BGSG
Volume 54

Research Paper

Correspondence to:
Koukouzas N.
koukouzas@certh.gr

DOI number:
http://dx.doi.org/10.12681/bgsg.19352

Keywords:
Mesohellenic Trough, Coal, GIS, Aspect, Hillshade, Petrography

Citation:
Koukouzas N., Krassakis P., Koutsovitis P., Karkalis C. (2019), An integrated approach to the coal deposits in the Mesohellenic Trough, Greece. Bulletin Geological Society of Greece, 54, 34-59.

Publication History:
Received: 15/12/2018
Accepted: 21/06/2019
Accepted article online: 13/07/2019

The Editor wishes to thank two anonymous reviewers for their work with the scientific reviewing of the manuscript and Ms Erietta Vlachou for editorial assistance.

AN INTEGRATED APPROACH TO THE COAL DEPOSITS IN THE MESOHELLENIC TROUGH, GREECE

Koukouzas Nikolaos [1], Krassakis Pavlos [1], Koutsovitis Petros [1]

Karkalis Christos [1]

[1] **Centre for Research and Technology, Hellas (CERTH), 52 Egialias St. 15125, Maroussi- Athens, Greece,** koukouzas@certh.gr , krassakis@certh.gr , koutsovitis@certh.gr , karkalis@certh.gr

Abstract

A considerable amount of coal deposits occur within the Mesohellenic Trough in Greece. It is considered as the largest and most important basin of the last orogenic stage of the Hellenides, which is interpreted as a back-arc basin that evolved during the period of Late Oligocene to Miocene. In this study, a simplified geological map has been constructed emphasizing on the coal formation occurrences of the Mesohellenic Trough. This work has been accomplished, through Geographic Information Systems (GIS) and has been organized via geodatabase as GIS data files (feature classes). For the creation of the geological map suitable homogenization and discrete representation has been implemented different geological sheets, original source and traditional maps. Next step was the geostatistical analysis using polygonal methods linked to the corresponding tabular information. Regarding the stratigraphical age, and petrographic data related to geographic distribution of the coal occurrences, these are divided into three categories: Oligocene, Middle Miocene and Upper Miocene coals, exhibiting various physicochemical and topological properties. Upper Miocene coal exhibits the greatest area and perimeter values, while the lowest values correspond to those of the Middle Miocene. Terrain models such as aspect (angle-direction) and hillshade (shaded relief) showed the spatial relation between coal occurrences and *morphotectonic as long as geometrical characteristics of the study area. Coals are mainly classified as huminites including mainly huminite group minerals (90%). Their S contents can probably derive from parent plant material or a combination of parent plant material with seawater sulfates. Moisture contents are strongly connected with the sustainability of the coal use in the energy production, while their carbonation grade is strongly associated with their age and expressed by their reflectivity values. All these data have been inserted in an integrated database and can be useful for pre-mining or post mining activities (e.g. planning, analysis, management, restoration). Results of this study are available for the effective evaluation of the existing coal occurrences, which can be used with renewable energy sources providing sustainable solutions, in combination with the upcoming innovative CCS and CCU technologies. Results also showed that coals from the Mesohellenic Trough present excellent quality traits. However, their value as combustible coal is very low due to the absence of economically recoverable reserves. The largest coal lenticular bodies have been extracted in the past and the remaining occurrences do not exceed several thousand tones. Based upon existing literature and from geospatial estimations, coal deposits in the Mesohellenic Trough Basin cannot be considered as economically valuable for exploitation.*

Keywords: *Mesohellenic Trough, Coal, GIS, Aspect, Hillshade, Petrography*

Περίληψη

Σημαντική είναι η ποσότητα κοιτασμάτων γαιάνθρακα που εντοπίζεται στην περιοχή της Μεσοελληνικής Αύλακας στην Ελληνική επικράτεια. Αποτελεί μία από τις πιο σημαντικές λεκάνες της τελευταίας ορογενετικής φάσης των Ελληνίδων, όπου εξελίχθηκε κατά την περίοδο του Ανώτερου Ολιγοκαίνου – Μειοκαίνου. Στην παρούσα εργασία κατασκευάστηκε ένας απλοποιημένος γεωλογικός χάρτης με ιδιαίτερη έμφαση στις εμφανίσεις γαιανθρακικών κοιτασμάτων στη λεκάνη της Μεσοελληνικής Αύλακας. Σκοπός της εργασίας ήταν η χρήση Γεωγραφικών Συστημάτων Πληροφοριών (ΓΠΣ) και η οργάνωση των θεματικών επιπέδων πληροφορίας σε δομή Γεωβάσης. Συγκεκριμένα για την κατασκευή του γεωλογικού χάρτη εφαρμόστηκε κατάλληλη μέθοδο ομογενοποίησης των διαφορετικών γεωλογικών φύλλων καθώς και αξιοποίηση ιστορικών και παραδοσιακών χαρτών. Επόμενο βήμα ήταν η γεωστατιστική ανάλυση με χρήση πολυγώνων και η σύνδεσή τους με την αντίστοιχη περιγραφική πληροφορία. Σύμφωνα με τη στρωματογραφική ηλικία και τα πετρογραφικά δεδομένα αλλά και *της γεωγραφικής κατανομής των γαιανθρακικών εμφανίσεων, αυτοί διακρίνονται σε τρείς κατηγορίες: Γαιάνθρακες Ολιγοκαίνου, Μέσου και Ανώτερου Μειοκαίνου, που αποτελούνται από διάφορα φυσικοχημικά και τοπολογικά χαρακτηριστικά. Αξιοσημείωτο είναι το γεγονός ότι οι γαιάνθρακες Ανώτερου Μειόκαινου καταλαμβάνουν τη μεγαλύτερη έκταση και περίμετρο, ενώ οι γαιάνθρακες Μέσου Μειοκαίνου έχουν τις μικρότερες εμφανίσεις. Όσον αφορά τα παραχθέντα μοντέλα εδάφους και συγκεκριμένα το επίπεδο προσανατολισμού και σκίασης του αναγλύφου ανέδειξαν χωρική συσχέτιση μεταξύ των γαιανθρακικών εμφανίσεων, των μορφοτεκτονικών χαρακτηριστικών αλλά και της γεωμετρίας της περιοχής μελέτης. Οι γαιάνθρακες κατηγοριοποιούνται κυρίως ως χουμινίτες εμπεριέχοντας κυρίως ορυκτά της ομάδας των χουμινιτών (90%). Το περιεχόμενο σε θείο πιθανώς οφείλεται σε οργανική (φυτική) προέλευση με ή χωρίς συμμετοχή θαλάσσιου νερού. Η εμπεριεχόμενη υγρασία συνδέεται πολύ στενά με την βιωσιμότητα της χρήσης των γαιανθράκων στην παραγωγή ενέργειας, ενώ ο βαθμός ενανθράκωσης των γαιανθράκων σχετίζεται άμεσα με την ηλικία τους και τις τιμές ανακλαστικότητάς τους. Όλα αυτά τα δεδομένα έχουν εισαχθεί σε μία εμπλουτισμένη βάση δεδομένων και μπορούν να αξιοποιηθούν για εξορυκτικές δραστηριότητες σε αρχικό η μεταγενέστερο στάδιο όπως σχεδιασμός, ανάλυση, διαχείριση, αποκατάσταση. Τα αποτελέσματα αυτής της εργασίας είναι διαθέσιμα για την αποτελεσματική αξιολόγηση των υφιστάμενων εμφανίσεων γαιάνθρακα, και μπορούν να χρησιμοποιηθούν στον τομέα ανανεώσιμων πηγών ενέργειας παρέχοντας βιώσιμες λύσεις σε συνδυασμό με τις ανερχόμενες και καινοτόμες τεχνολογίες δέσμευσης και επαναχρησιμοποίησης διοξειδίου του άνθρακα. Επίσης, τα αποτελέσματα δείξανε ότι οι γαιάνθρακες της Μεσοελληνικής Αύλακας έχουν άριστα ποιοτικά χαρακτηριστικά. Ωστόσο, η χρησιμότητα τους ως καύσιμη ύλη είναι πολύ χαμηλή λόγω απουσίας οικονομικά απολήψιμων αποθεμάτων. Τα μεγαλύτερα γαιανθρακικά φακοειδή στρώματα έχουν εξορυχθεί στο παρελθόν, ενώ το εναπομένον απόθεμα δεν είναι μεγαλύτερο της τάξης των μερικών χιλιάδων τόνων. Με βάση την υπάρχουσα βιβλιογραφία αλλά και τα αποτελέσματα των γεωχωρικών αναλύσεων, τα κοιτάσματα των γαιανθράκων στην περιοχή της Μεσοελληνικής Αύλακας δεν μπορούν να χαρακτηριστούν ως οικονομικά εκμεταλλεύσιμα.*

Λέξεις κλειδιά: *Μεσοελληνική Αύλακα, Γαιάνθρακας, ΓΠΣ, Προσανατολισμός, Σκίαση ανάγλυφου, Πετρογραφία*

1. Introduction

Brown coal (lignite) is the most common type of coal that outcrops in Greece, satisfying 30% of the country's electricity needs. Coal is the second most dominant fuel used in Greece, accounting for 19% of Total Primary Energy Supply (TPES) in 2016. Coal supply has nearly halved over the past decade, from 8.4 million tons of oil equivalent (Mtoe) in 2006 to 4.4 Mtoe in 2016, due to decreasing use of coal-powered plants (IEA, 2017). Coal deposits (lignite, sub-bitumenous coal, turf) in Greece are in their vast majority of Cenozoic age, having been deposited in inland or coastal basins. Greek lignite deposits of economic importance are exploited (opencast) in the regions of: Ptolemais-Amynteo (Pliocene), Florina (Miocene) and Megalopolis (Pleistocene). Coal outcrops have been identified in almost all of the geological formations of the Mesohellenic Trough, but without significant mining activity. The Mesohellenic Trough sedimentary basin comprises of four distinct formations (namely Eptachorion, Pentalofon, Tsotillio and Burdigalian) that include scattered and rather small lenticular shaped lignite occurrences, which display variable petrographic and geochemical features (Koukouzas and Koukouzas, 1995). Their formation occurred within paleogeomorphology reinforced coastal basins or within deltaic accumulations. Thick deltaic deposits occur between the Krania and Eptachorion formations as well as within the southern parts of Pentalofon and Tsotillio formations (Ferriere et al., 2004).

In the present study, a new geological map has been reconstructed emphasizing on the coal formation occurrences of the Mesohellenic Trough using Geographic Information Systems (GIS) and ArcGIS v 10.x. A Geographic Information System allows easy distribution, dissemination of spatial and non-spatial data and has the ability to storage different types of data in a visual or attribute table (Schweik et al., 2013). For the optimal spatial and non-spatial analysis of the geological setting related to the coal deposits of the study area, former analog geological sheets were digitized combined with bibliography data, research, historical mapping and original drawing features. The physicochemical and petrographic properties of coal occurrences are also presented in order to provide a more integrated approach. These properties are usually associated with the suitability of coal use in the energy production and the sources of their chemical components. For example, reflectivity is connected with the carbonation grade, S contents are indicative of specific sources such as seawater environments, while moisture contents usually affect their heating value and cost of transport.

2. Geological Setting of the Mesohellenic Trough

The Mesohellenic Trough is a basin with a length exceeding 200 km and a width of 30-40 km, located in NW Greece (Vamvaka, 2009). It is the largest and most important molasse basin of the last orogenic stage of the Hellenides, extending from Albania in the North towards Thessaly to the South. It was developed between the Mid-Late Eocene to the Mid-Late Miocene and is sited between the Apulian (non-metamorphic) plate and the Pelagonian (metamorphic) nape pile (Kilias et al., 2015).

The Mesohellenic Trough is juxtaposed on the Olonos-Pindos external unit and Pelagonian internal unit on its western and eastern side respectively. It is interpreted as a back-arc basin, which evolved during the Late Oligocene to Miocene period (Brunn, 1956; Aubouin, 1959; Papanikolaou et al., 1986; Vamvaka, 2009). Oligocene transgression led to a continuous marine sedimentation until Late Miocene, characterized by rather thick sediments (up to ~5 km thick). The Trough is characterized by a complicated structure with numerous changes in sedimentary phases (Tasianas and Koukouzas, 2015), composed of deltaic, alluvial and turbiditic sequences (Vamvaka, 2009). The deposits exhibit variability in thickness values, both longitudinally and transversally to the axis of the basin (Vamvaka, 2009). The lower formations of the sedimentary sequence occur along the southwestern margin of the Trough, whereas the younger formations gradually outcrop towards the northeastern parts.

The lithostratigraphic formations of the Mesohellenic Trough are displayed in the geological map of Figure 1 and include the following formations:

Eptachorio Formation (Olm-s.st,m) is a thick sedimentary sequence (1000-1500 meters). It is composed by a turbiditic system of marls, alternating with fine sandstone intercalations which upwardly transitioning to semi-pelagic argilites. The base of the Eptachorio Formation consists of clastic sediments (conglomerates, sandstones), as well as base deposits. In the area of Mount Taliaros, a local sedimentary phase comprising of sandstone, marl and limestone, consists the upper part of the Eptachorio Formation. The age of the formation refers to Late Eocene to Early Oligocene (Priabonian - Chattian) (Vamvaka, 2009; Kilias et al., 2015; Tasianas and Koukouzas, 2015).

Pentalofo Formation (Fig.1 abbreviation: M1c, M1.st2) is of Late Oligocene to Early Miocene age and mostly occurs in the northwestern and central parts of the Trough. It mainly includes two types of sedimentary clastic rocks, separated by marl-sandstone intercalations. Its thickness ranges from 2250 to 4000 m (Vamvaka, 2009; Kilias et al., 2015; Tasianas and Koukouzas, 2015).

Tsotillio Formation (Fig.1 abbreviation: M1-2.st, M1-3.c,stm) has an Early to Middle Miocene age and mainly outcrops in the northern, eastern and southern parts of the Trough. It mostly consists of marls accompanied by conglomerates, sandstones and limestones. Its total thickness is locally variable ranging from 200 to 1000 m (Vamvaka, 2009; Kilias et al., 2015; Tasianas and Koukouzas, 2015).

Burdigalian Formation. During the Burdigalian, various phases of sediments were deposited appearing as sediment wedge's with lateral transitions, with variable lithostratigraphic section profiles from one region to another (Vamvaka, 2009; Kilias et al., 2015; Tasianas and Koukouzas, 2015). This succession consists of the following individual members:

Formation M2.m is a relatively thick formation (up to 450 m), mostly exposed in the northern parts of the Trough, mainly including sandy marls. There are three main phases with wedges and lateral transitions. The lower part consists of bluish sand-clays and silty marls. Moving stratigraphically upwards, there are reef limestones that are found in the Ontria highlands. The upper parts include calcareous sandstones and micro-conglomerates (Vamvaka, 2009; Kilias et al., 2015; Tasianas and Koukouzas, 2015).

Ontria Formation (Fig.1 abbreviation: Mi.d) mainly consisting of limestones and outcropping in the eastern and northwestern parts of the Trough (Vamvaka, 2009; Kilias et al., 2015; Tasianas and Koukouzas, 2015).

Omorfoklissia Formation (Fig.1 abbreviation: Mi.O). The lowermost part consists of sandstones and micro-conglomerates, followed by a marly series with sandy intercalations, whereas the uppermost part consists of sandstones with accessory micro-conglomerates. Locally, clays, coal, marly limestones and silicified branches and trunks are observed (Vamvaka, 2009; Kilias et al., 2015; Tasianas and Koukouzas, 2015).

Zevgostasio Formation occurs in the northern side and includes sandstones-marls and silty marls. The sequence ends up with the uppermost Orlia formation (Mi.Or) which occurs in the northern side and consists of sandy marls and sandstones (Vamvaka, 2009; Kilias et al., 2015; Tasianas and Koukouzas, 2015).

Orlia Formation (Fig.1 abbreviation: Mi.Or). The base of the formation comprises of sandy marls and loose sandstones with abundant fossils of Ostrea (Ostrea cf. crassissima) and thin intercalations of clays, sands and locally coal.

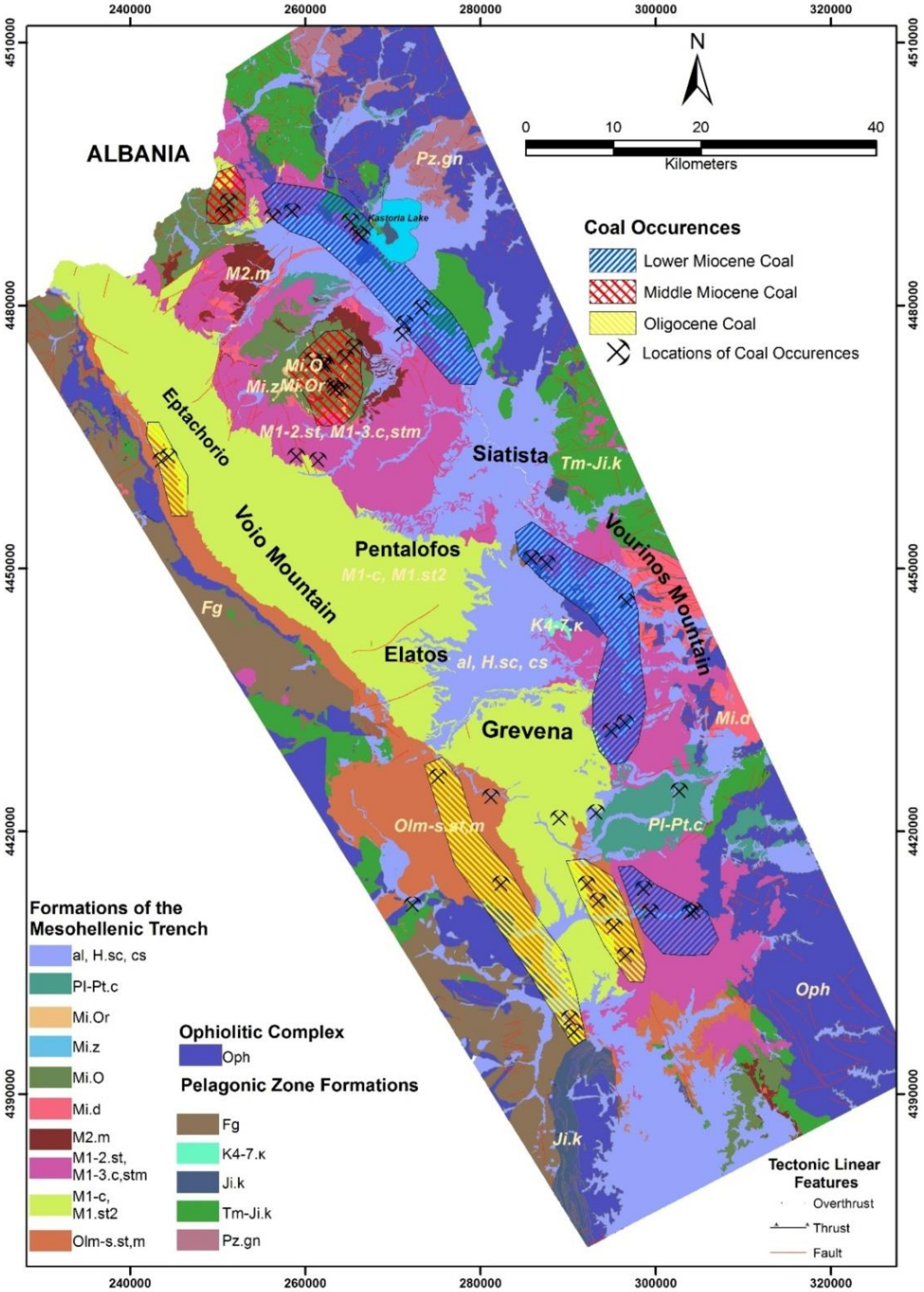

Fig. 1: Geological Map of the Mesohellenic Trough, indicating coal occurrences. Explanation of legend : al, H.sc, cs : Olocene deposits, Pl-Pt.c : Plio – Pleistocene conglomerate, Mi.Or: sandy marl, sandstone (Orlia

Formation), Mi.z: silty marl (Zevgostasio Formation), Mi.O: sandstone & marl (Omorfoklissia Formation), Mi.d: Ontria Formation, M2.m: sandy marl, M1-2 st, M1-3.c,stm: conglomerate, sandstone, marl (Tsotilio Formation), M1-c, M1.st2 : sandstone in alternation with marl (Pentalofos Formation), Olm-s.st,m: (Eptachorio Formation), Oph: ophiolites & ultrabasic Formation), Fg: flysch, K4-7.k : limestone (Upper Cretaceous), Ji.k: limestone (Middle Upper Liasio), Tm-Ji.k: limestone (Jurassic – Triassic), Pz.gn: metamorphic system e.g gneiss, schist, amphibolite (Paleozoic).

Stratigraphically upwards, the succession continues with coarse sandstones with Ostrea, and pseudo-oolithic limestones. The total thickness of Orlia Formation is estimated at ~90 meters. Sedimentary layers are almost horizontal, overlying the Zevgostasio formation, with a Late Burdigalian age. During the Late Eocene -Middle Miocene, the molassic sediment accumulation in the Mesohellenic Trough ended, following a period characterized by uplifting and local deposition of continental sediments of various phases (fluvial, lacustrine and terrestrial). During the Pliocene to Early Pleistocene, fluvial and lacustrine sediments were deposited locally in the Mesohellenic Trough. These consist of blue-greenish clays, sands and loose conglomerates, occasionally hosting lignite horizons (Kastoria, Argos Orestiko, Grevena). Quaternary lacustrine and fluvial sediments and terraces represent the most recent sediments of the Trough (Vamvaka, 2009; Kilias et al., 2015; Tasianas and Koukouzas, 2015).

3. Methodology

Geographic Information Systems (GIS) have been applied in order to represent spatial distribution and qualitative data linked to coal occurrences in the Mesohellenic Trough Basin. These data were collected and organized via geodatabase as GIS data files (feature classes or shape files). For the efficient capture and management of geological map data and for better spatial analysis, we have applied a topology technique for the coal deposits and geological formations in our study area. This is a digital representation of spatial data in two dimensions, pertains to the relationships among feature geometry objects such as points, lines and polygons. Topology is useful to define the functional relationships among geologic map objects, the feature geometries of which provide the framework for these representations (Wahl, 2013). Geologic maps provided in this study contain abundant data regarding the areas of interest that bear coal/lignite deposits, as well as relative information for the geological units, the nature of contacts and faults. Physicochemical properties and petrographic data provided have been derived based upon literature review.

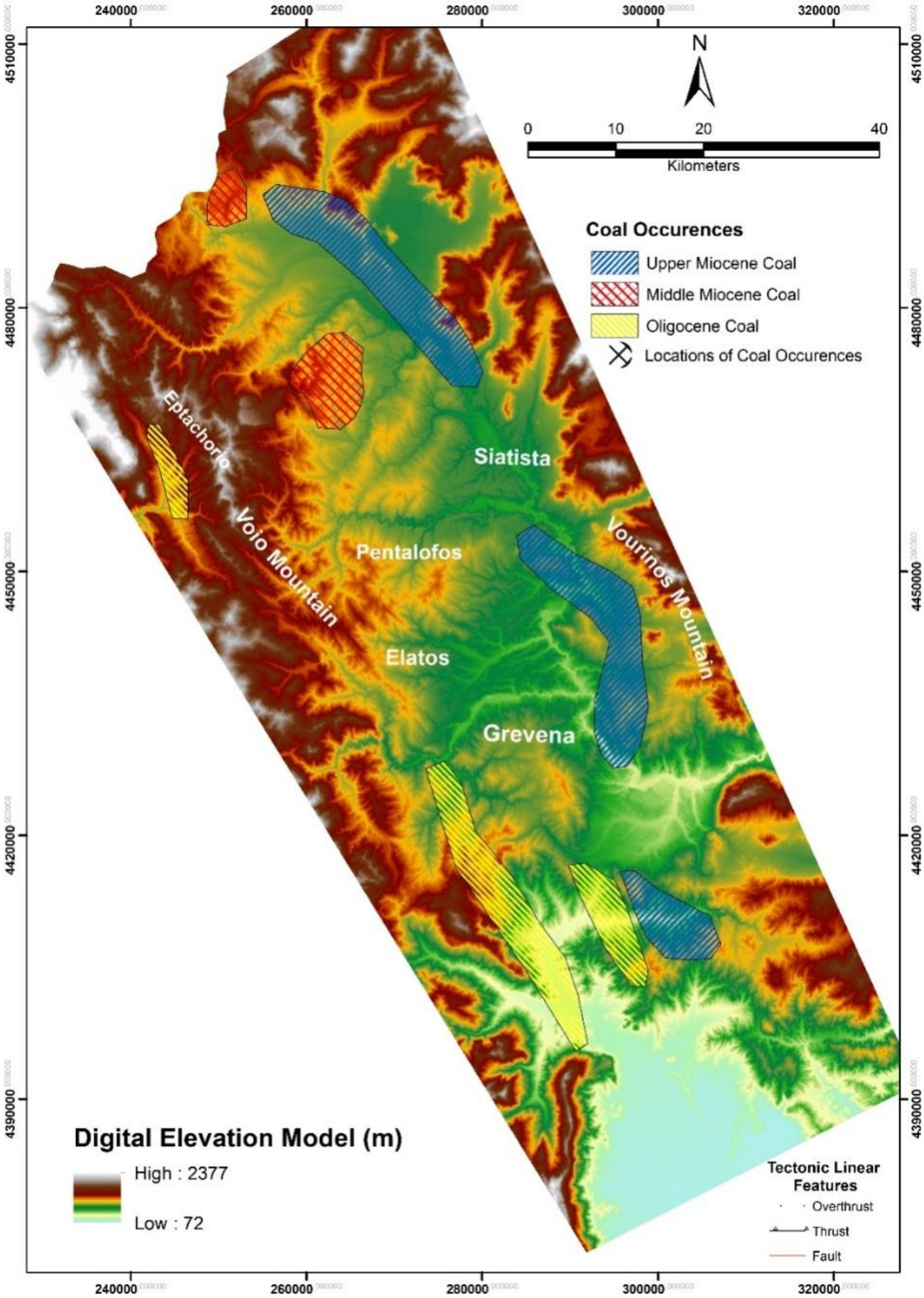

Fig. 2: Digital Elevation Model (DEM) map of the Mesohellenic Basin with Coal Occurrences (based on ASTER satellite dataset).

4. Results and Discussion

4.1 GIS Data acquisition

The spatial database has been developed in GIS environment using ArcGIS v10.x software, containing various datasets (geological formations, coal occurrences, faults, strike and dip of beds, areas, contour lines). Database elements were developed by digitizing features from regional geological maps (Aubouin, 1961; Brunn, 1977; Koumantakis and Mataragkas, 1980, 1989; Mavridis et al., 1982; Plastiras 1985; Plastiras and Rozos, 1990; Savoyat and Lalechos, 1969a,b, 1972; Savoyat and Monopolis, 1971, 1972; Stamatis, 1992), contours from topographical sheets (1:50.000 scale) and SRTM satellite datasets. Original source maps were georeferenced in order to recognize deviations of the study area and to identify coal occurrences. In some cases, base-map projection information from the original source maps was not provided. For this purpose, maps were scanned and adjusted to fit a base map with the following parameters: Projection, HGRS87; False Easting, 500000 meters; Central Meridian, 24° E.; Linear Unit, Meter; Datum, GRS80 ellipsoid. Polygon locations of coal occurrences were digitized from the original source maps and incorporated in an integrated geological map (Fig. 1) that displays the code and extent for each geological formation. Based on our modified geological map (Fig. 1), four main formations are distinguished from the lower to the upper parts of the Mesohellenic Trough. Eptachorio formation (Olm-s.st,m) has a Late Eocene to Early Oligocene age and mainly occurs in the western and southern parts of the Trough.

Surface analysis was obtained in Mesohellenic Trough as terrain (elevation) analysis related to aspect (slope direction) and hillshade was calculated on Digital Elevation Model (DEM) as surface raster (Fig. 2). Digital Elevation Model (DEM) is the most common digital 3D representation of a topographic surface with respect to any reference datum. DEM is frequently used to determine terrain attributes that include elevation at any point, slope and aspect (direction). In our study area, DEM was created from data obtained using 1:50.000 (scale) topographic maps from the Hellenic Military Geographical Service and the Advanced Spaceborne Thermal Emission and Reflection

Radiometer (ASTER), with a nominal horizontal accuracy of 15 and 20 meters respectively (Jacobsen, 2004).

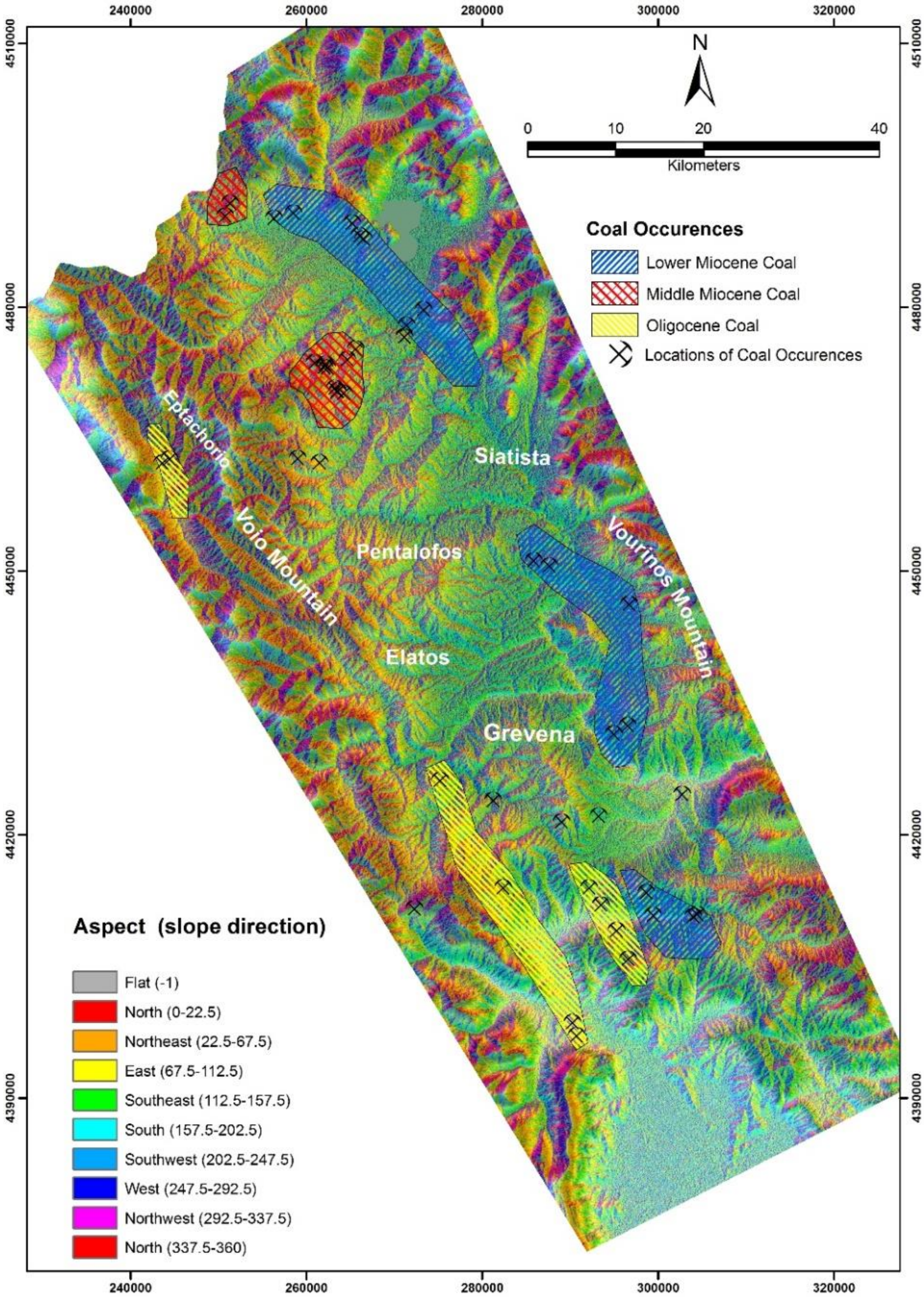

Fig. 3: Aspect function map of the Mesohellenic Basin with coal occurrences, based on Digital Elevation Modeling, displaying surface window of aspect algorithms and aspect directions.

From Digital Elevation Map, it is noticed that Upper Miocene coal occurrences appeared in area with elevation range from 476 m to 820 m, Middle Miocene coal appeared in area with elevation range from 800 m to 1020 m and Oligocene coal appeared in area with elevation range from 800 m to 1200 m. Regarding the results from DEM, indicates that coal occurrences are mostly exposed in area with an average elevation of 600 m.

Furthermore, aspect function map (direction of slope) (Fig 3) was designed in order to analyze and visualize landforms, coal occurrences and geological characteristics (Schweik, 2011). According to the Environmental Systems Research Institute (Burrough, 1998), aspect function identifies the downslope direction of the maximum rate of change in value from each cell to its neighbors. The output aspect raster values represent the compass direction of the slopes. The aspect raster function generates a map that categorizes aspect (surface direction) into eight classes (Burrough, 1998) that are symbolized using an orderly progression of color hues (such as red, orange, and yellow). In Geographic Information Systems aspect identifies the steepest down slope direction from each cell to its neighbors and can be defined as the slope or the compass direction the slope faces. Aspect is measured clockwise in degrees from zero, due north to 360, again due north, coming full circle. The value of each cell in an aspect dataset indicates the direction the cell's slope faces. Flat areas having no down slope direction were given a value of -1 (Babita, 2012).

As mentioned above, in the study area most of the coal occurrences are located within the Holocene deposits (al, H.sc, cs) as well as the Eptachorio (Olm-s.st,m), Tsotillio (M1-2.st, M1-3.c,stm) and Burdigalian formations (Mi.Or, Mi.z, Mi.d,Mi.O, M2.m). Evaluating the results of the exported thematic map a geostatistical analysis of aspect dataset has been conducted. The distribution of the relative frequency of coal occurrences in each data layer has been investigated. The frequency histogram of slope directions regarding the aspect dataset (Fig.4) indicates that coal occurrences are mostly exposed in the following classes (descending order): Northeast (13.8%), Southwest (13.4%), South (13.2%), West (12.9%), Southeast (12%), Northwest (10.7%) and Flat (0.6%).

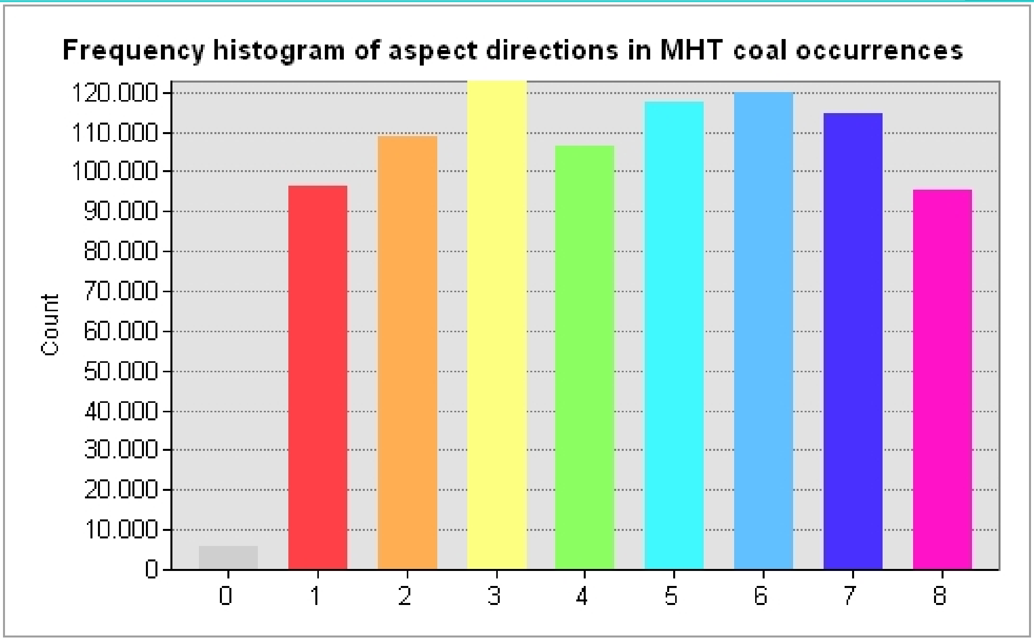

Fig. 4: Frequency histogram of aspect directions in MHT coal occurrences. Explanation of X axis values. (0 = flat, 1= North, 2 = Northeast, 3= East, 4 = Southeast, 5 = South, 6 = Southwest, 7 = West, 8 = Northwest). The Y-axis (vertical axis) represents the count of raster cells of each aspect class.

In accordance with aspect zonal statistics in coal occurrences (Fig. 4) represent an equal and balanced interpolation between nine categories in the study area. Based on geospatial analysis, influence of aspect in occurrence of coal is highly connected with east, south and southwest direction (40.4%) in the Mesohellenic Trough Basin.

Next step was the construction of the hillshade (shaded relief) map, which represents the illumination of a surface (Fig.5) from some hypothetical, user-defined light source such as the sun (Burrough, 1998). Hillshade is strongly related to the parameters of azimuth and altitude and is a grayscale 3D representation of the surface, with the sun's relative position taken into account for shading the image. Hillshading is a method of visualization of the topographic relief, based on simulating the effect of natural light on earth’s surface, under some necessary assumptions and simplifications that make the result usable for mapping and cartographic purposes.

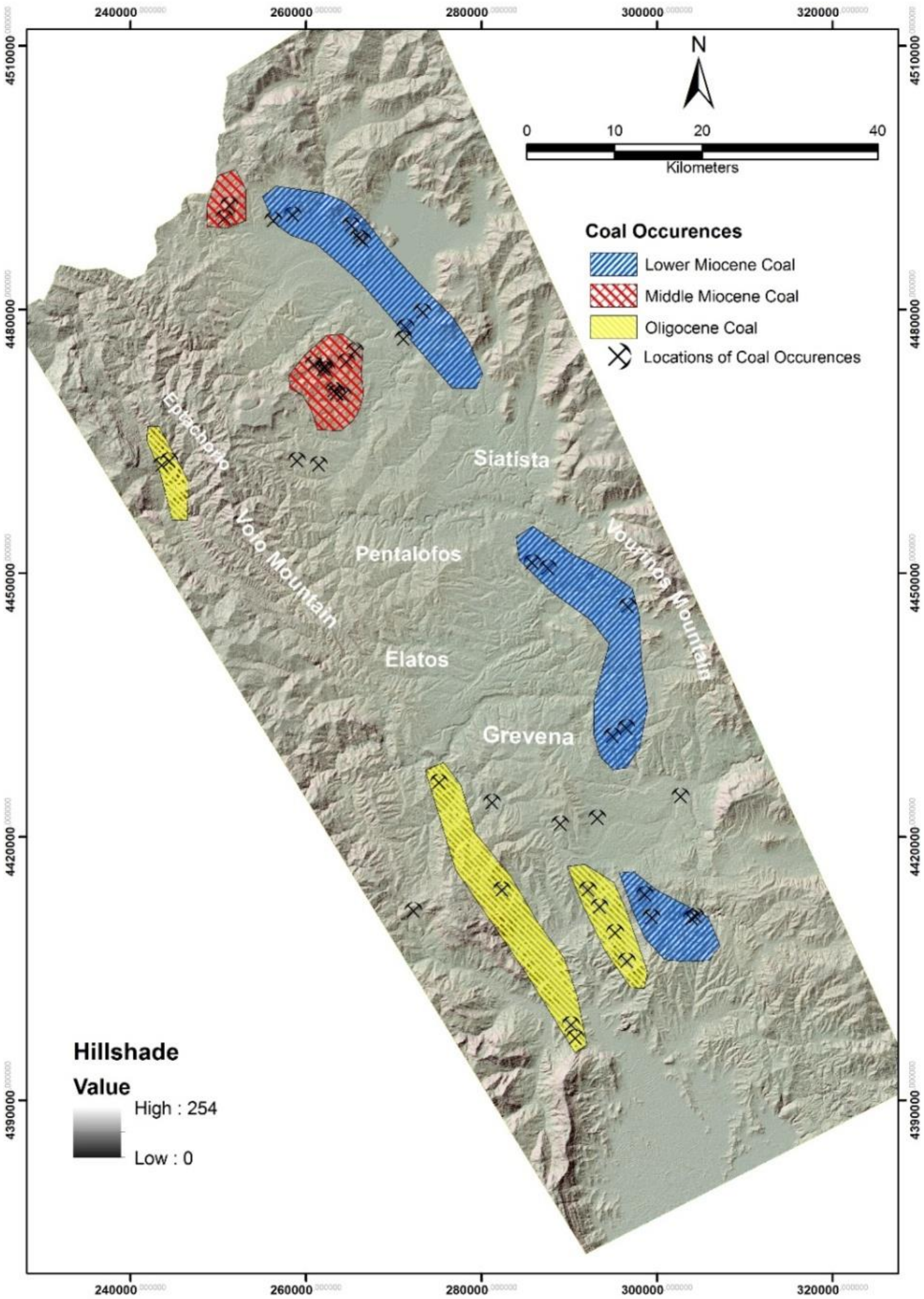

Fig. 5: Hillshaded Elevation Model of the Mesohellenic Basin with coal occurrences, based on Digital Elevation Model raster surface.

Azimuth and altitude indicate the sun's relative position and angle of elevation above the horizon range from 0 to 90 degrees, respectively. Particularly, azimuth is the sun's relative position along the horizon (in degrees) and its position is indicated by the angle of the sun measured clockwise from due north. An azimuth of 0 degrees indicates north, east is 90 degrees, south is 180 degrees, and west is 270 degrees. Moreover, the slope of a hill is relatively brightly when facing the sun and dark when facing away. Using the surface slope, aspect, angle of incoming light, and solar altitude as inputs, the hillshade process codes each cell in the output raster with an 8-bit value (0–255) increasing from black to white. From the above, hillshade representations are an effective way to visualize the three-dimensional nature of land elevations on a two-dimensional monitor. The hillshade map (Fig. 5) has been developed based on spatial relations between the frequency of hillshade values and coal occurrences mostly located in the following classes (descending order): 175°-200° (36%), 150°-175° (29.5%), 200°-254° (15.60%), 114°-150° (14.5), 0°-114° (3.9%).

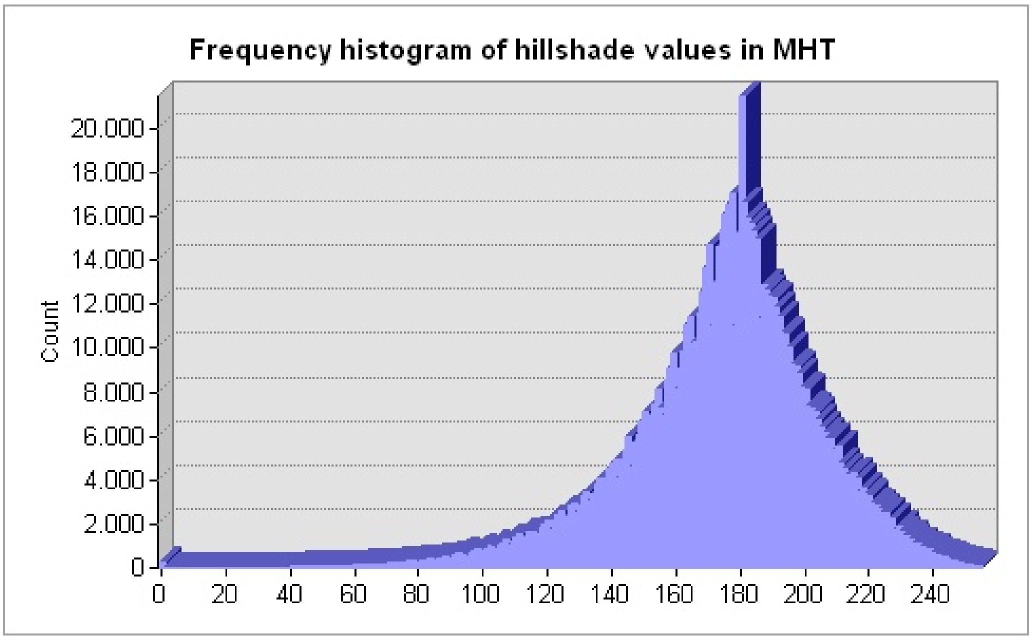

Fig. 6: Frequency histogram of hillshade values in MHT coal occurrences. The Y-axis (vertical axis) represents the frequency count of raster cells of each value, while the X-axis (horizontal axis) represents the values of each hillshade class.

According to zonal statistics of hillshade values (Fig. 6) in coal occurrences represent a maximum count in 180° and an interpolation between 80°-240° in the study area. Based on geospatial analysis, influence of hillshade in occurrence of coal is highly connected with range of 150° – 175° values (65.5%) in the Mesohellenic Trough Basin. The 3D visualization methodology has also been applied on the aforementioned thematic layers using *ArcScene*. The 3D model is just representing thematic layers in a GIS data stack, referenced to the same coordinate system, showing different raster datasets, which have been used for zonal statistics and surface modeling, related to coal occurrences in the Mesohellenic Basin (Fig. 7).

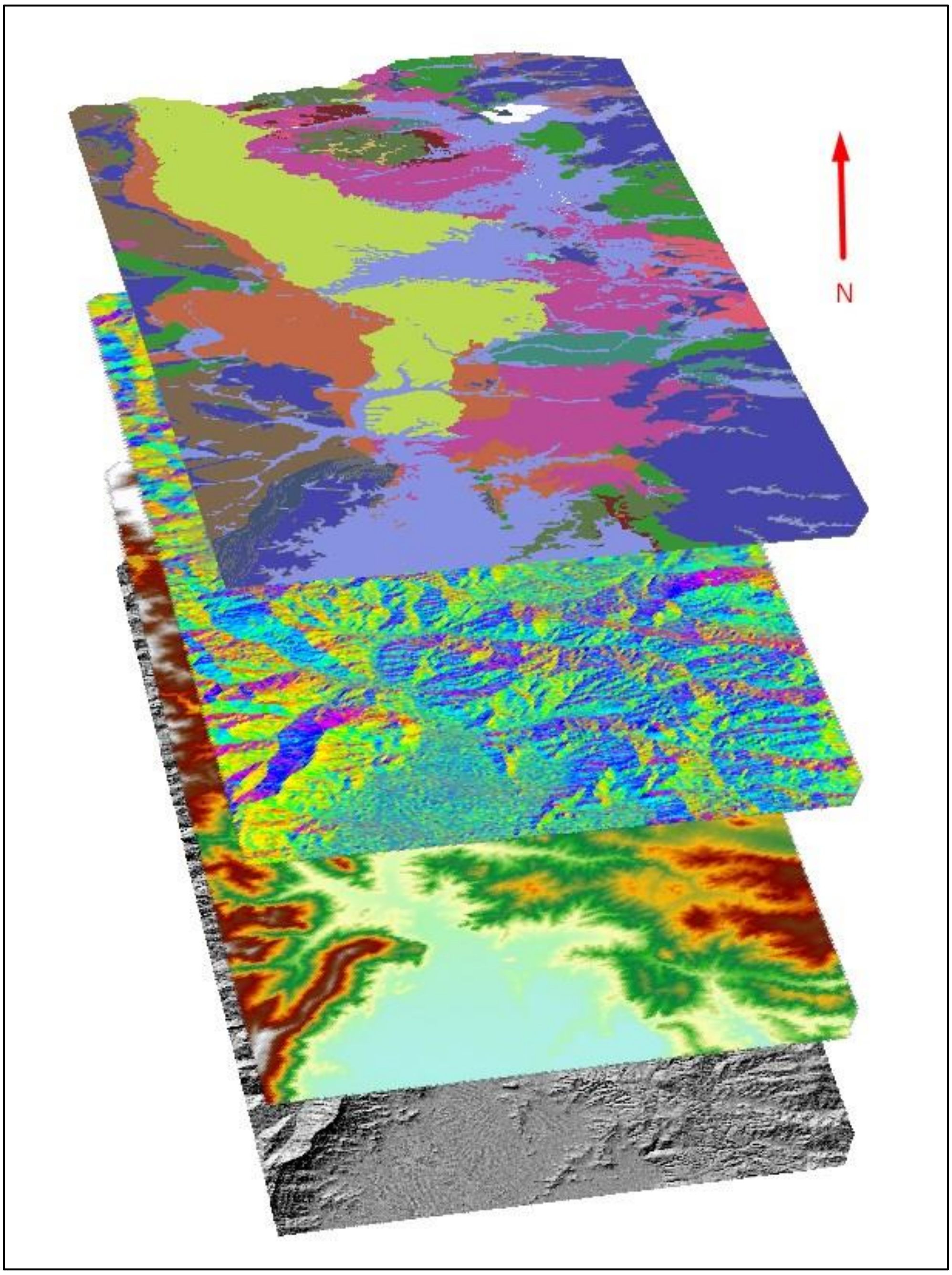

Fig. 7: 3D - overlay of thematic layers which used for zonal statistics and surface modeling related to coal occurrences in the Mesohellenic Basin.

Table 1: Geometric properties -Topology of the geological formations in the Mesohellenic Trough.

MHT Formation	Form-Code	Area (km^2)	Perimeter (km)	Geometry
Eptachorio	Olm – s.st, m	400.27	798.12	Polygon
Pentalofos	M1c, M1.st2	1146.95	845.77	Polygon
Tsotilio	M1-2.st, M1-3.c,stm	915.67	2187.90	Polygon
Burdigalian	Mi.Or, Miz, Mi.d	385.42	1361.79	Polygon
Plio – Pleistocene deposits	PI-Pt.c	127.61	406.65	Polygon
Holocene deposits	al, H.sc, cs	1398.25	4409.98	Polygon

4.2 Topological layering

Topological features of Mesohellenic Trough formations as well as their total percentage (%) are presented in Table 1. It can be observed that the Holocene deposits (al, H.sc, cs) presents the highest area and perimeter values (1398.25 km^2 and 4409.98 km) corresponding to the 31.97% and 44.05% of the total perimeter, while the Plio-Pleistocenic formations (PI-Pt.c) exhibit the lowest values (127.61 km^2 and 406.65 km) corresponding to 2.92% and 4.06 % of the total perimeter. Pentalofos and Tsotillio formations also present high area values (1146.95 km^2 and 915.67 km^2 for Pentalofos and Tsotillio respectively), whereas Tsotillio formation presents high perimeter values (2187.90 km), corresponding to 21.86% of the total perimeter (Table 5; Fig. 3). The Pentalofos formation does not present high perimeter values (845.77 km) corresponding to 8.45% of the total perimeter. Burdigalian formations perimeter is 1361.79 km, corresponding to 13.60%, while their area value is relatively low (385.42 km) corresponding to the 8.81%. Eptachorio formation presents low area and perimeter values. Topological features of Mesohellenic Trough coal occurrences, as well as their total percentage (%) are presented in Table 2. It can be observed that the Lower Miocene Coal presents the highest area and perimeter values (374 km^2 and 38.5 km), whereas the Oligocene Coal exhibit the median values (217 km^2 and 9.4 km) and Middle Miocene Coal exhibit the lowest values (88 km^2 and 17 km).

4.3. Coal occurrences- physicochemical properties and petrographic data

Lenticular coal outcrops have been identified in almost every formation of the Mesohellenic Trough. Lenticular sub-bituminous coal deposits of good quality and small thickness (<1 m) outcrop within the molassic sediments. Scattered lenses with minor granules of yellowish resin are also present. These coal occurrences are not considered as economically important to sustain any serious mining effort.

In particular, coal horizons are found within Late Eocene sediments of Krania Formation and Middle and Upper Oligocene (Rupelian-Chattian) sediments of Eptachorion Formation. Less frequently they appear within Lower Miocene (Aquitanian-Burdigalian) sediments of the Pentalofon and Tsotillio Formations, as well as in the Upper Burdigalian sediments of the Orlia Formation. Late Eocene coal deposits have only been identified at an altitude of 920 m, within

Table 2. Geometric properties -Topology of the coal occurrences in the Mesohellenic Trough, calculated from spatial analysis.

MHT Coal	Area (km^2)	Perimeter (km)	Geometry
Oligocene Coal	217	9.4	Polygon
Middle Miocene Coal	88	17.0	Polygon
Lower Miocene Coal	374	38.5	Polygon

the upper sequence of the Krania formation, consisting of alternating horizons of sandstones and bluish marls. The coal layer has a lenticular shape with a length of 50 m and maximum thickness of 40 cm. Lower level Oligocene coals are present within the lower parts of the Eptachorion formation, which consist of marine and coastal-deltaic sedimentary rocks to the northern and to the southern parts of the Eptachorion formation respectively. Despite their good quality, these do not present any economic interest due to their relatively small size of these deposits (Koumantakis and Matarangas, 1980; Papaspyrou, 1981; and Plastiras, 1985).

Miocene coal deposits are stratigraphically positioned at the lower levels of the Tsotillio formation. These are interbedded with sedimentary rocks such as conglomerates, sandstones and clay-marls. They exhibit rather small dimensions, accumulated as lenticular concentrations within coastal basins or deltaic environments. Locally, small lenticular bodies of good coal quality are also interbedded within clastic sediments of the Pentalofos formation. In Omorfokklisia formation, coal lenses occur within marly limestones in the form of lenticular intercalations. Middle Miocene coals, appear as lenticular intercalations within the lower horizons of the Orlia Formation.

Coals are mainly classified as shiny hard huminites, presenting brittle to conchoidal fracture with dark grey color (Table 3). They are further divided into: a) Bituminous coal to Subbituminous A-type coal (Eptachorio Formation - Upper Oligocene), b) Subbituminous A- to B-type coal (Tsotillio Formation - Lower Miocene) and c) Subbituminous B- to C-type coal (Formation Orlia - Middle Miocene). Their mineral assemblage mostly consists of huminite group minerals (90%) of collinite, telinite, ulminite and rarely corpohuminite. Leiptinite and more specifically rezinite, as well as inertinite appear less often, whereas FeS_2 is present in slightly higher amounts (Gerolymatos et al., 1988; Kotis and Metaxas, 1988).

Table 3. Classification / Petrographic data of the Mesohellenic coal occurrences (from Gerolymatos, Jacobshagen and Kingdom, 1988; Kotis and Metaxas, 1988).

Classification / Petrographic Data		
Basic lithotypes	**Reflectivity**	**Classification**
Huminite hard coal, shiny, with brittle to conchoidal fracture and dark grey color. Locally granules of yellowish resin.	Reflectivity of Ulminite-b ranges between 0.45-0.60% Reflectivity of Collinite- Telinite ranges between 0.28-0.52%.	Subbituminous coal (A, B and C).

The age of the coal occurrences is strongly associated with their carbonation and can be expressed by the reflectivity of ulminite-b, collinite and telinite. Ulminite-b from Krania formation presents reflectivity values ranging from 0.60 to 0.62%, reflectivity of Eptachorio formation ranges from 0.50 to 0.58%, whereas Uminite-b reflectivity from Tsotillio Formations is 0.45% (Table 4). The reflectivity of collinite and telinite from Krania and Eptachorio formations range between 0.48-0.52 and 0.43-0.46% respectively. In addition, reflectivity of collinite and telinite from Tsotillio formation ranges from 0.28 to 0.34%.

Table 4. Reflectivity values (%) for ulminite and collinite-telinite from the Mesohellenic Trough (from Gerolymatos, Jacobshagen and Kingdom, 1988; Kotis and Metaxas, 1988)..

Reflectivity (%)			
Mineral/Formation	**Late Eocene** **Krania Formation**	**Late Oligocene** **Eptachorio Formation**	**Early Miocene** **Tsotillio Formation**
Rm Ulminite-b%	0.60-0.62	0.50-0.58	0.45
Rm Collinite-Telinite %	0.48-0.52	0.43-0.46	0.28-0.34

Based on data provided from Varvarousis et al., (2000) and Kotis and Metaxas, (1988), coal occurrences from Eptachorion formation (Table 5) exhibit moisture contents which range from 8.30 to 12.00 wt.%. Their ash content and volatile matter range from 2.40 to 2.50 wt.% and 17.50 to 24.30 wt.% respectively. Fixed carbon and total S contents range from 65.00 to 68.00 wt.% and 2.00 to 2.20 wt% respectively. In addition, their Gross heating and Net heating values range from 7100 to 7110 Kcal/kg and 6660 to 6670 Kcal/kg respectively. The moisture value of Tsotillio formation coal is 8.70wt.%, while their ash and volatile matter contents are 7.50 wt.% and 37.10 wt.% respectively. Fixed carbon and total S values are 45.50 and 0.80 wt%. In addition, their Gross heating and Net heating values are 6160 kcal/kg and 5940 kcal/kg respectively. Coals from Orlia formation contain 9.40 wt% moisture and 17.00 wt% ash. Their volatile matter is 35.10 wt%, while their fixed carbon and total S value is 38.50 wt.% and below the detection limit respectively. In addition, Gross heating and Net heating values are 4670 kcal/kg and 4460 kcal/kg respectively. It is evident that Eptachorio coal occurrences present higher moisture contents compared to those of Tsotyli and Orlia respectively, while they also include high carbon and total S values. Based on their S contents the studied coal occurrences are divided into two groups. Low-S group (S < 1%) includes coals from Tsotyllio and Orlia formations, while Eptachorio coals are classified as medium-S (S:1-3%) (Chu, 2012). However, their ash and volatile matter are quite low, whereas Orlia coals tend to be enriched in ash content. In addition, Eptachorion coals present the highest Net and Gross heating values compared to both Tsotyli and Orlia coals

Table 5. Physicochemical Qualitive Data of the Mesohellenic coal occurrences (from Varvarousis et al., 2000 and Kotis and Metaxas, 1988).

Physicochemical Qualitative Data			
Formation / Age	**Eptachorion Formation / Late Oligocene**	**Tsotyllio Formation / Early Miocene**	**Orlia Formation / Middle Miocene**
Moisture (wt.%)	8.30-12.00	8.70	9.40
Ash (wt.%)	2.40-2.50	7.50	17.00
Volatile matter (wt.%)	17.50-24.30	37.10	35.10
Fixed Carbon (wt.%)	65.0-68.0	45.50	38.50
Total S (wt.%)	2.00-2.20	0.80	-
Gross heating value (Kcal/Kg, daf) [h.h.v.]	7100-7110	6160	4670
Net heating value (Kcal/Kg, daf) [l.h.v.]	6660-6670	5940	4460

5. Remarks - Conclusions

The use of geospatial analysis applied in this study yielded reproducible results and provided a quantitative description of coal occurrences areas related to morphotectonic landforms. Reproducibility is an improvement as compared with traditional morphological map analysis and visual image interpretation. Quantitative geometric characterization of landforms and coal occurrences based on DEM and grey-scale terrain images analysis combined with analog processing of scanned images and drawing maps. The presented digital terrain analysis procedure thus provided a systematic and consistent framework for quantitative description of coal occurrences in Mesohellenic Trench Basin. Furthermore, orientations provided from the thematic maps showed the same directional trends as lineaments in the satellite images from ASTER (NASA, 2009) DEM. In comparison with the geological characteristics, geospatial analysis demonstrated that the major fault zones and drainage network were easily recognized by the aspect (angle-direction) and hillshade datasets. In addition, coal occurrences are highly connected. with east, south and southwest slope directions (40,4%) and are strongly correlated with range of 150^o – 175^o hillshade values (65,5%). Key point of this study, was also the calculation of the geometric properties of the coal occurrences (polygonal method), combined with terrain measurements in an integrated geospatial database as a powerful tool for future investigations in the area of Mesohellenic Trough Basin.

In the present study, Geographic Information System (GIS) data represented coal occurrences in the Mesohellenic Trough Basin and organized via geodatabase as GIS data files (feature classes). According to the produced geological map, nine main formations distinguished from the lower to the upper parts of the Mesohellenic Trough, while five Burdigalian formations have been distinguished as well. Additionally, coal occurrences can be distinguished into three main types according to their geological age: Oligocene, Middle Miocene and Upper Miocene coals. Lower Oligocene coals tend to present the highest moisture and lowest ash values compared to those of Miocene ones. Mesohellenic Trough coals are mainly humintitic and their carbonation grade is positive correlated with the increasing of their age. Moreover, carbonation seems to be expressed by their reflectivity. They are C-S richer, while their volatile values are quite low. The presence of low inertinite contents as well as the high amounts of framboid pyrite are possibly indicative of reducing formation conditions. Upper Miocene coal occurrences have the greatest area value, whereas the lowest area values as well as the shortest perimeter belong to Middle Miocene coal occurrences of the total area and the longest perimeter.

Results for this study also showed that coals from the Mesohellenic Trough present excellent quality traits. However, their value as combustible coal is very low due to the absence of economically recoverable reserves. The largest coal lenticular bodies have been extracted in the past and the remaining occurrences do not exceed several thousand tones. Based upon the above-mentioned literature and from geospatial estimations, coal deposits in the Mesohellenic Trough Basin cannot be considered as economically valuable for exploitation.

In low-S coals of Tsotyllio and Orlia formations, S was primarily derived from parent plant material, while in the case of medium-S Eptachorio coals a combination of parent plant material and sulfate contents in seawater is probably the source of S (Chu, 2012). The moisture content is strongly associated with the sustainability of the coal use in the energy production, since high amounts of moisture tend to reduce the heating value, while at the same time their additional weight can increase the cost of transport (Radovic, 1998). Thus, coals of Tsotyllio formation should probably exhibit the lowest cost of transport since they present the lowest moisture contents compared to the other ones.

Future studies on MHT's coal deposits related to geospatial techniques could have a key role, to play in the chemical and petrochemical industries (e.g. production of fuels, alternative raw materials), providing sustainable solutions for the upcoming innovative CCS and CCU technologies, combined with renewable energy sources.

6. References

Aubouin, J., 1959. Contribution à l 'étude géologique de la Gréce septantrionale: les confins de l' Epire et de la Thessalie. Ann. Geol. Pays Hellén., 10, p. 1-483.

Aubouin, J., 1961. Geological Map of Greece 1:50.000, Sheet Kastanea. I.G.M.E., Athens.

Babita, P., Sailesh, S., 2012. Topography and Land Temperature Investigation Using Arc GIS 10. International Journal of Basic & Applied Sciences. 01. 403-414. 10.17142/ijbas-2012.1.2.27.

Brunn, J., 1956. Contribution à l 'étude géologique du Pinde septentrional et d' une partie de la Macedoine Occidentale. Ann. Geol. Pays Hellén., 7, p. 1-158, Athénes.

Brunn, J., 1977. Geological Map of Greece 1:50.000, Sheet Pentalofos. I.G.M.E., Athens.

Burrough, P. A., and McDonell, R. A., 1998. Principles of Geographical Information Systems (Oxford University Press, New York), 190 pp.

Chu, C.L., 2012. Sulfur in coals: A review of geochemistry and origins. Int. Jour. Coal Geol. 100, 1-13.

Ferrière, J., Reynaud, J. Y., Pavlopoulos, A., Bonneau, M., Migiros, G., Chanier, F., Proust, J. N. and Gardin, S., 2004. Geologic evolution and geodynamic controls of the Tertiary intramontane piggyback Meso-Hellenic basin, Greece. Bull. Soc. Geol. Fr., t.175, no 4, pp. 361-381.

Gerolymatos, E., Jacobshagen, V., Kingdom, P., 1988. Geothermal development in Mesohellenic Trough and maturity of organic material. Air Transfers. Third session. Greek Geological Society, May 1986. Bull Eng. Geological. Soc., T. XX, vol.2, pp. 363-377, Athens, 1988.

IEA (International Energy Agency) 2017. World Energy Balances 2017, OECD/IEA, Paris.

Jacobsen, K., 2004. DEM generation from satellite data. In: Goossens, R. (Ed.): Remote Sensing in Transition, Proc. of the 23rd EARSeL Symposium 2003, Ghent, Belgium, pp. 513–525.

Kilias AD, Vamvaka A, Falalakis G, Sfeikos A, Papadimitriou E, et al. 2015. The Mesohellenic Trough and the Paleogene Thrace Basin on the Rhodope Massif, their Structural Evolution and Geotectonic Significance in the Hellenides. J Geol Geosci 4, (2), 1-17. doi:10.4172/2329-6755.1000198.

Kotis, Th. and Metaxas, A., 1988. Report on the results of geological –ore deposits recognition for coal of Asprokklisia community of Trikala prefecture. H. R. Rep. Department of Energy Raw Materials (ADHD) Institute of Geology and Mineral Exploration (IGME), 11 pp., Athens, July 1988.

Koukouzas, N., 1998. Distribution of lignite deposits based on the age, quality and their deposits, Mineral Wealth, 106/1998.

Koukouzas, C. and Koukouzas, N., 1995. Coals of Greece: distribution, quality and reserves. European Coal Geology, Geological Society Special Publication, 82, 171-180.

Koumantakis, I. and Mataragkas, D., 1980. Geological Map of Greece sc.: 1:50,000, sheet "Panagia". Institute of Geology and Mineral Exploration (IGME), Athens 1980.

Koumantakis, I., Mataragas, D., 1989. Geological Map of Greece 1:50.000, Sheet Panagia. I.G.M.E., Athens.

Mavridis, A., Kelepertzis, A., Faugeres, L., 1982. Geological Map of Greece 1:50.000, Sheet Siatista. I.G.M.E., Athens.

NASA, 2009. ASTER Global Digital Elevation Map. Archived from the original on 3 July 2009. Retrieved 2009-06-30.

Papanikolaou, D., Lekkas, E., Mariolakos, E. and Mirkou, P., 1986. Contribution to the geodynamic evolution of Mesohellenic Trough. Air Transfers. 3rd Conference Eng. Geological Company, May 1986. GSG T. XX, pp. 17-36, Athens 1988.

Papaspyrou, A., 1981. Ore recognition for lignite in Kastoria. Solicitous. H. R. Rep. Institute of Geology and Mineral Exploration (IGME), 15 pp., Athens.

Plastiras, B., 1985. Geological Map of Greece sc.: 1:50,000, sheet “Chionades - Grammos”. Institute of Geology and Mineral Exploration (IGME), Athens, 1985.

Plastiras, V., Rozos, D., 1990. Geological Map of Greece 1:50.000, Sheet Kastoria. I.G.M.E., Athens.

Radovic, L.R., 1998. Energy and Fuels in Society, Department of Materials Science and Engineering, College of Earth and Mineral Sciences, Penn State University, USA

Savoyat, E., Lalechos, N., 1969a. Geological Map of Greece 1:50.000, Sheet Karditsa. I.G.M.E., Athens.

Savoyat, E., Lalechos, N., 1969b. Geological Map of Greece 1:50.000, Sheet Trikala. I.G.M.E., Athens.

Savoyat, E., Lalechos, N., 1972. Geological Map of Greece 1:50.000, Sheet Kalabaka. I.G.M.E., Athens.

Savoyat, E., Monopolis, D., 1971. Geological Map of Greece 1:50.000, Sheet Nestorio. I.G.M.E., Athens.

Savoyat, E., Monopolis, D., 1972. Geological Map of Greece 1:50.000, Sheet Grevena. I.G.M.E., Athens.

Schweik, C. M., 2011. Introduction to Geographic Information Systems for Natural Resources Management (University of Massachusetts, Amherst), 126 – 134 pp.

Schweik, C. M, Bradley, B., Smith, R., 2013. Introduction to Geographic Information Science using ArcGIS V10 (University of Massachusetts, Amherst).

Stamatis, A., 1992. Geological Map of Greece 1:50.000, Sheet Deskati. I.G.M.E., Athens.

Tasianas, A., Koukouzas, N., 2015. CO_2 storage capacity estimate in the lithology of the Mesohellenic Trough, Greece. 8th Trondheim Conference on CO_2 Capture, Transport and Storage. Energy Procedia, 86, 334 – 341.

Vamvaka A. 2009. Geometry of deformation and kinematic analysis in Mesohellenic Trough. PhD thesis from the Aristotle University of Thessaloniki, Department of Geology.

Varvarousis, C., Metaxas, A., Kotis, Th., Ploumidis, M. and Vretos, K., 2000. Research and Evaluation lignite basin deposits Kozani-Servia, Sarantaporo Kastoria. Kastoria Basin. H. R. Rep. IGME, 45 pp.

Wahl, R., 2013. The use of topology on geologic maps, U.S. Geological Survey, accessed at https://pubs.usgs.gov/of/2004/1451/pdf/wahl.pdf