillings, pseudo-boreholes), specific electrical resistivity values (VES), punctual elevation data and 2D linear features representing surface boundaries of stratigraphic formations and faults. The integration of the above data sets suggests the implementation of a homogenous stratigraphic and lithologic description, constrained by topography, faults and surface stratigraphic boundaries. Firstly, specific electrical resistivity values were translated into lithologies according to the lithologies observed in the field, pseudo-boreholes and drillings. Secondly, the stratigraphic formations that lithologies belong to were determined, based on their spatial position in accordance with the stratigraphic column of the region. Finally, five lithologies were modeled belonging to Viannos and Skinias Formations, namely clay, marl, sand, sandstone and an undefined lithology. The purpose of this action was to model the lithologic succession of Viannos and Skinias Formations (fig. 2). Moreover, we distinguished between loose sand and solid sandstone based on the electrical resistivity data.

3.2 Pseudo-boreholes

The term pseudo-borehole (coming from the greek word "ψευδές" = fake, virtual) stands for a virtual borehole log that comes from the study of a naturally or artificially made slope, as it is shown in figure 3. Several slopes along a road that crosses the study area in an N-S direction were used for that purpose. Using a scale of 2m in height, we took photos of 11 slopes. For each of the slopes, a borehole was defined in the vicinity of the scale. Because the slopes were nearly vertical, the coordinates at the top of the borehole were assumed to be the same as the measured coordinates at the bottom. Each of the pseudo-boreholes was described in stratigraphical and lithological terms.

This specific methodology is a coarse way of emplacing virtual boreholes in space, the precision of which depends on the extension of the borehole. In other words, the used scale is not representative for the whole photography-slope, as something like that is constrained by geometric rules, but only for the parts very proximal to it. In figure 3, the top of the borehole should not be extended even higher because in that case the used scale would no more be representative.

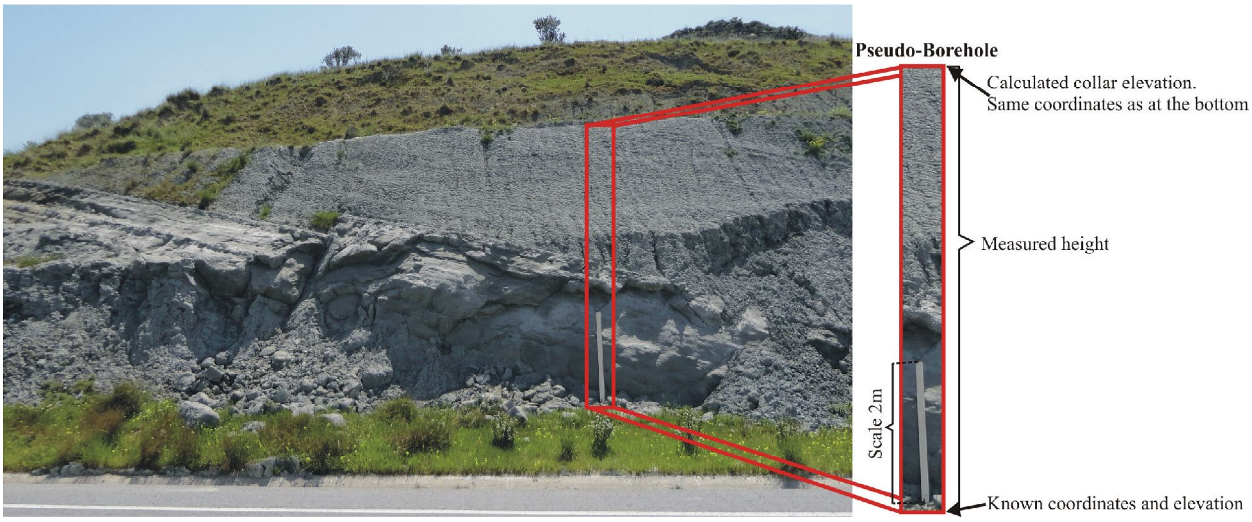

Figure 3: The "construction" of a pseudo-borehole.

3.3 Modeling of lithologies

A block model of the working area has been set up, in order to simulate the spatial distribution of the attributes of the subsurface formations, namely the lithologies' distribution inside the stratigraphic formations, as described in chapter 2 above (fig. 2). Block dimensions were defined as 100X100X10 m, and the model base is located at an elevation of -250 m. The attribute lithology is estimated from the well data set described in 3.1 and 3.2. The block values for lithology are calculated by the nearest neighbour method, using a very flat search ellipsoid with a radius of 2.5 km and vertical radius of 250 m, dipping 20o to the south. The calculation has been geometrically restricted by the contact surfaces between the different stratigraphic units. The deeper parts of the model have not been estimated, since the available data reach down only to 400 m.

4 Results

The modeling resulted in a first coarse estimation of the volume of the gas-hosting lithologies (sands, sandstones) inside the Shinias and Viannos formations (Table 2). No measurements are available for the porosities, so we have to rely on literature values for these formations. We assume that Sand porosity varies from 0.25 to 0.50 and for Sandstone it varies from 0.05 to 0.30 (Freeze and Cherry, 1979). For a conservative estimation of the pore volume we accept the lowest values, e.g. 0.25 for sand and 0.05 for sandstone. In the Ampelouzos Formation no gas is expected, since it contains limited clay and silt strata to act as cap rocks. Fig. 4 shows the distribution of the lithologies.

Table 2: Volume estimation for each lithology belonging to Viannos and Shinias Formations

Formation	Lithology	Volume (m^3)	Porosity	Pore Volume(m^3)
Viannos & Skinias	Clay	6.340.400.000		
	Marl	3.510.800.000		
	Sand	340.300.000	0.25	85.075.000
	Sandstone	624.600.000	0.05	31.230.000
		Total Pore Volume for Gas hosting		116.305.000
Ampelouzos		8.178.800.000		

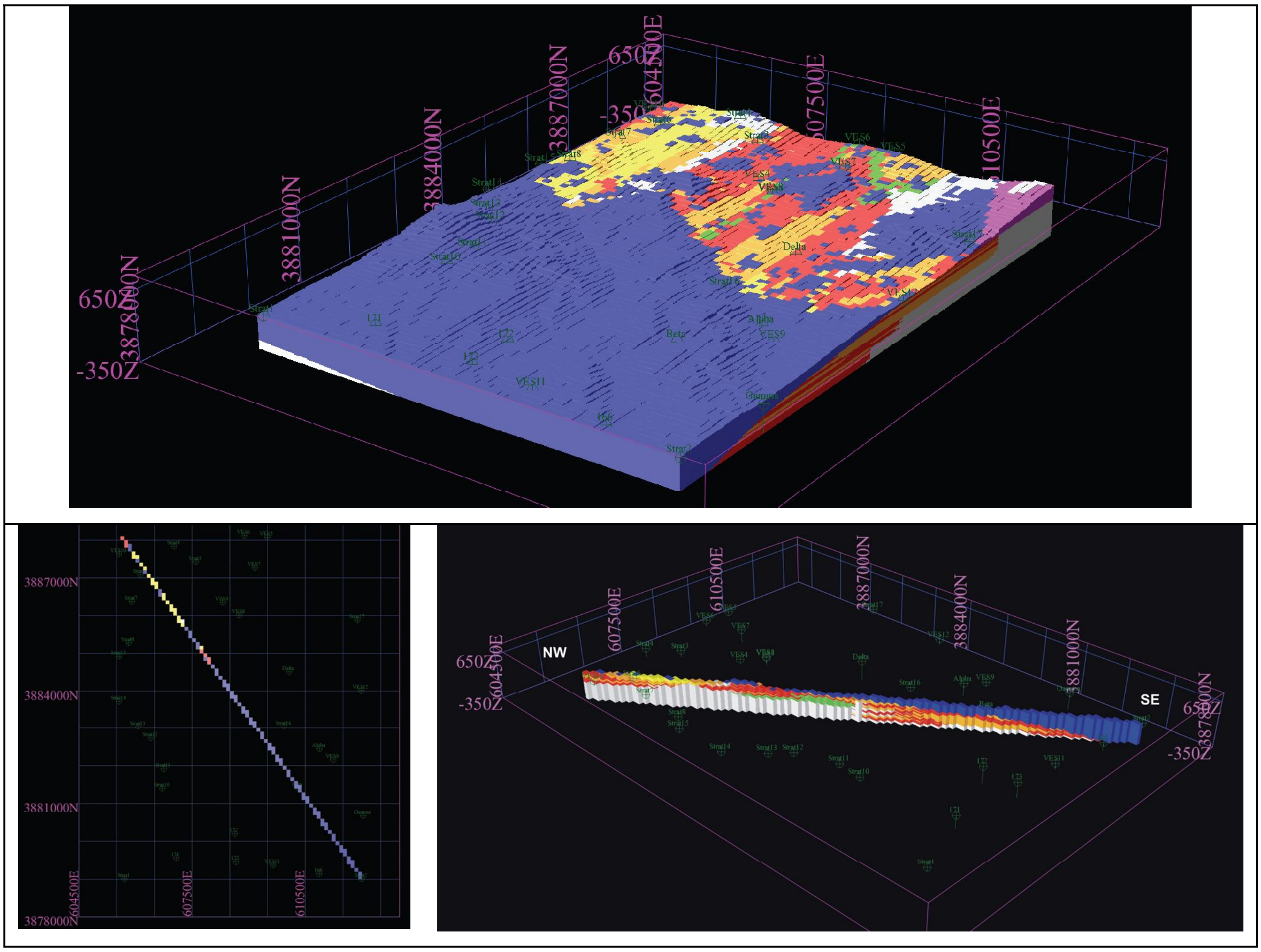

Figure 4: 3D visualization of lithological types belonging to Viannos and Shinias Formations. Red = clay, orange = marl, yellow = sand, green = sandstone. Abelouzos Formation is shown undivided in blue. Above: Perspective view from SE. Below: Cross section along NW-SE axis.

5 Conclusions

A geological model of the Alkalochori subbasin was developed using data from geological mapping, geophysical measurements and drillings. This model takes into account the stratigraphic and tectonic evolution of the Messara basin. The proposed approach demonstrates a preliminary way to estimate the biogenic gas potential of shallow Neogene sediments, based on a variety of data. The scope of the work was not an exact determination of the possible reserves, but to estimate the potential at a very early stage of the study, in order to support the decision whether the project should be continued or abandoned.

Different sets of data were integrated for that purpose. The preliminary model set up for this work can build the basis for future detailed work and can be enriched with additional well data and quantitative measurements (grain size distribution, hydraulic properties etc).

Acknowledgments

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