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TWINNING TO SUSTAINABLE ENERGY TRANSITION

WP2: Building Research Excellence of the IG/FORTH

DELIVERABLE 2.4: Handbook on the Field Trips to sites of Geological interest for Geothermal, H2 and CO2 storage

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DOCUMENT CHANGE CONTROL

Version Number	Date	Author(s)	Brief Description of changes
1.0	31.3.2026		Final version

Table 1. Document Change Control

EXECUTIVE SUMMARY

Deliverable D2.4 presents the handbook developed under TWINN2SET for field trips to geological and industrial sites of relevance to geothermal energy, geological hydrogen storage and CO2 capture and storage. The handbook brings together the knowledge generated through three visits implemented during the project: the field visit in the Chania region of Crete, Greece; the industrial visit to the Dunkirk site in France; and the geothermal field visit in the Aidipsos–Kammena Vourla area in Euboea, Greece. Collectively, these visits cover complementary aspects of the sustainable energy transition, ranging from geological formations and geothermal systems to industrial-scale CO2 capture applications.

The deliverable contributes directly to the objectives of WP2, which aimed to strengthen the scientific research and technological capacity of IG/FORTH in the fields of geological CO2 sequestration, geological hydrogen storage and geothermal energy. In this context, the field visits were not conceived as stand-alone observational activities, but as integrated learning and capacity-building actions closely connected with staff exchanges and collaboration among consortium partners. Through this combined approach, participants were able to engage with geological settings, industrial practices, field observations and expert knowledge in a structured and practice-oriented manner.

More specifically, the handbook provides analytical field-trip guides and background information on sites of geological and technological interest, while also documenting the broader educational and collaborative value of these activities. The visits supported the exchange of best practices, enhanced understanding of relevant geological, geochemical and technological processes, and promoted interaction between researchers from Greece, Norway and France. In doing so, they contributed to the development of a stronger common knowledge base within the consortium and to the expansion of scientific cooperation beyond individual mobility actions.

Overall, Deliverable D2.4 demonstrates that the field visits successfully complemented the staff-exchange program and enriched the implementation of the research component of TWINN2SET. By linking field-based learning, industrial exposure and inter-institutional collaboration, the deliverable supports the broader ambition of the project to build research excellence at IG/FORTH and to reinforce its long-term scientific positioning in the area of sustainable energy transition.

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1. OBJECTIVES

The objective of the WP2: Building research excellence of the IG/FORTH is to strengthen the scientific research and technological capacity of IG/FORTH staff of all research levels, in CO2 geological sequestration technologies, geological hydrogen storage and geothermal energy by:

-Enhancing understanding of the underlying chemical processes

-Exchanging best practices between scientists at senior staff level, visit of laboratories and centres of advanced partners, Field trips to geological sites

-Enhancing interaction of researchers from EL, NO, FR, for joint research projects, publications and expansion of their collaborative network

The objective of Deliverable D2.4 is to provide **a comprehensive field trip guide** of geological sites of interest related to geothermal energy, CO_2 and H_2 storage. This guide will provide specific guidelines, regarding geological and environmental criteria, in **choosing the appropriate site of interest**. In addition, will **promote knowledge transfer** between industry and academia, while **contributing to capacity building** in sectors of geothermal energy, CO2 and H2 storage. The handbook will **enrich knowledge in terms of chemical processes** and **strengthen interactions** between partners.

2. INTRODUCTION

According to the proposal 3 field visits to sites of Geological and Geothermal interest have been promised. These field visits can be an ideal case to combine simulation activities in the lab with actual plant designs and geothermal wells. An indicative list of sites:

Greece: Geothermal sites/wells: 2 visits. **Milos Island** (Cyclades, Aegean Sea) with measured temperatures in wells ranging between 280 and 320°C (High Enthalpy). A pilot Unit of 2MW is installed. **Lesvos Island** (Aegean) with Medium Enthalpy measured temperatures in wells locally ranging higher than 90°C.

France: City of Dunkerque (Dunkirk) for CO2 capture, where IFPEN is currently working on an industrial pilot plant expected to capture 0.5 tCO2/hour from steel industry by 2022 in light of the EU-funded project: 1 visit

“DMX Demonstration in Dunkirk”

Timing of these visits will depend on staff exchange activity. A special handbook for these geological sites will be developed.

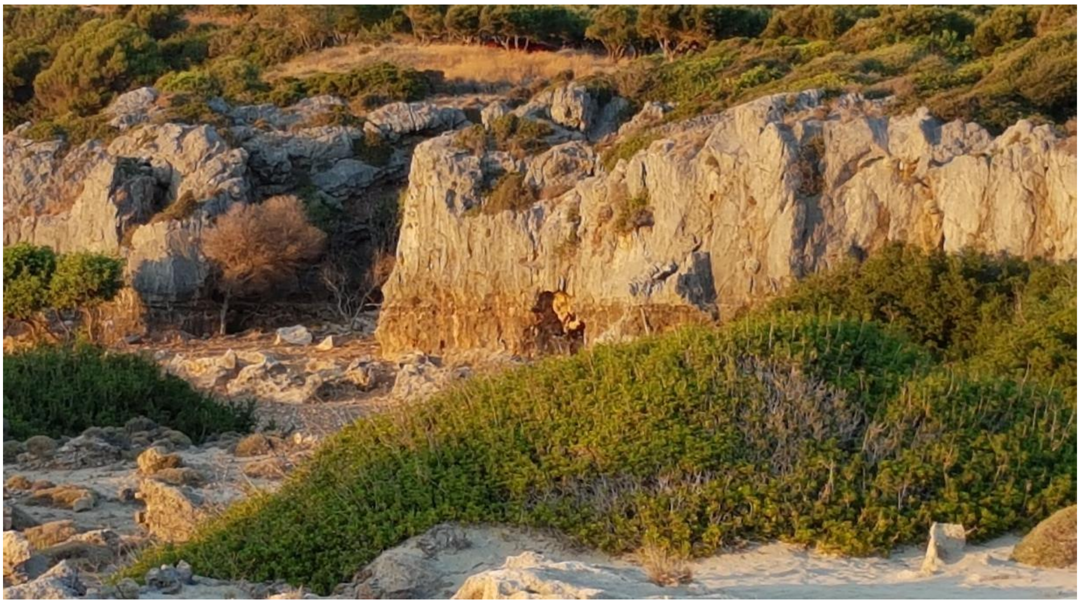
During the project implementation, 3 field visits were organized, the first in Northwestern Crete Island, Greece, the second at ArcelorMittal’s Dunkirk site in France, and the third in Aedipsos - Kammena Vourla area, in Euboea.

3. GEOLOGICAL FIELD TRIP GUIDES

3.1 Field visit in Chania Region

IFPEN	POIRIER	Simon
IFPEN	FOURNIER	Frédérique
UiS	PECK SZE LIM	KATRINE
UiS	ESCALONA VARELA	Alejandro
UiS	PUNTERVOLD	Tina
UiS	ABDULINA	VERONIKA
IG/FORTH	BELLAS	Spyridon
IG/FORTH	GONTIKAKI	EVANGELIA
IG/FORTH	STAMATAKIS	Emmanouil
IG/FORTH	FRAGKOU	Efsevia
IG/FORTH	CHARALAMPOUS	GEORGIA
IG/FORTH	TALLAROU	CHRYSOULA
IG/FORTH	MAKRI	Vagia Ioanna
IG/FORTH	TELEMENIS	Dimosthenis
IG/FORTH	LAMPROPOULOS	Anastasios
IG/FORTH	AMVROSIATOS	KONSTANTINOS

GEOLOGICAL FIELD TRIP GUIDE



Area of interest: **Northwestern Crete Island, Greece**

Instructor: Dr. Spyridon Bellas, Principal Researcher at FORTH/IG

Project Support: TWINN2SET (*Twinning to Sustainable Energy Transition*)

Funded by the European Union

CHANIA, September 2023

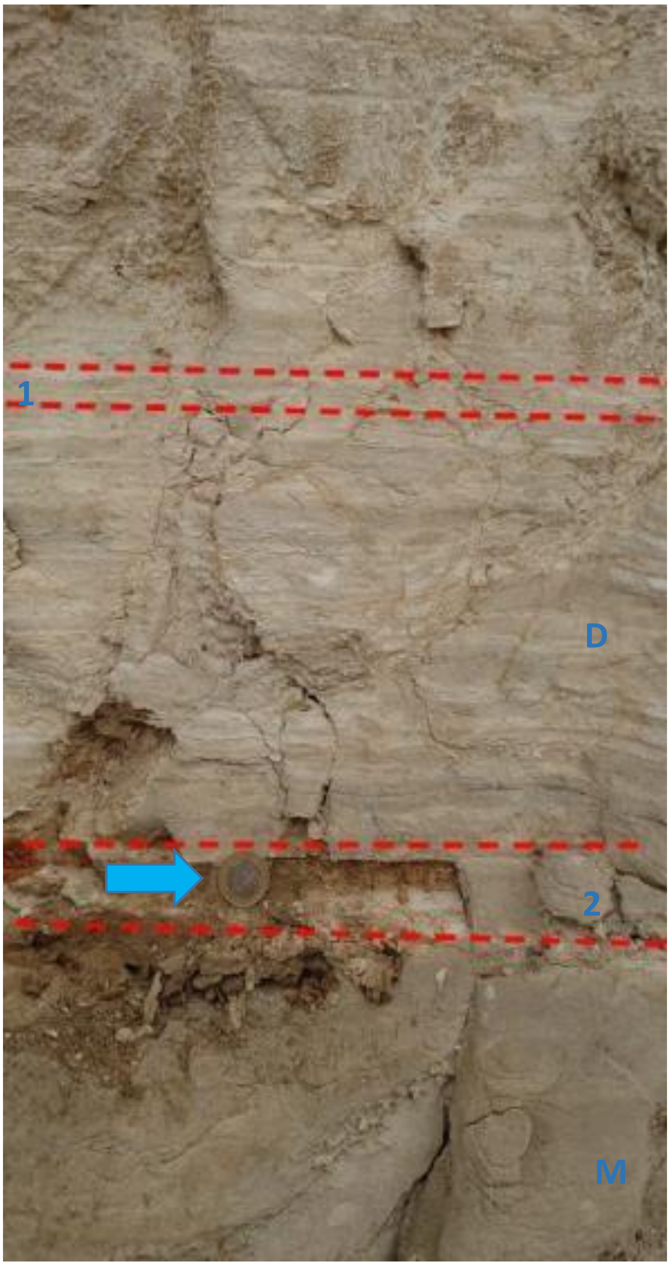


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Photo above: Mudstones (**M**: at the base) transition to fine laminated Diatomites (**D**: top), Kalyves, Apokoronou, West Crete Island. Upper red dashed-lines (1) indicate the (almost horizontal) orientation of the laminae. Lower red-dashed lines point to the transition layers (2). Age: Upper Miocene. Note one-euro coin (light-blue arrow) for scale.

Photo cover: Upper Eocene platform carbonates with benthic Foraminifera (*Nummulites*) of Tripolis geotectonic Unit with uplifted old shorelines, Falassarna Bay, NW Crete. Photos courtesy: Dr. S. Bellas.

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Main photo: Marine, shallow-water, bioclastic, massive, highly cemented, sandy-carbonates of the Akrotiri Formation with Red-algal fragments. An aromatic, Rosemary evergreen shrub, native to the Mediterranean region is grown along thin joints (cracks) that developed after recent tectonics affected Crete and were secondary filled in with Terra Rosa material (see upper left inlet). Technical University Campus outcrop, Akrotiri, Chania. Photo courtesy: Dr. S. Bellas.

1.

Abstract

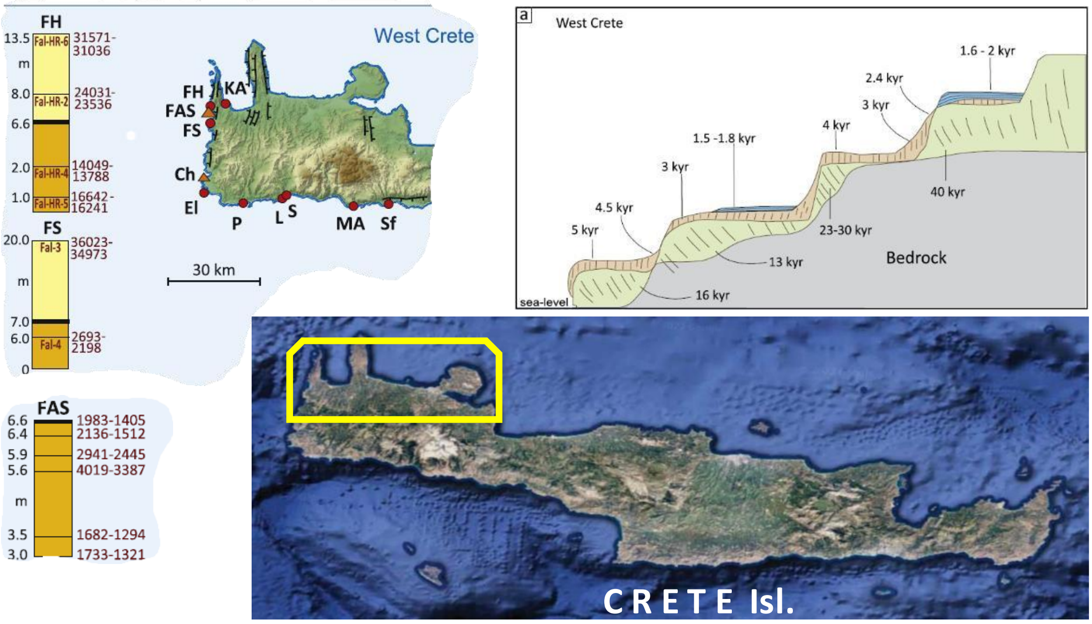
The present Field Trip Guide is compiled for the needs of the TWINN2SET (Twinning to Sustainable Environment) EU project, and is organized as an one-day geo-excursion. It roughly describes the geology of northwestern Crete Island and mostly focuses on specific Neogene strata that comprise several bio- and lithofacies (Formations) that represent various sedimentary depositional environments, mainly developed during three successive sedimentary cycles (a Miocene, a Pliocene and a Pleistocene one). In Holocene both eustatic and tectonic control due to vertical motions of the Hellenic Subduction Zone (i.e. earthquakes) resulted to differentiation of the raised shorelines at various locations of western Crete. It also provides the general tectonic framework under which all these strata were deposited in restricted or open marine basins that have been evolved in the course of Neogene (i.e. Miocene onwards).

The idea behind, is that in the Energy Transition period towards a Net Zero Era, geology and petroleum geology skills can be very useful for a number of actions that are of great importance to minimize the carbon footprint and reach the decarbonization goal. Therefore, the prementioned deposits and subsurface geology may play a significant role for the next few decades. Some of these deposits may be used as potential reservoirs (i.e. for natural gas, hydrogen, or Carbon Dioxide (CO2)), some others are investigated for their usefulness as source rocks and some for their ability and integrity to cap (seal) potential store sites.

In the following is presented, a basic description of the northwestern Crete Neogene rocks, their occurrences at specific locations/outcrops (delineated as STOPSxx during the field trip), few of their properties, stratigraphy and main potential utilization. Five main locations and a few sublocations are considered, including most well-developed Neogene and Mesozoic rocktypes and almost all depositional paleoenvironments vs tectonics of northwestern Crete.

The below figures show the paleoshoreline data after isotope analyses in specific points (red circles) and older data (triangles). Numbers to the left of the columns indicate the altitude (above present sea-level) and to the right 2σ ages in calibrated yr BP. FH, FS and FAS are for Falasarna (Mouslopoulou et al., 2015).

2.

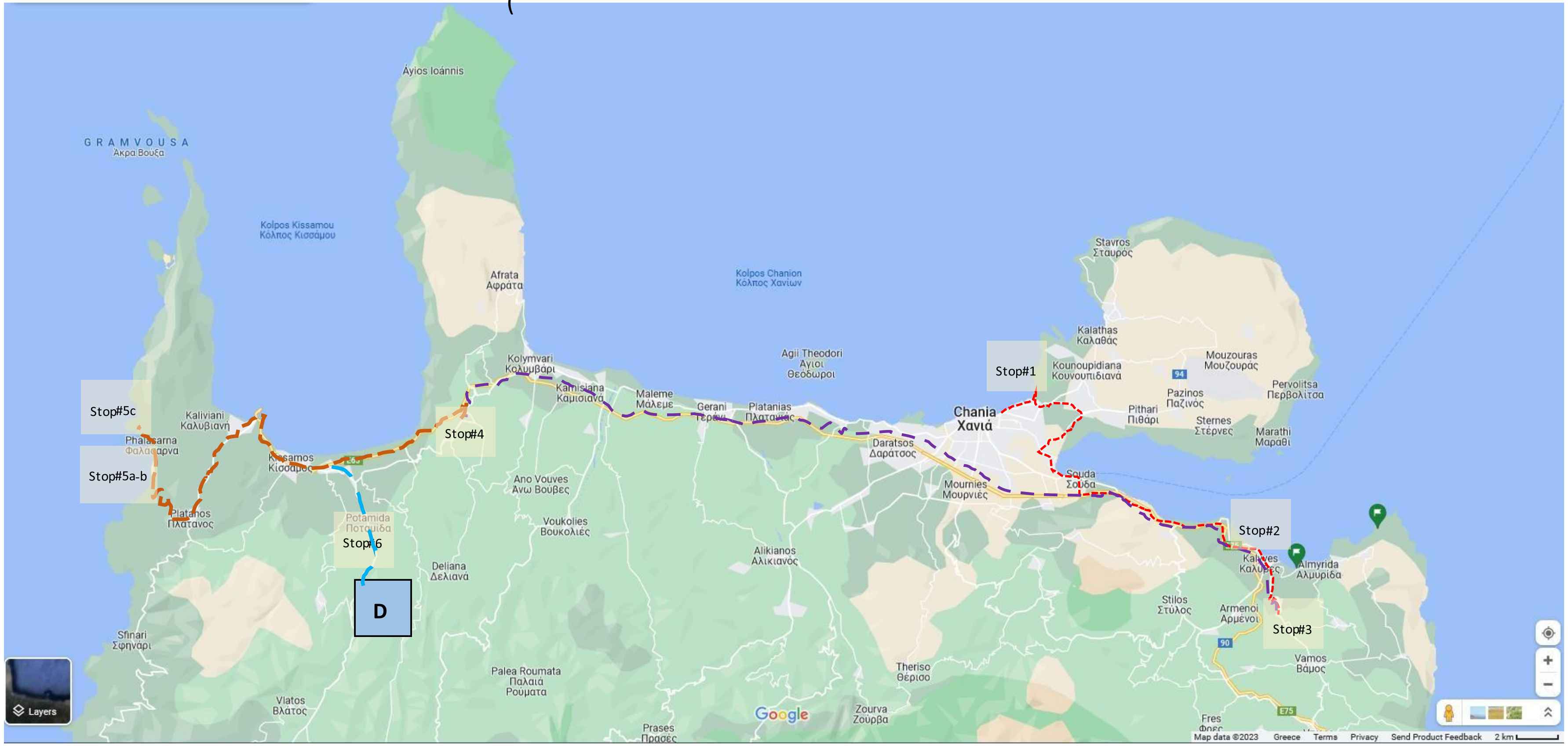


Google-Map of northwestern Crete Island, S. Greece with main Geo-Stops

3.

Red dashed line shows the start point and the first three geol-stops (#1-#3) as we move to the east.

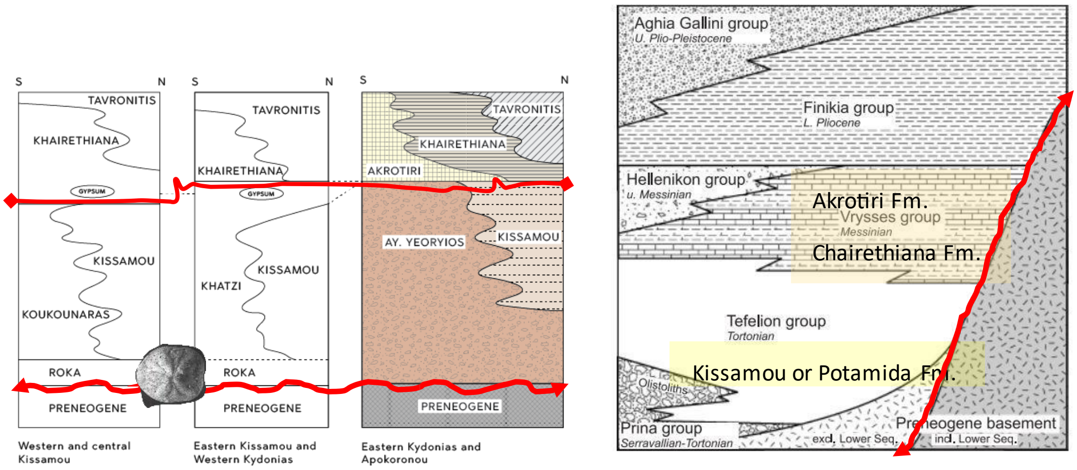
Purple dashed line gives the next geol-stops as we will then turn to the west (#4 and #5), while geol-stop#6 will be the last one, turning again to the east, before approaching the dinner site (D) (light -blue dashed line).



4.

Introduction

This field-guide report refers to the northwestern Crete island area in Greece (eastern Mediterranean Sea). Miocene to Recent Neogene deposits dominate the area of interest. They rest uncomformably on the pre-neogene basement, which consists either of carbonates or of metamorphic rocks. Christodoulou (1963) followed by Freudenthal (1969) studied the Neogene. The later author during a detailed field mapping distinguished 11 Neogene geologic formations with specific lithostratigraphic correlations among them. Miocene depositional sequences consist mostly of transgressive and upstanding system tracts. The boundaries of the regressive system correspond to discontinuity surfaces with numerous features of subaerial exposure, clear evidence of sea-level subsidence. Evaporitic formations and relevant rocks mark the Mio-Pliocene boundary, a significant regressional system track, usually known as the Messinian Salinity Crisis (MSC). The Pliocene corresponds to a transgressive phase in which yellow, sandy marls form, changing upward into marly limestones. Locally, the Pliocene begins with thin conglomerates that grade upward into cemented, sandy limestones with marly intercalations. Many other researchers followed last four decades, among them the work of Meulenkamp et al (1979) is to note. A thorough review of this research and new findings can be found in Keupp & Bellas (2000) (see below map with the four main Neogene Subbasins I-IV).



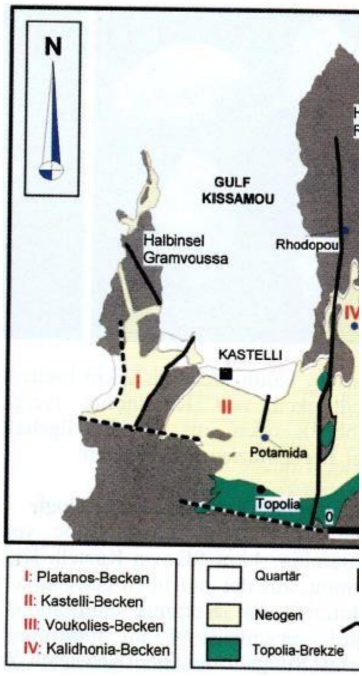
Left: *Schematic lithostratigraphy of western Crete. Main lateral transitions and lithostratigraphic correlations of the formations in several parts of Chania Province, Crete are given (modified from Freudenthal, 1969). Upper red line shows the Messinian unconformity well-known in the Mediterranean Sea as the Messinian Salinity Crisis (MSC), where several hundred up to thousands of meters of evaporites (gypsum, anhydrite, salts, etc.) deposited almost everywhere within the Mediterranean basin. Lower curved red line shows the unconformity that separates the Pre-Neogene basement rocks from the Neogene deposits (an erosional surface of several millions of years). Fossil echinoids Clypeaster dominate the first transgressional depositit (Roka F.)* ***Right***: *Same mod. after Meulenkamp et al. (1979).*

In this context, Meulenkamp (1979) subdivided the Neogene sedimentary sequence of Crete into six lithostratigraphic groups. The (former) Akrotiri Fm. is categorized and referred as belonging to the Vrysses Group in his classification; it conformably overlies the Tefelion Group (which includes at the base the former Roka Fm. under the name Fotokadhon Fm.) or unconformably directly overlies the pre-Neogene basement. It

5.

consists of marine bioclastic or reefal limestones or alternating laminated and homogeneous marls, which contain evaporite intercalations in some spots. Its age is determined within late Tortonian to Messinian (Meulenkamp et al., 1979).

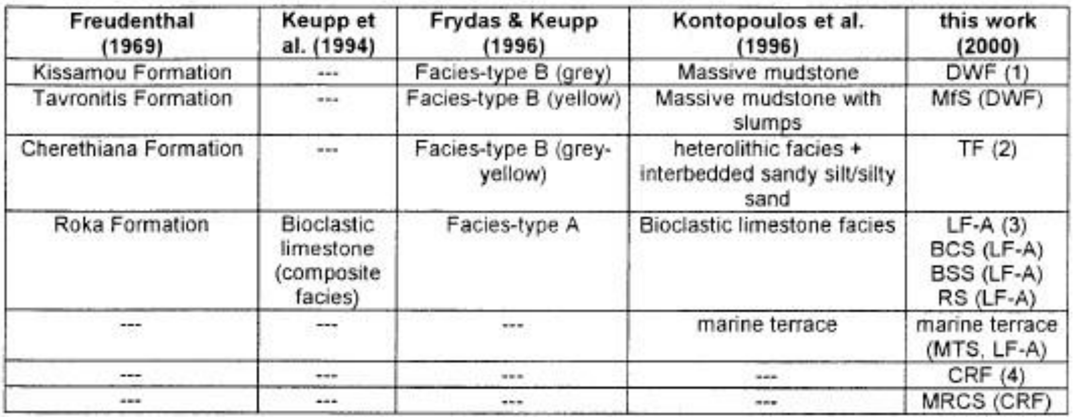
6.



***Left Figure**: The four Neogene subbasins of northwestern Crete (I-IV);*

I: Platanos, II: Kastelli-Kissamou, III: Kalydhonia and IV: Afrata.

They were developed in the Miocene and their basal marine deposits have a Tortonian age.



Freudenthal (1969)	Keupp et al. (1994)	Frydas & Keupp (1996)	Kontopoulos et al. (1996)	this work (2000)
Kissamou Formation	---	Facies-type B (grey)	Massive mudstone	DWF (1)
Tavronitis Formation	---	Facies-type B (yellow)	Massive mudstone with slumps	MfS (DWF)
Cherethiana Formation	---	Facies-type B (grey-yellow)	heterolithic facies + interbedded sandy silt/silty sand	TF (2)
Roka Formation	Bioclastic limestone (composite facies)	Facies-type A	Bioclastic limestone facies	LF-A (3) BCS (LF-A) BSS (LF-A) RS (LF-A)
---	---	---	marine terrace	marine terrace (MTS, LF-A)
---	---	---	---	CRF (4)
---	---	---	---	MRCS (CRF)

***Table above**: Correlation of the various lithofacies/sedimentary facies types as they have been published by various authors. Last column is after Keupp & Bellas (2000).*

Below are given descriptions of a few most significant sedimentary formations after the original schemes that were proposed by the authors of the table above.

Kissamou Formation: The Kissamou Formation consists of blue or purple amorphous clays, but locally stratified. Within these clays, strongly indurated, graded and ungraded sandstones, calcarenites, and organic limestones occur at various stratigraphic levels. In the Kissamou district, the formation conformably overlies the Roka Formation (a basal, transgressive, sequence, LF-A after Keupp & Bellas, 2000) while in the Kydonias district near Mournies, the Kissamou Formation is underlain by the Ayios-Yeoryios Formation, while it is also a lateral equivalent of the top of the latter formation. In addition, it is probably overlain by the Tavronitis Formation between Ayia Marina and Chania, and near Mournies it is overlain by the Akrotiri Formation. It is a Deep Water Facies (DWF).

Akrotiri Formation: The Akrotiri Formation is composed of either unbedded or of thick, well bedded, white to yellow marly limestones. They consist of organic detritus, mainly of algae and in minor occurrence of shell debris or mollusc shell-fragments. Its basal part generally consists of coarse- to medium-grained, brown, unconsolidated sands, but frequently conglomerates are included as well. A rich fauna of macro- and microfossils, amongst which *Ostrea*, *Pecten, Clypeaster* and *Heterostegina* occur in the sand beds. This fauna is similar to the one from the Roka Formation and of the limestones in the uppermost part of Khatzi formation as well. At most other locations, in which the base of the Akrotiri Formation is exposed in the surface, it is overlying preneogene Phyllite-Quartzites or dark black crystallized limestones. It is not overlain by other Neogene strata but in the Apokoronou district laterally passes into or overlain by the Khairethiana Formation. This Formation is referred in literature as "pietra di Malta". It is a Shallow (Littoral)-Water Facies (LF-A), RS, i.e. of rather regressive character, not included in the above table, since it is only present in the area of Chania and the Peninsula Akrotiri, surrounding the Soudha bay (Soudha: main port of Chania/Crete).

Khairethiana or Cherethiana Formation: This Formation consists of plenty of alternations of yellow to brown predominantly, laminated marls, clays or sandy clays, and yellow amorphous marls or marly limestones. Coarse, graded intercalations are not often. In general, the thickness of one sequence of laminated and amorphous layers does not exceed 5 m. Graded beds generally are 0.5 m thick or less. The amorphous marls contain scarce molluscs or other macrofossils, but microfossils occur in abundance, especially *Discospirina*, and other, smaller miliolids. These foraminifera are not reported from the laminated clays and marls, which contain plant debris. Furthermore, sponge needles and diatoms are very common in the laminated beds. In the Apokoronou District the Khairethiana Formation is overlying the Kissamou Formation (area of Vryses village). Also, it is overlying partially and also lateral equivalent of the Akrotiri Formation. The exact same superposition and lateral transition can be seen on Akrotiri Peninsula. In the Kydonias District the Khairetiana Formation is overlain by the Tavronitis Formation but it is also a lateral equivalent of it (Khairetiana Formation in the south, Tavronitis Formation in the north). In the Apokoronou District the Khairetiana Formation is not overlain by any other strata of Neogene age. It is a Transitional Facies (TF)., usually from a DWF (i.e. Kissamou) to an RS (i.e. Akrotiri).

Tavronitis Formation: This Formation consists of amorphous marls, which in the upper part of the formation mainly alternate with graded beds. In the marls many slumps of coarse material can be observed. In its lower part this formation consists mainly of white, amorphous marls. The middle part consists of gravel masses slumped into similar marls and finally, the upper part is composed of grading sand layers alternating with amorphous marls. The Tavronitis Formation is the youngest in age since it is not covered by any other Neogene deposits. It conformably overlies the Khatzi Formation. In the western part of the Kissamou District, near Lardhas this Formation is seen to overlie the Khairetiana Formation, which is its lateral equivalent in the eastern part of the Kissamou District. It is a Massive Mudstone bearing extensive Slumping (MfS), which points to a DWF in most of the cases.

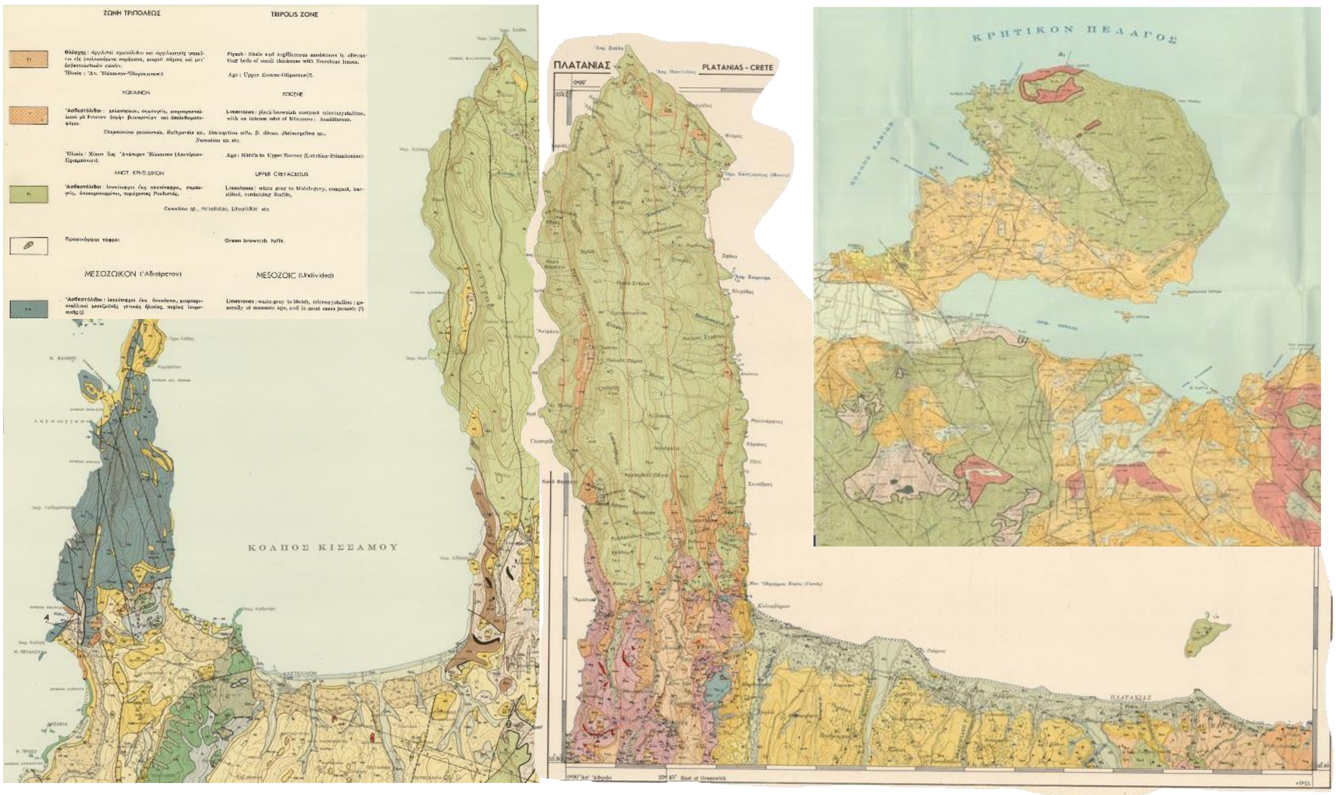
Aeolian deposits: Not attributed to a specific facies yet, it is an onshore Facies of paleodunes that probably deposited during the late Holocene and have been well-compacted and show adequate thicknesses in the range of 2 to 6 meters. They are very extensive in a few locations such as the Falassarna (west Cretan coast), and the Stavros area (Akrotiri peninsula).

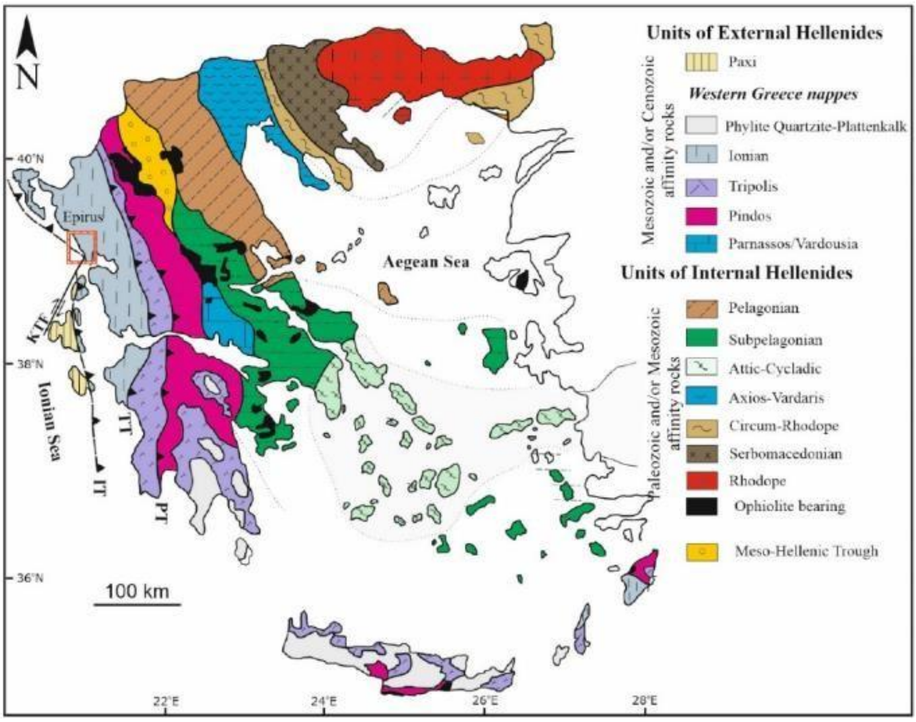
The lithostratigraphic grouping of Meulenkamp et al. (1979), refers and can be applied mostly to central Cretan deposits. According to their description, Akrotiri and Chairethiana

Formations belong to the Vrysses Group (compare our figure above, the right one in the Introduction chapter). Zachariasse & Lourens (2021) and this work use the older approach of Freudenthal (1969) and that of Keupp & Bellas (2000).

4. Geological map of northwestern Crete

IGME, Geological Map Sheets "Kastelli" (upper left), "Platanias" (middle) and "Chania" (upper right), original scale 1:50,000.





Simplified geotectonic map of Greece from Nikolakopoulos et al., (2022).

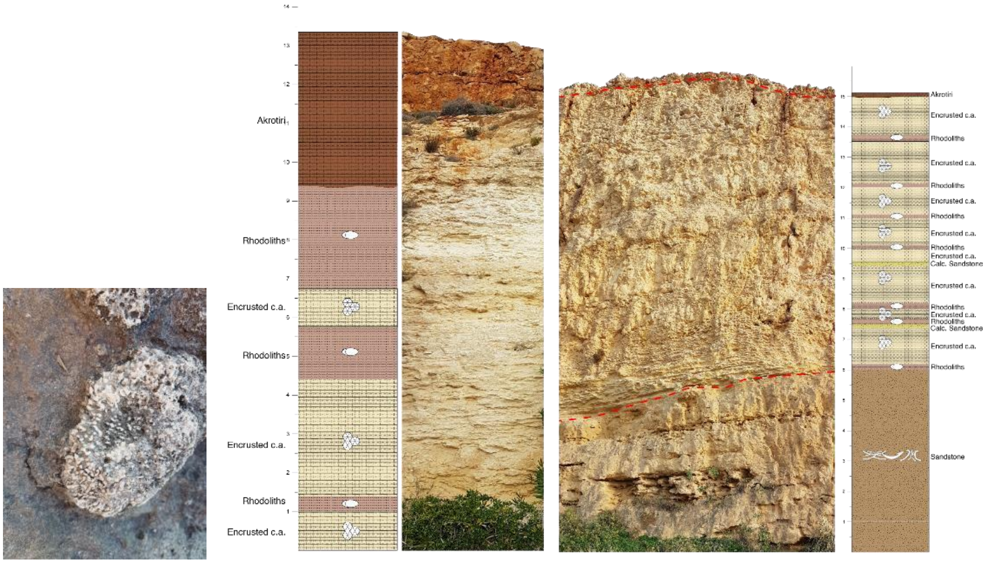
Note the diversification of the Tripolis zone carbonates/flysch along western Greece and Crete (in purple).

The same for the Tripolis zone in western Crete, where it is shown in light green, orange and dark-blue colors (upper part of the figure, geologic maps of Crete, sheets, Kastelli, Platanias and Chania (from west to east direction), left to right respectively.

5. Geological Interest Stops:

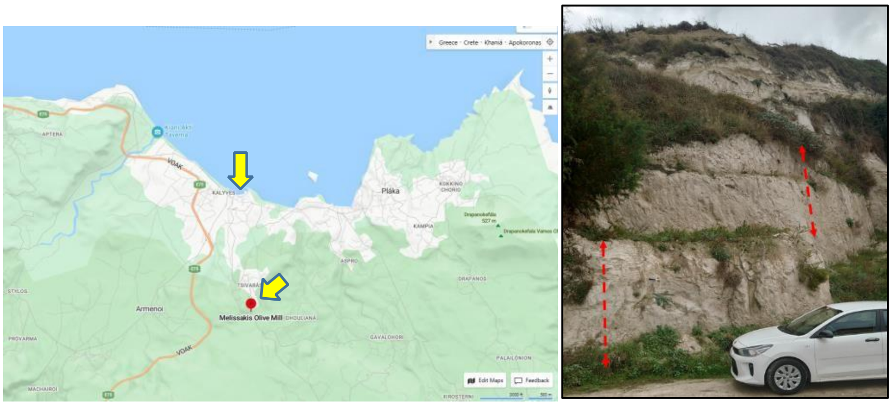
1. Agia Kyriaki-Koumpeli (fluvial/coastal sandstones > Rhodoliths ramp > shallowwater carbonates - R)

<u>Left</u>: *Agia Kyriaki-Koumpeli, a ~2km long outcrop along the Posidonos Street in the background (and focused in the upper inlet). Photo is taken from KoumKapi bay/Chania and looks to the Northeast.* ***<u>Right</u>***: *The well-developed and extended Rhodolithic beds underlying the Akrotiri Fm. Dr.S.Bellas courtesy.*

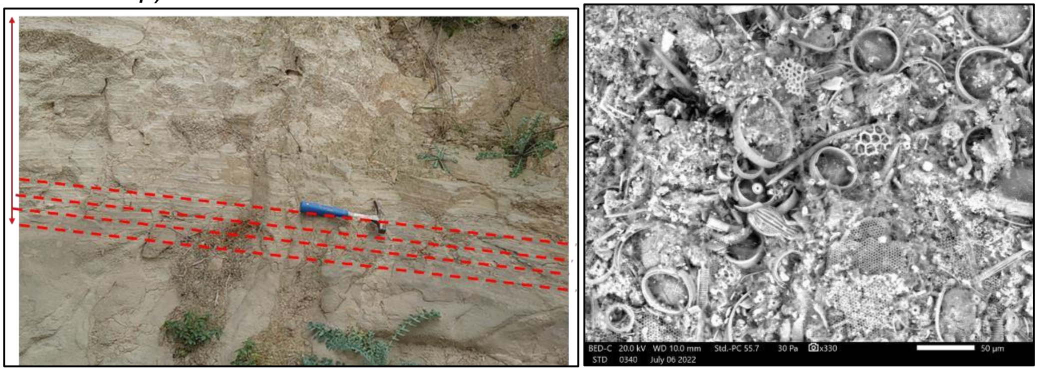


The Agia Kyriaki- 'Koumpeli' outcrop with a length of 1900 m and a thickness of 45 m, can be subdivided into four distinct lithofacies (A to D). From the base to the top, the succession is composed by two sets of sandstones (a yellowish and a reddish one, parts A and B respectively), passing upwards into rhythmical marine, coralline-red-algal carbonate facies (C) that underlie thickly bedded, homogenous, neritic bioclastic limestones (D) that have been assigned to the Akrotiri Formation or Vrysses Group (Freudenthal, 1969; Meulenkamp et al., 1979). Such an extensive occurrence of coralline algae was described for the first time from western Crete by Makridou *et al*. (2022). The prevailing paleo-bio-feature of the abundant coralline algae of the outcrop corresponds to specific palaeo-environmental conditions; the structure and appearance of their development are sequence stratigraphically interpreted to be related as to a Transgressive–Highstand System Track of relative sea-level change (TSTHST). Thus coralline algae are further introduced as a major reef-like contributor (and possibly as a significant reservoir builder, bearing high porosities and permeabilities) predating the Messinian Salinity Crisis and this occurrence highlights a new location in the coralline algae/Rhodoliths palaeo-distribution global and Mediterranean map (Makridou *et al*., 2022).

2. Kalyves-a (diatomites - SR)



Locations of the Diatomite outcrop and the traditional olive mill (yellow arrows) at the road-map (left), and the main stop (Kalyves outcrop) at the right picture (the car for scale, red dashed arrows point to the two terraces making easily the access to the upper part of the outrcrop).



The outcrop documents an Upper Miocene (Tortonian/Messinian) pre-evaporitic age of the deposits within the Apokoronas sedimentary Basin. Kalyves section is well-laterally extended, presents adequate thickness and is subdivided into three subsections (due to dense vegetation and steepness). Its stratigraphic analysis illustrates clear alternations of fine sandlayers, siltstones/mudstones and finely laminated diatomaceous beds (see above photo left and SEM of it at right- with abundant Diatom frustules, Silicoflagellates and sponge spicules) and sandstones (as we move upwards) from bottom to top in Apokoronas basin, while mudstones alternating with sandstones, that prevail by the top dominate in Kalydhonia Basin (co. next stop 5). The diatomitic deposits is believed that were developed during a High-stand sequence stratigraphy Systems Track (HST).

Geochemical analysis by the means of Rock-Eval 6 pyrolysis applied to facilitate the understanding of hydrocarbon potential of these deposits as source rock. Total organic carbon (TOC) values of the samples reach up to 3.3 %. A kerogen type of II-III, leaning towards type III is documented by the analyzed samples of Kalyves section. The potential of Diatomites as source rock for hydrocarbon generation is therefore well documented and this new occurrence supports the extent of Messinian, pre-evaporitic Diatomites in Western Crete and the Mediterranean (co. Telemenis *et al*., 2022; 2023).

3. Kalyves-b (Akrotiri Formation - R, Traditional Oil Mill visit)

This site (compare google map above) presents with a two-fold interest;

- The first one, is geological, and refers to the Akrotiri Formation, marine, shallowwater, well cemented, sandy carbonates that crop out along the road after Tsivaras village exit (about 3 kms south of Kalyves (previous stop Kalyves-a)), to show its expand and to compare it with the previous occurrence at Agia Kyriaki/Chania (it is considered a very good reservoir), while,
- the second one, is a visit to the traditional Olive Mill of Melissakis Family located in Tsivaras village. An authentic experience about everything that has to do with oil harvesting, extracting and processing up to the extra virgin olive oil production. Every step is explained in great detail, including a tasting tour of various oil types.

Homogenous, highly cemented carbonates with abundant Read-Algae (mostly redeposited)

4. Kalydhonia (deep-water silty mudstones > shallowing upward)

The Kalydhonia section is considered as a sub-typus locality for the Deep Water Facies (DWF) (i.e. the "Kissamou Formation"), but the outcrop as a whole represents a shallowing-upwards deposition. Following three subfacies can be distinguished: 1) Thick grey, amorphous, homogenous, slightly sandy mudstones are overlain by slightly laminated marls and claystones of middle/outer shelf to slope or mesopelagic environment (Deep Water Facies, DWF), which consists most of the section's sediments). "*When alternate, the former marls are generally considered to correspond to insolation* *minima, while the later one to insolation maxima*“ (Krijgsman, et al. 1999). Axial Octocoralls (*Keratoisis melittensis*) characterize this sequence. 2) Yellowish marls to marlstones and sandy marls of transitional origin to a rather neritic environment (Transitional Facies, TF) with abundant *Pectenidae* (the "Khairethiana Formation"), and other important fossil elements, including Brachiopods (*Terebratulina* and *Megerlia* area shown in the photo above) and a paleo-bio-horizon of the benthic foraminifer *Heterostegina* sp. firstly reported by Freudenthal (1969). 3) A kind of caprock, consisting of the reefal bioclastic limestones facies (RF) or the upper regressional, littoral facies Type A (Bellas *et al*., 2007) is the top-closure- upper part of the section, with a thickness of about 3.5m. It also includes Brachiopods of the species *Terebratula sinuosa,* a shallow-water level indicator.

5. Falasarna a

Old uplifted strandlines. Situation after Holocene tectonic uplift d/t high magnitude earthquakes.

Time: Ten minutes walking distance from the main street (not asphalt), along a path towards the beach (to the west).

Type of Rock: Platform carbonates / Geotectonic Zone: Gavrovo-Tripolitza

Fossils: *Nummulites* (dominant) /Age: Upper Eocene

Status: As tectonic nappe, part of the Hellenides Thrust and Fold Belt (HFTB), running in a NNW-SSE direction.

In the above photos it is clearly shown the old sea-lines indicating the palaeo-sea-level (yellow doublearrow) changes, a few meters above the current sea-level. A sudden event (earthquake: 365 A.D. > followed by a catastrophic tsunami) exposed the (under the sea) carbonates to the air (episodic uplift).

13.

In front there is plenty of recent unconsolidated beach-dunes and uplifted beach-rocks as well as Aeolian (palaeo-dune) deposits bearing characteristic cross-stratification (photos below) to observe (north of Agia Paraskevi church, co. google map above). Beachrocks diagenesis includes abiotic and/or biotic processes, such as dissolution, precipitation, and recrystallization, which are controlled by various factors such as water-salinity, temperature and ph, abundance in Mg, and possible microbial activity interactions. Cement composition and morphological characteristics mostly control the mechanism of beachrocks formation (Nikolakopoulos *et al*., 2022).

Aeolian paleo-dune deposits of Late Holocene, unconformably cover the Upper Eocene marine, darkgrey, shallow-water carbonates of the Gavrovo-Tripolis zone.

Falasarna b

Exposure of shallow-water carbonates bearing macrofossils rich in benthic foraminifera (mostly frequent to abundant Nummulites)

Time: Five minutes walking distance from the main street (not asphalt), along a path (to the east).

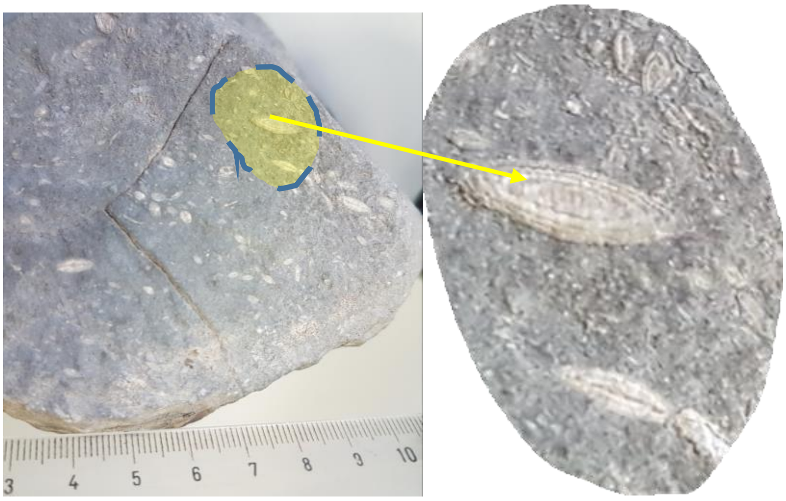
Type of Rock: Platform carbonates, gray in color, highly compacted

Geotectonic Zone: Gavrovo-Tripolitza

Fossils: small to medium-sized *Nummulites*, *Lepidocyclina*, etc) / Age: Upper Eocene

Status: As tectonic nappe, part of the Hellenides Thrust and Fold Belt (HFTB).

14.



Nummulitic limestone bearing various sizes of Nummulites. The right picture is enlargement of the upper right part of the left one (dashed ellipse). For scale the liner in cm.

Petroleum Geology: This type of rock has been considered as a potential reservoir, particularly in western Greece, where the geotectonic zone of Gavrovo-Tripolis crops out extensively along the regions of southern Epirus, Aitoloakarnania and Peloponnesus (HFTB). Then as we move southwards, the belt curves and changes its orientation from NNW-SSE to almost W-E (Crete) and further to SSW-NNE (Rhodes Island in Greece and Tavrides Monuntain range in Turkey). During the Eocene period, Nummulitic carbonate reefs of high porosity and permeability were quite widespread in Europe and the northern part of Africa (Libya, Egypt, etc.). Additionally, this type of carbonates is highly Karstified (Montenegro, Albania, Greece), thus increasing the poro-perm parameters (Hank, 2013). Such hydrocarbon traps may potentially be present at the tectonic contacts between the Ionian zone to the west and Gavrovo zone (Karakitsios, Rigakis, 2007). In the cons is rather the tectonic fragmentation character of the formation, particularly on Crete, which is not the case in the offshore sector to the south of the island, where it seems to dominate over vast areas.

Falasarna c

This stop includes the Ancient Falasarna Harbor city (shaded and depicted by the yellow dashed-line in the upper google-map modified for the needs of the field-trip), that has been uplifted d/t earthquakes.

The Dorian city was founded around the 7th century BC on Cape Koutri of the Gramvousa peninsula (the northwesternmost part of Crete island). Its extend is roughly given within the dashed yellow closed curve.

Note the “Throne of Poseidon” or according to others dedicated to the goddess Astarte (the protector of sailors), a stone King-like-Chair, on the road to the ancient harbor site, about 240 meters before it to the south-southeast (light blue arrow-inlet).

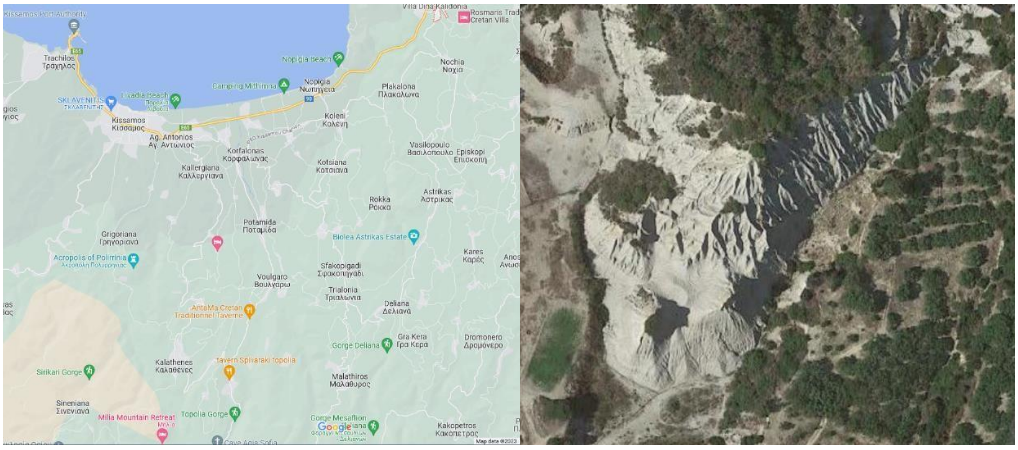
The above figure (left) is a picture of the archaeological reconstruction of the harbor, with the towers at the entrance to control each arrival/departure. To the right the photo shows exactly the same area under currently situation (taken from the south).

The side-walls of the harbor as well as various metal circular objects such as round links of them, provide evidence of an uplift of at least 6-7m over the present sea-level. A cluster of coastal uplifts in the East Mediterranean radiocarbon dated approximately ~1500 BP, as well as historical and archaeological data are evidence for major, although poorly documented seismic destruction on a nearly-Mediterranean scale in 4th-5th c. AD, including the destruction of the Nile Delta in Egypt by a tsunami in AD365 (Stiros, 2010), which closely related to that of Crete. The site has been included in the National Importance database of Cretan geotopes (Fassoulas *et al*. 2007).

Uplifted old strandlines age estimated by Pirazzoli et al. (1982) at ca. 1550 yrs BC (Holocene), while eight distinct episodes of small-scale submergence between 4299 and 1760 BC proved in Falassarna Bay and western Crete by radiometric dating (Thommeret et al., 1980). The latter uplift followed the Pliocene one, which was accompanied by a tilt of NW-Crete to the north (Sakellariou & Tsampouraki-Kraounaki, 2019).

6. Potamidha (Deep water facies DWF, Tortonian / Messinian transition)

16.

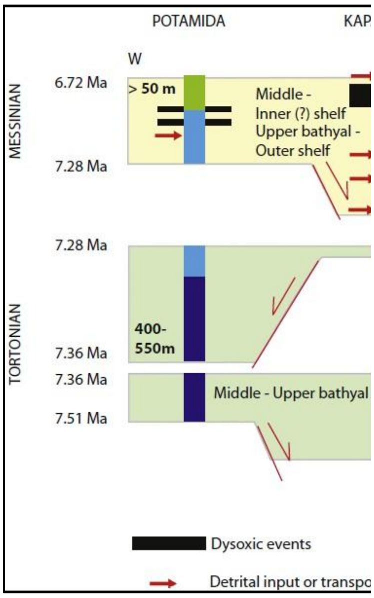


*Google-map of the Potamidha location (**left**) and satellite image of the outcrop (at the **right**).*

This well-studied outcrop is located about 5km to the south-east of Kissamos (Kastelli) town, near the village of Potamidha. In the local language these small hills are called "Komolithi" and the earth-fine-grained-material is still used for the local pottery and ceramic. These 40m in thickness grey, silty- to fine sandy mudstones and siltstones are well layered, sometimes in alternation with laminated layers. They are developed over a large area (more than 500m in length), which was a former depocenter of a Tortonian-Messinian paleobasin within the Neogene sea. Four distinct pyrite layers are easily recognized (as dysoxic events). The marine strata include deep-water fossil macro- and micro-fauna, such as soft-bottom solidary corals (left: *Caryophylla*) and fish-otoliths (*Grenadier* of the family Macruridae) to the right respectively (see photos below from Keupp & Bellas, 2001). Depositional depths ranged between min. 150m between ~7.5 and 7.45 Ma and max. 400-550m between 7.36 and 7.28 Ma (by the Tortonian/Messinian transition ~7,24Ma, Hilgen *et al*., 2000), while upwards they decrease again in the "mid" Messinian to 100-150m (Agiadi *et al*., 2017). This is clearly due to the sea-level drop of the Messinian that was driven by the progressive restriction of the Mediterranean basin towards the MSC. Reconstructed Sea Surface temperatures along the main section, based on stable isotope and biomarker data documented a warm phase to prevail at the late Tortonian (increased salinity), while sea surface temperatures fall in earliest Messinian (indicating a cooling and normal salinity) (Besiou *et al*., 2021).

The site (also called "nunes" landform) has been included in the National Importance database of Cretan geotopes by Fassoulas *et al*. (2007).

17.



Correlation of Potamida (West), Kapariana (central) and Faneromeni (East) Cretan sections development during

a) the Tortonian and

b) the Messinian.

The clear deep water character of Potamida (middle-upper bathyal) in the Tortonian record is again well-documented, following older research and publications (*e.g.* Keupp & Bellas, 2000)

In: Moissette *et al.* (2018)

6. Selected References

Agiadi, K., Antonarakou, A., Kontakiotis, G., Kafousia, N., Moissette, P. Cornée, J.-J., Manoutsoglou E., and Karakitsios, V. (2017). Connectivity controls on the late Miocene eastern Mediterranean fish fauna. *Int. J. Earth Sci.*, 106/3: 1147-1159.

Bellas, S., Frydas D., Keupp H., (2007). Late Miocene calcareous Nannofossil Stratigraphy and bioevents correlation: Kalidonia Case Section, (NW Crete), Greece. *Bull. Geol. Soc. Greece*, 40(1): 1-13.

Besiou, E., Kontakiotis, G., Antonarakou, A., Mulch, A., and Vasiliev, I. (2021). Climate and carbon cycle changes drive the hydrographic configuration of the eastern Mediterranean through the TortonianMessinian Transition, *EGU General Assembly*, online, 19–30 Apr 2021, EGU21-8853.

Fassoulas, C., Paragamian, K., and Iliopoulos, G. (2007). Identification and Assessment of Cretan geotopes. *Bull. Geol. Soc. Greece*, XXXX: 1780-1795.

Freudenthal T. (1969). Stratigraphy of Neogene deposits in the Khania Province, Crete, with Special Reference to Foraminifera of the Family Planorbulinidae and the Genus Heterostegina. *Utrecht Micropaleontol. Bulletins*, 1: 208 p.; Utrecht.

Frydas, D. & Keupp, H. (1996). Biostratigraphical results in Late Neogene deposits of NW Crete, Greece, based on calcareous nannofossils. *Berliner Geowissenschaftliche Abhandlungen* 18: 169–189.

Geological Map of Greece (1:50,000), Sheet "Platanias". *Institute of Geological and Mining Research* (IGME) (1956).

Geological Map of Greece (1:50,000), Sheet "Kastelli". *Institute of Geological and Mining Research* (IGME) (1970).

Geological Map of Greece (1:50,000), Sheet "Chania". *Institute of Geological and Mining Research* (IGME) (1971).

Hank, D. (2013). On the Prospectivity of Greece. IENE, *2nd SE Europe Regional Upstream Workshop* Athens, October 31st - November 1st, 2013.

Hilgen, F. J., Iaccarino, S., Krijgsman, W., Villa, G., Langereis, C. G., and Zachariasse, W. J. (2000). The Global Boundary Stratotype Section and Point (GSSP) of the Messinian Stage (uppermost Miocene). *Episodes*, 23/3: 172-178.

Keupp, H. and Bellas, S.M. in collaboration with D. Frydas & J. Bartholdy (2000): Neogene development of the sedimentary basins of NW Crete island, Chania Prefecture, South Aegean Arc System (Greece).- *Berliner geowissenschaftliche Abhandlungen*, E (34): 3-117; Berlin.

Keupp, H. & Bellas S. (2001). Zur Paläontologie der Jungtertiär-Becken in NW-Kreta (Prov. Chania, Griechenland.- Natur und Mensch (Naturhistorische Gesellschaft Nürnberg e.V.), *Jubiläumsausgabe 200 Jahre N.H.G*.: 109-126; Nürnberg.

Keupp, H., Bellas, S.M., Frydas, D. & Kohring, R. (1994). Aghia Irini, ein Neogenprofil auf der Halbinsel Gramvoússa/NW-Kreta.- *Berliner geowissenschaftliche Abhandlungen*, E (13): 469-481; Berlin.

Kontopoulos, N., Zelilidis, A. & Frydas, D. (1996). Late Neogene sedimentary and tectonostratigraphic evolution of northwestern Crete island, Greece. *Neues Jahrbuch für Geologie und PaläontologieAbhandlungen,* 202: 287–311.

Meulenkamp, J., Dermitzakis, M., Georgiadou-Dikeoulia, E., Jonkers, H., Boger, H., (1979). Field guide to the Neogene of Crete. *Publications of the Department of Geology & Paleontology, A,* 32. N. K. University of Athens, 32 pp.

Makridou, Z., Telemenis, D., Bellas, S. (2022). Late Miocene Coralline Algae/Rhodolith Carbonate Formation record in Chania Region, Western Crete; stratigraphy and paleoenvironment. Conf. Proc.

“Paleontology and Stratigraphy in Greece in the 21st century”, *Bull. Geol. Soc. Greece, Spec. Publ*.

9: 46-47; Department of Geology and Geoenvironment, NKUA.

Moissette, P., Cornee, J.J., Antonarakou, A., Kontakiotis, G., Drinia, H., Koskeridou, E., Tsourou, T., Agiadi, K., Karakitsios, V. (2018). Palaeoenvironmental changes at the Tortonian/Messinian boundary: a deep-sea sedimentary record of the eastern Mediterranean Sea. *Palaeo-3*, 505: 217– 233.

Mouslopoulou, V., Begg, J., Nicol, A., Oncken, O., Prior, C. (2015). Formation of Late Quaternary paleoshorelines in Crete, Eastern Mediterranean. *Earth and Planetary Sci. Letters* 431: 294-307

Nikolakopoulos, K.G.; Koukouvelas, I.K.; Lampropoulou, P. (2022). UAV, GIS, and Petrographic Analysis for Beachrock Mapping and Preliminary Analysis in the Compressional Geotectonic Setting of Epirus,Western Greece. *Minerals* 2022, 12, 392.

Pirazzoli, P., Thommeret, J., Thommeret, Y., Laborel, J., Montaggioni, L. (1982). Crustal block movements from Holocene shorelines: Crete and Antikythira (Greece). *Tectonophysics* 86: 27–43.

Sakellariou, D., Tsampouraki-Kraounaki, K. (2019). Chapter 14: Plio-Quaternary extension and StrikeSlip tectonics in the Aegean. In *Transform Plate Boundaries and Fracture Zones*; Duarte, J.C., Ed.; Elsevier: Amsterdam, The Netherlands; pp. 339–374.

Stiros, S.C. (2010). The 8.5+ magnitude, AD365 earthquake in Crete: Coastal uplift, topography changes, archaeological and historical signature. *Quaternary International*, 216: 54-63.

Telemenis, D., Makridou, Z., Bellas, S. (2022): New evidence of Diatomitic occurrences in western Crete, Greece; A preliminary stratigraphic and geochemical approach and its implications. Conf. Proc.

“Paleontology and Stratigraphy in Greece in the 21st century” Geol. Soc. Greece, Athens, June 3,

2022, *Bull. Geol. Soc. Greece, Spec. Publ*. 9: 81-82; Dept. of Geol. and Geoenvironment, NKUA.

Telemenis, D.; Makri, V.-I.; Manoutsoglou, E.; Bellas, S. (2023). Exploring Neogene Marine Diatomites in Western Crete: A New Source-Rock Candidate with Hydrocarbon Generation Potential? *Eng* 2023, 4: 285–300.

Thommeret, Y., Laborel, J., Mantaggioni, L., & Pirazzoli, P. (1980): Late Holocene shoreline changes and seismotectonic displacements in western Crete (Greece) . *Z. Geomorph. N .F.*, suppl . Bd. 40: 127- 149: Berlin-Stuttgart.

Zachariasse, W.J. & Lourens, L. (2022). About the age and depositional depth of the sediments with reported bipedalfootprints at Trachilos (NW Crete, Greece). *Sci. Reports (Nature)*, 12: 18471.

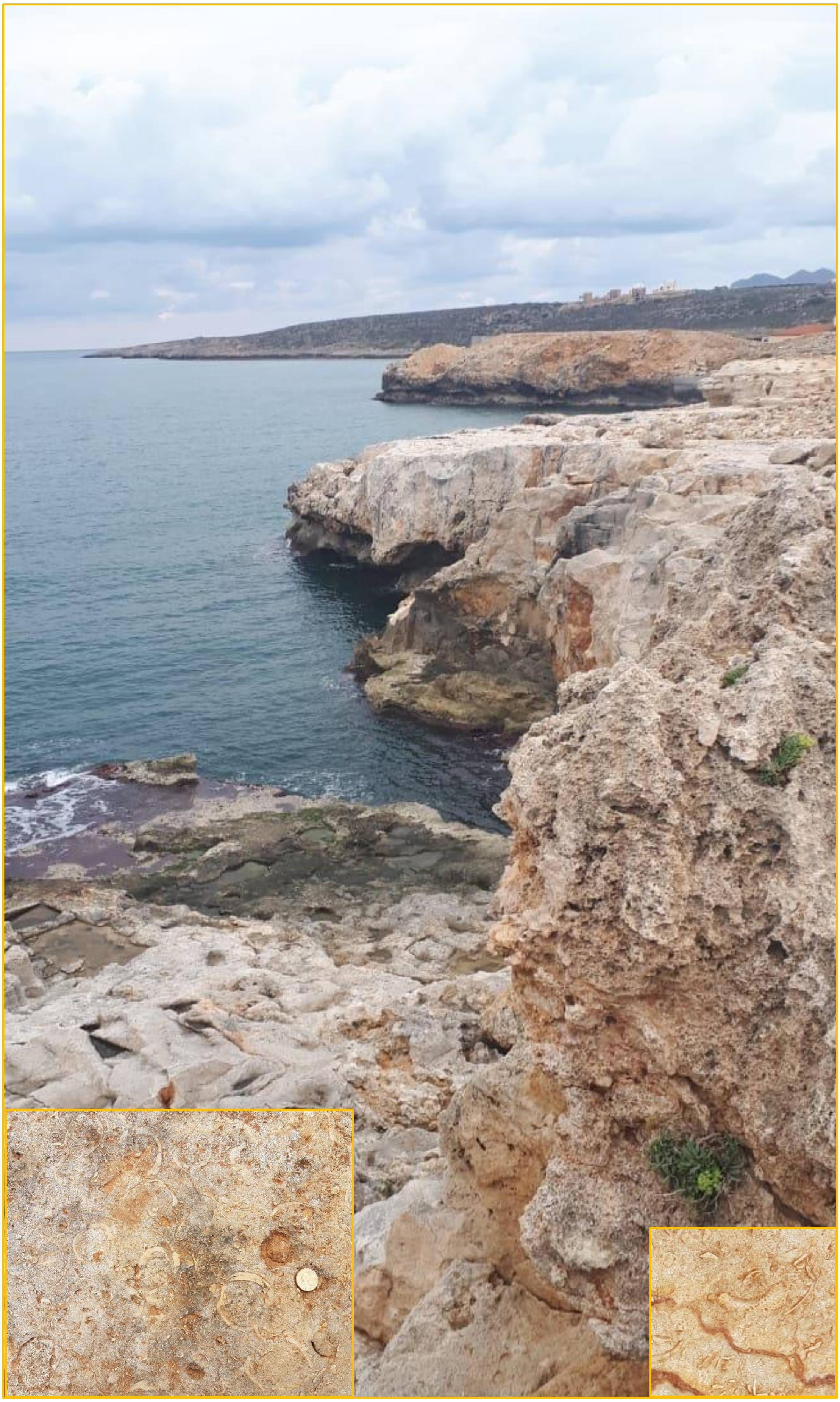
20.

Upper Photo: A well-preserved Coral colony of *Porites*, developing a carbonate-reef build-up. Roka Formation, the basal transgressive sedimentary facies of the Neogene basins of Crete island (LF-A in Keupp & Bellas, 2000). East side of Rodopou Peninsula (R-P in the inlet), Kolymbari-Afrata road, Location Agia Triada (red arrow in the inlet gives the approximate position). Hand-section (blue) of a geological hammer for scale at the left. Photo courtesy: Dr. S. Bellas.

Back-cover photo: Raised upper Miocene marine, shallow-water to littoral, bioclastic, massive to thickbedded, silty-sandy-carbonates of the Akrotiri Formation. Dispersed Lamellibranch shell-fragments (see left inlet from Technical University campus outcrop -1cent coin for scale) and fragmented, redeposited red-algae and Echinoids (see right inlet) are locally included in the fossil content of this formation. “Koubeli” Area, Chania, Crete.

Photos courtesy: Dr. S. Bellas.

21.



3.2 Industrial visit in Dunkerque, France

France venue in January / February 2024

Participants:

IFPEN	POIRIER	Simon
IFPEN	FOURNIER	Frédérique
IFPEN	GARCIA	Bruno
IFPEN	MARAGKOZOGLOU	Elpida
UiS	GHOLAMI	Raoof
UiS	ESCALONA VARELA	Alejandro
UiS	PUNTERVOLD	Tina
IG/FORTH	BELLAS	Spyridon
IG/FORTH	PASADAKIS	Nikolaos
IG/FORTH	GONTIKAKI	EVANGELIA
IG/FORTH	STAMATAKIS	Emmanouil
IG/FORTH	FRAGKOU	Efsevia
IG/FORTH	MAKRI	Vagia Ioanna
IG/FORTH	TELEMENIS	Dimosthenis
IG/FORTH	LAMPROPOULOS	Anastasios

1. **Lab visit**

Date:31/01/2024

Location:IFPEN lab buildings, 1-4 avenue Bois-Préau, 92852 RUEIL-MALMAISON

- Cal X (high throughput experiment bench) by Matthieu Mascle
- Geochemistry and biology by Julia Guélard & Elodie Muller
- Corefloods by Samir Bekri
- Micromodels by Nicolas Pannacci

2. Industrial site : DMX

Date:01/02/2024

Location:Dunkerque, France

7.51: TGV Departure at Gare du Nord

10.04: Arrival at Dunkerque

10.30 – 12.30 : **DMX Visit**

13.00 : Lunch break

15.56 : TGV departure at Dunkerque

18.08 : Arrival at Paris

Operational since April 2023 on ArcelorMittal's Dunkirk site, the industrial pilot for the capture of CO2 present in blast furnace gases has delivered promising results. The objective of this pilot is to validate the DMX™ capture process to enable the decarbonization of a whole range of industrial activities, including steelworks, cement plants, glassware manufacture, refining, chemicals and petrochemicals.

Developed and patented by IFPEN, the DMX™ process, a French technology marketed by Axens, uses an amine demixing solvent to capture CO2 contained in the flue gases produced by heavy industries.

Results obtained since April 2023 are in line with expectations for the technology and confirm, even at this early stage, the efficiency and energy performance of DMX™

technology. A comprehensive series of operational tests has been conducted with the unit operating 24/7. CO_2 capture rates exceed 90%. The pilot unit produces CO_2 with a high level of purity (> 99.5%) while energy consumption remains remarkably low. Moreover, after thousands of operational hours, no solvent degradation has been observed in spite of the high concentrations of contaminants present in the gas treated.

3.3 Geological Field trip guide (Aidipsos)

IFPEN	ADELINET	MATHILDE
IG/FORTH	BELLAS	Spyridon
IG/FORTH	YENTEKAKIS	IOANNIS V.
IG/FORTH	GONTIKAKI	EVANGELIA
IG/FORTH	STAMATAKIS	EMMANOUIL
MINISTRY OF ENERGY AND ENVIRONMENT	TSIFOUTIDIS	GEORGE
HSGME	KANELLOPOULOS	CHRISTOS
IG/FORTH	TRIMI	POLYANTHI
IG/FORTH	FRAGKOU	EFSEVIA
IG/FORTH	SELEKOU	KONSTANTINA
IG/FORTH	LAMPROPOULOS	Anastasios

25.

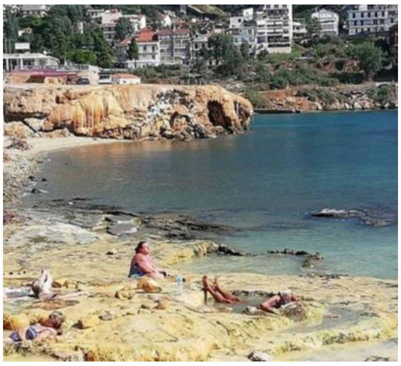
FORTH
INSTITUTE OF GEOENERGY

Universitetet i Stavanger

ifP Energies nouvelles

TWINN2SET

GEOLOGICAL FIELD TRIP GUIDE



<u>Areas of interest</u>: AIDIPSOS (AEDIPSOS) – KAMMENA VOURLA

<u>Aim</u>: Geothermal Energy

Funded by the European Union

Chania, January, 2025

26.

Project Support: TWINN2SET (*Twinning to Sustainable Energy Transition*)

Project Coordinator: Dr. Emmanuel Stamatakis (FORTH / IG)

This project is funded by the European Union under Horizon Europe (GA 101079246)

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INSTITUTE OF GEOENERGY

Compiled by Polyanthi Trimi (MSc), Dr. Spyridon Bellas

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Photo cover of first page: View of famous for its thermal springs Aidipsos, northwestern Euboea Island, Greece. Photo Sources:

Left: https://www.diavlosnews.gr/diavlos2/index.php/politismos/istorika-xnaria-tis-evvoias/80-i-aidipsos-kai-oi-thermes-piges-tis-video

Right: “Loutra at Aidipsos”, Carte Postal, in https://www.visitedipsos.gr/history.php

27.

Contents

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1.

1 STUDY AREA

The actual areas of geothermal interest that are going to be considered in the present geological field-trip guide are mainly located in Euboea and its opposite continental Greece area of Spercheios. Euboea Island belongs to the Greek regional units (one of them is Chania/Crete that you are most familiar with) and consists of eight (8) municipalities, including another island as well, namely the Skyros at the east.

Aidipsos (or Edipsos) is located at the northern west end of Euboea island. It is a renowned seaside large village which developed due to the presence of natural thermal springs and the large volume of tourists that annually attracts.

While Aidipsos is the most prominent geothermal site in northern Euboea, other noteworthy sites exist as well, such as the geothermal field of **Gialtra** and **Ilia** hot spring (6km from Aidipsos approximately). Further, the volcanic center of **Lichades** is located ca. 20km away from Aidipsos at the end of Lichades peninsula (see below figure 1).

On the opposite side of the Euboean Gulf (to the west), notable hot springs can be found in the **Kammena Vourla** wider region and the Spercheios River basin (Figure 1).

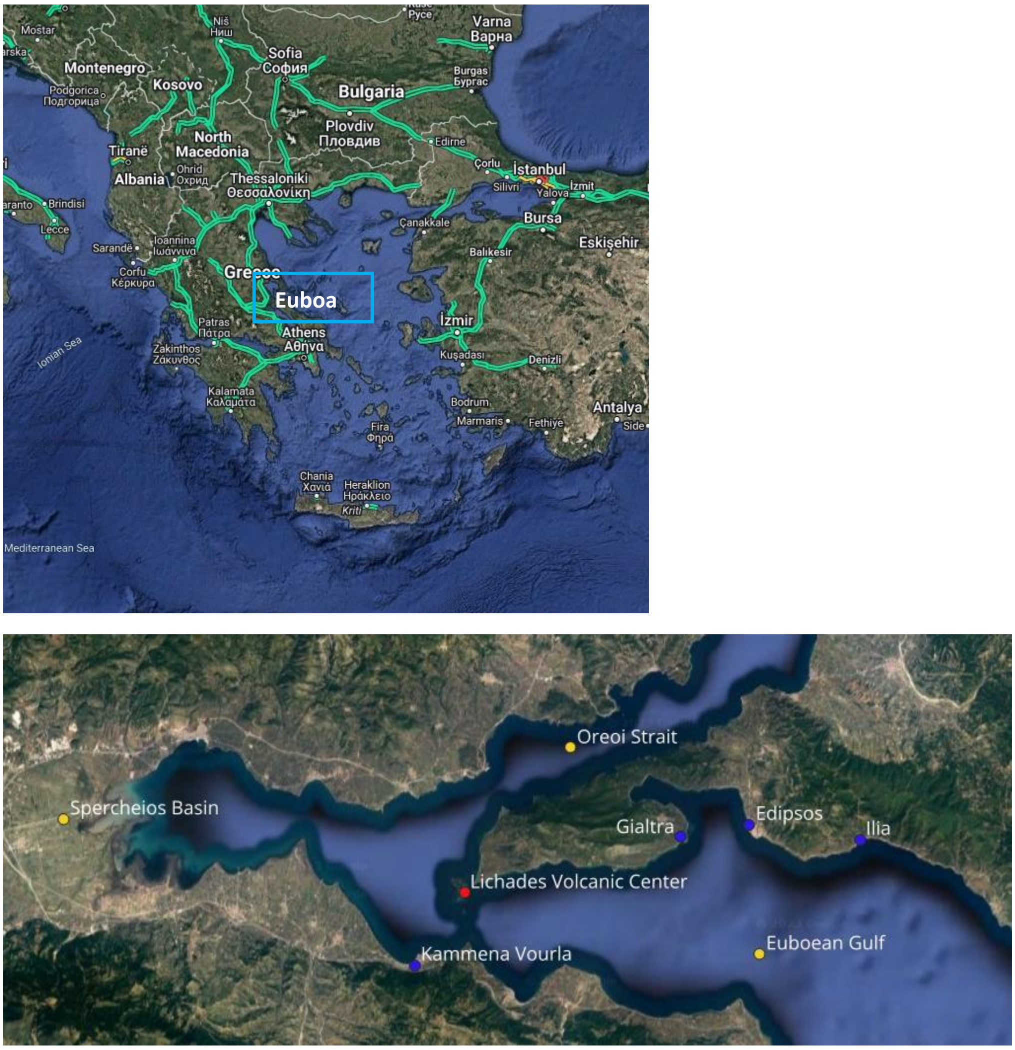


Figure 1: General map of Greece (upper figure), focused in the area of interest (source: google maps)

Aidipsos-Kammena Vourla Geothermal Springs- History in short

1.1 Aidipsos

It has been long well-known for its beneficial underground hot-water resources, therefore it was/is (still) called “Loutropolis” in Greek meaning the City of Loutro, or the bathing city. The natural thermal springs of Aidipsos were known for their healthy, “healing” properties since antiquity as noted by Aristotle, Strabo, and other classical scholars. Aidipsos even participated in the Trojan War alongside Istiaia (or Histiaia), as it is mentioned by Homer (in “Iliad”).

The town with the unique thermal “healing” springs was first mentioned as:

- the "Ellopia" of the Ionians in Herodotus' "*Histories*" (484-425 BCE),

but later on, the Aidipsos was also mentioned by other various important historians-philosophers-geographers, like:

- Aristotle in "*Meteorologika*" (384–322 BCE)
- Pliny in "*Natural History*,"
- Strabo in "*Geography*" (63 BCE–24 CE)
- Plutarch in “Syllas’ Life” gives a detailed reference to the “*Aidipsos of Euboea*" (50-125 CE),
- While it was also known from the folk tradition of Lipsi, and
- from the work of Lypso (Lipsos was called the Aidipsos in the past, Ληψός ή Λειψός in Greek), of the Greek theater writer Alexandros Moraitidis,

These are all long historical references to the same town, the “Spa City” of Aidipsos. It remains unknown when and by whom it was built, however, it is certain that the water with the healing properties was known for sure before the 4th century BC, as according to Strabo's descriptions, it was named "*Therma Heracleus*" from the mythic hero (semi-God) of the ancient Greeks named Heracles. The unique healing properties of the waters became a source of inspiration for mythology. An ancient Greek myth says that the Goddess Athena asked her brother Hephaestus (God of Fire) to create the baths of Aidipsos, so that her beloved hero Heracles could rest there after each of his labors. Hephaestus struck the earth with his hammer, causing the thermal springs to gush forth. The myth also said that the Goddess Hera (wife of Zeuss) advised Deucalion and Pyrrha to bathe in the warm spring waters in order to have many healthy children. Shortly thereafter, they gave birth to Hellen(-ique), the ancestor of the Greek tribes (Hellenas, Hellas= Greece).

In particular, the Greek philosopher Aristoteles mentioned above, had caught the Geo-concept of the geothermal springs as in his work called ‘Meteorologika’ mentions that the sea forms underground rivers which in turn create thermal springs. An interpretation that is not so far away of its present geological synthesis, even after 2.500 years ago!

During the Roman period (100b.c. to 100a.c.) the roman general Syllas constructed the first thermal baths in the area of interest (see left picture below, fig. 2), and subsequently Aidipsos gained reputation across the known world. Nowadays, Aidipsos still attracts many tourists that visit the area for its thermal natural springs.

3.

Figure 2. Aidipsos. Left: 1896-1910- Syllas' Thermal Springs Hotel ("Αι θέρμαι του Σύλλα" in Greek) in the famous Loutra Beach of Aidipsos, Right: 1920- Kastallia Hotel, built as a (Public) Center for War Disabled Rehabilitation Treatment. source:

http://dimbarsak.blogspot.com/2011/07/blog-post_23.html

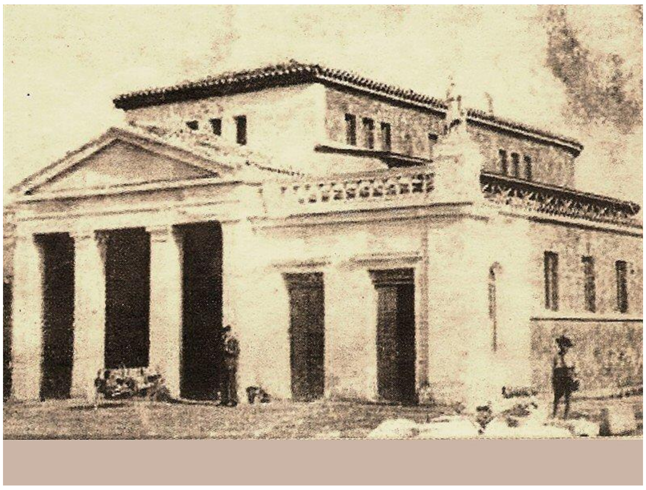


Figure 2a. Aidipsos, 1910- Building so-called "Hydrotherapy establishment"or the Municipal Hydrotherapy Center, source: http://dimbarsak.blogspot.com/2011/07/blog-post_23.html

Near the Syllas' Hotel, there is a cave with thermal spring water, that is known as the "Syllas' Cave" or "Syllas' Loutra". Below a text referring to this spring by the Greek writer Alexandros Moraitis (1851-1929):

> *"Μέχρι σήμερον δε, σώζεται ακόμη αρχαίον θολωτόν οικοδόμημα, περί τον ναΐσκον των Αγίων Αναργύρων, λουτρά του Σύλλα καλούμενον, εν οίκημα αντρώδες, αποστρακωμένον διά των*
>
> *απολιθώσεων των άνωθεν καταρρεόντων μεταλλικών υδάτων, και ημίχωστον πλέον μέχρι των λιθίνων του τόξων..."*
>
> *>> Translation…*

4.

“Until today, an ancient domed building is still preserved, near the small church of the Holy

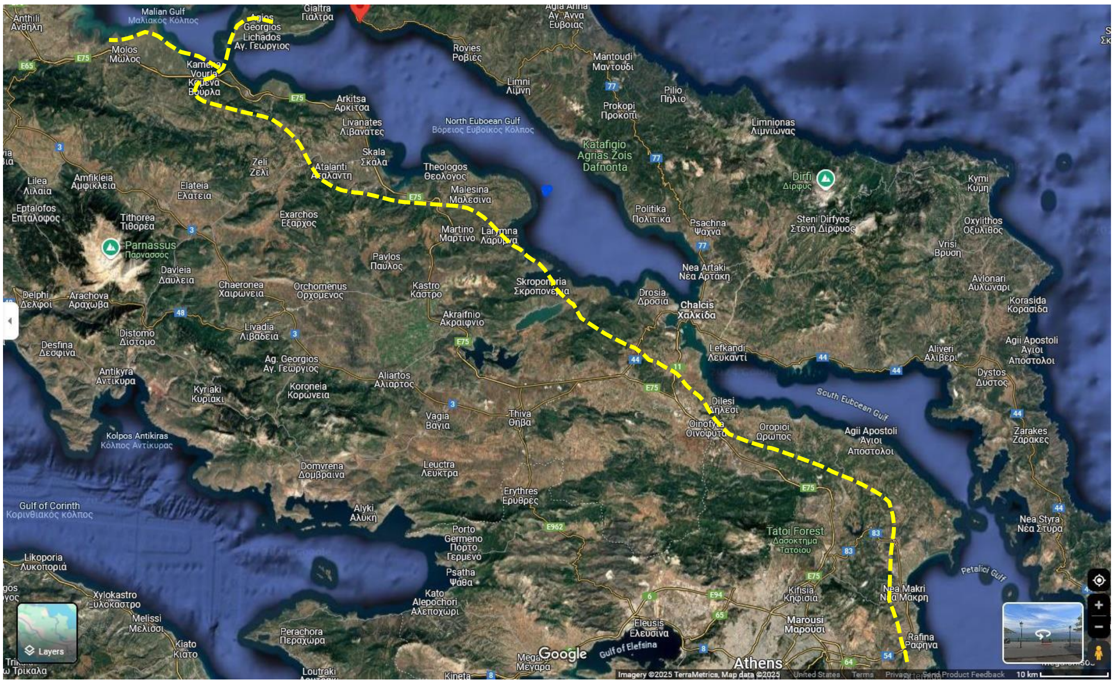
Unmercenaries, known as the Baths of Sylla, in a vaulted structure, calcified by the petrifications (fossilization) of the downward-flowing mineral waters, and partly still intact up to the stone arches...”

After World War II, Aidipsos regained its reputation as a premier destination. Among others, businessmen, politicians, and celebrities including Aristotle Onassis, Winston Churchill, Omar Sarif, Maria Callas and others visited the famous thermal baths. Even today, Aidipsos continues to attract tourists who come to experience its legendary thermal springs (Eviaportal, 2013).

1.2 Kammena Vourla

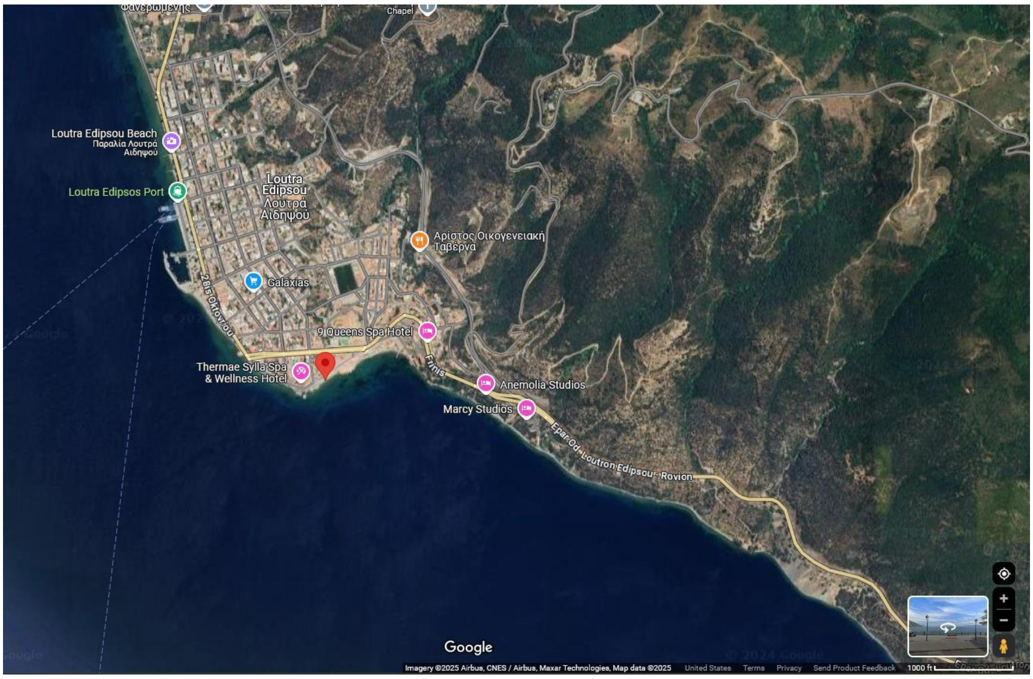
These hot springs began gaining recognition in 1926 when Michalis Pertesis discovered their high radon concentrations. The area reached the height of its prominence between the 1960s and 1980s, drawing local and international visitors attention, including notable political figures who came to use its therapeutic waters. However, the area has since experienced significant decline and abandonment.

Figure 3. Aidipsos-Kammena Vourla Geothermal Springs – The route details



6.

Below: Syllas' baths (in red). Dashed lines indicate the ferry boat routes from Aidipsos (Euboa) to Arkitsa port (continental Greece). *Site Coordinates*: 38°51'10.2"N 23°02'50.5"E, 38.852843, 23.047358

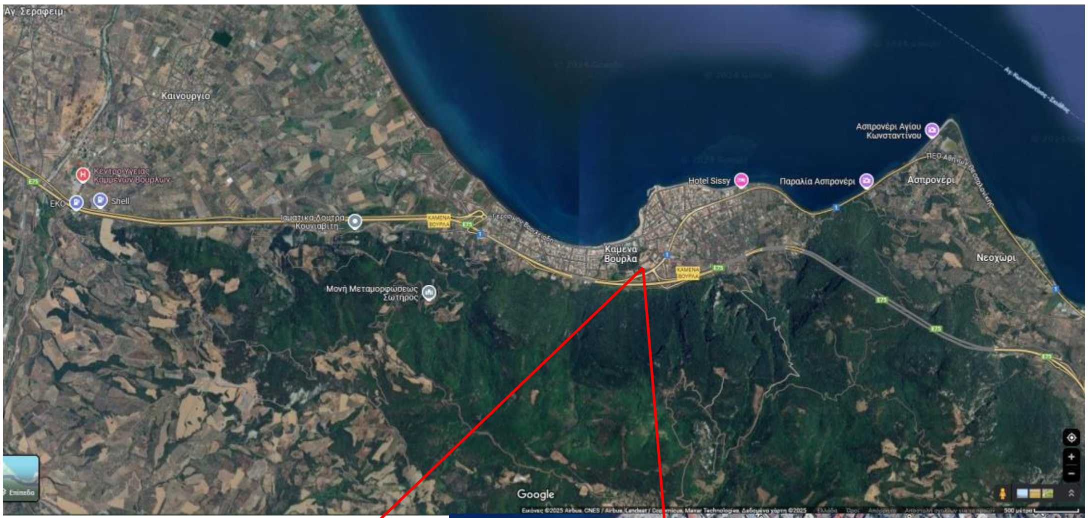


Below: Syllas' cave. *Site Coordinates*: 38°51'17.4"N 23°02'49.0"E, 38.854832, 23.046940

7.

Below: Syllas' Cave. Nearby hot springs provided temperatures up to 78° C!. *Site Coordinates*: 38°51'10.2"N 23°02'50.5"E

Below: Kammena Vourla thermal baths (central-eastern continental Greece, opposite to –at the west of- Euboa / Aidipsos hot springs). Yellow curve shows the National Road E75 (Athens to Thessaloniki)



Above: Hydrotherapy center "Hippocrates". *Site Coordinates*: 38.77521835082348, 22.7843638833704

2 GEOLOGY OF THE WIDER AREA

In geological terms, Greece is divided into two main sectors; an external and an internal one (geographically representing the western and eastern part of the country), based on the presence of non-metamorphic and metamorphic rocks respectively (figure 4: red dashed line). Euboea is located on the transition zone. The geological framework of northern Euboea is defined by the Pelagonic and Sub- Pelagonic geotectonic zones, each featuring distinct lithological and structural characteristics.

Pelagonic zone is discretized in the Pelagonic zone (Figure 4: Pl- *in brown*) constituted by metamorphic rocks and the Sub-Pelagonic (Figure 4: S_p- *in light green*) zone of non-metamorphic rocks. The latter acts as a transition zone between Pelagonic (Pl) and Parnassos (P_k) zone. Both start at the northern Greece with NNW-SSE direction. At the Lichades peninsula, the transition between these zones becomes apparent.

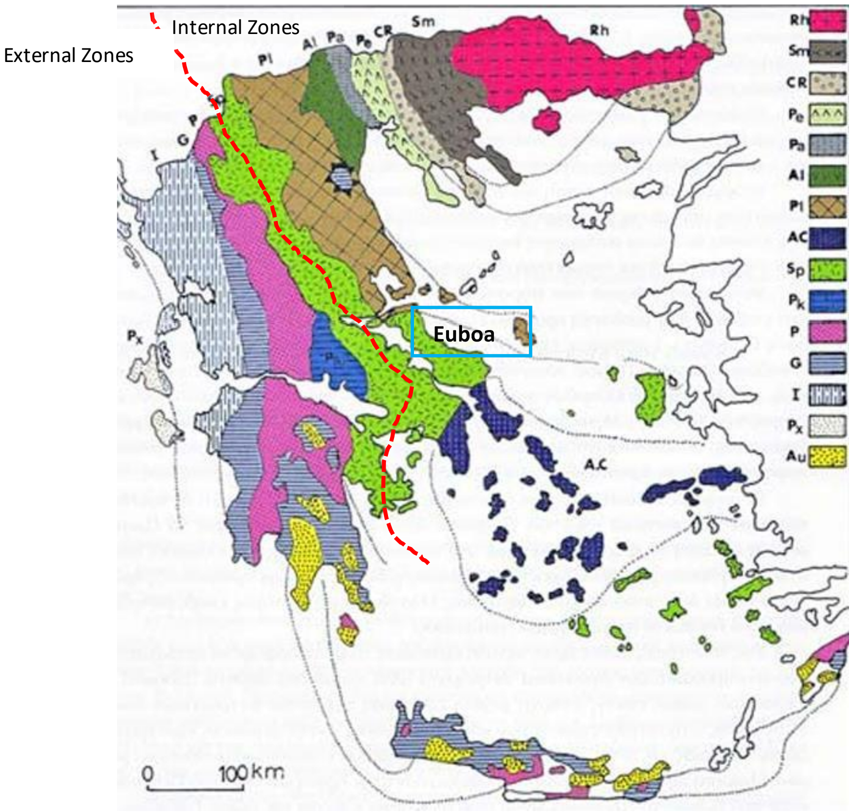


Figure 4: Geotectonic map of Greece (Mountrakis, 1985), slightly modified

Aidipsos and Ilia area geologically belong to the Pelagonic zone (i.e. metamorphic sector) while Gialtra and Kammena Vourla areas belong to the Sub-Pelagonic zone.

Briefly the Pelagonic zone (from older to younger stratigraphy) consists of the following group of rocks/formations:

1. Crystalline basement (gneisses and gneiss-schists)
2. Permian-Low Triassic metamorphic clastic formations
   Epizonally metamorphic rocks consisting of arkoses, sericitic and calcareous schists, schistose sandstones, and phyllites with intercalations of tuffaceous

rocks and greenstones. Locally, there occur intercalations of crystalline limestones.

3. Clastic, volcanic and limestone formations of a Lower-Middle Triassic age
    - Epizonally metamorphic mafic igneous rocks, created by submarine eruptions of diabase and basalt. At places are interspersed with schists and phyllites. Within the formation, there are intercalations of crystalline limestones
    - Crystalline limestones and dolomites.
    - Clastic rocks, slightly metamorphosed, consisting mainly of arkoses.
4. Non metamorphic carbonate formations of the Middle-Late Triassic – Early Jurassic (mainly limestones and dolomites)

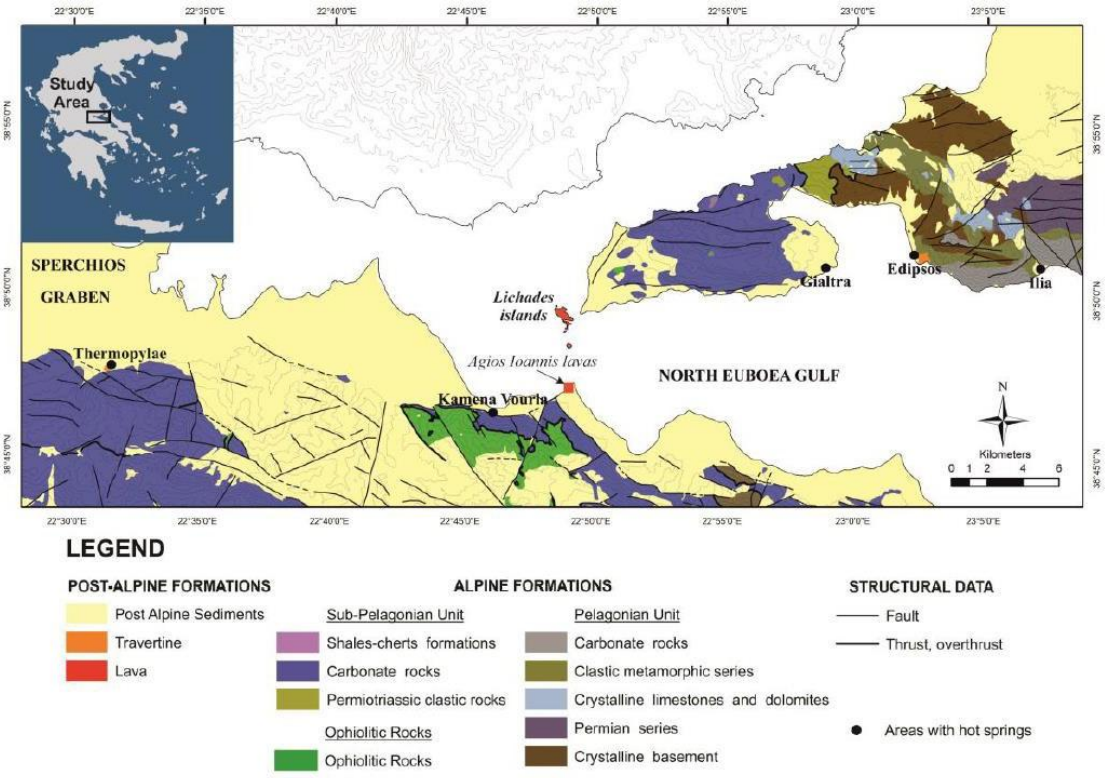


Figure 5: Geological map of the greater area, including part of central continental Greece with Kammena Vourla location (Kanellopoulos et al., 2019)

The Sub-Pelagonian zone (from older to younger stratigraphy) consists of the following group of rocks/formations:

1. Clastic series of Permian- Triassic age
   Including graywackes, shales, quartzites and conglomerates. Locally, limestones, keratophyre tuffs and ophiolites are found.
2. Carbonate rocks (dolomites and limestones) of Triassic-Jurassic age
3. Shales-Chert formations of upper Triassic-Jurassic age
   Consisting of alterations of calcareous schists, cherts and marly limestones. Within those formations volcanic rocks are to be found such as various ophiolitic members, tuffs and serpentines.

Additionally, ophiolites of Cretaceous age are predominantly found within the Sub-Pelagonic Zone, with significant development in the mountainous regions south of Kammena Vourla.
Later Paleogene and Neogene sediments have been deposited. Additionally, talus cones, scree and weathering material of surrounding rocks, alluvial deposits and travertine occur as well.

Volcanic activity from the Plio-Pleistocene is evidenced by andesites on the Lichades islands (for location see fig. 5) and at Asproneri (approximately 2km eastern of Kammena Vourla), dating to approximately 0.5 Ma and 1.7 Ma, respectively (Fytikas et al., 1976; Bellon et al., 1979).

2.1 Aidipsos – Ilia

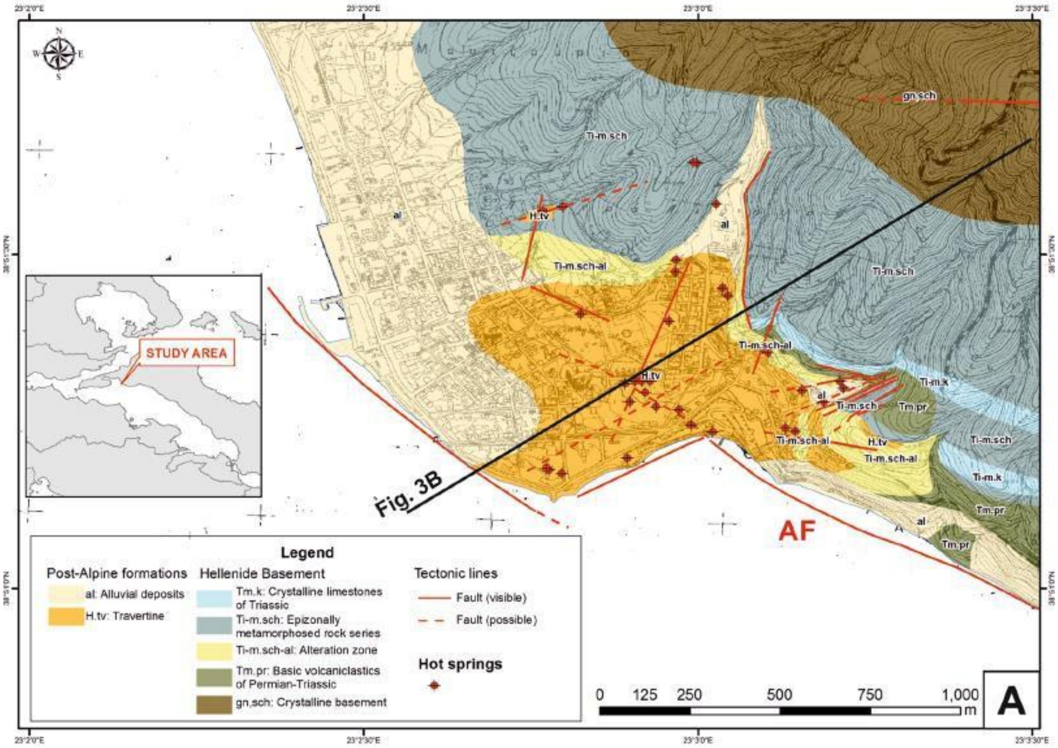


Figure 6: Geological map of the area of interest in Aidipsos, Euboa island (Kanellopoulos et al.,2020)

Aidipsos and Ilia areas share the same stratigraphic column consisting of the following rocks (Katsikatos et al., 1984):

1. Epizonally metamorphic mafic igneous rocks, created by submarine eruptions of diabase and basalt. Locally layers of schists and phyllites are intercalated. Further intercalations within the formation, include crystalline limestones.
2. Epizonally metamorphic rocks consisting of arkoses, sericitic and calcareous schists, schistose sandstones, and phyllites with intercalations of tuffaceous rocks and greenstones. Again, at places, intercalations of crystalline limestones are found.
3. Crystalline basement

On top of these formations various sediment types have been deposited. More specifically, in Aidipsos hot springs area a massive layer of travertine has been developed covering an area of ca. 0.5km^2 and be up to 20m in thickness, while moving away from springs and in the western part of Aidipsos, alluvial deposits prevail.

In Ilia area Pleistocene talus cones and scree including large limestone and dolomite blocks are found as well as unconsolidated Holocene talus cones, scree and weathering products from nearby rock exposures.

2.2 Gialtra

At the greater area of Gialtra dolomites and limestones of middle Triassic to Jurassic age are exposed. Neogene sediments mainly of Pliocene age such as marls, clays, gravels, sandstones, conglomerates and marly limestones overlay the Mesozoic basement.

2.3 Kammena Vourla

In Kammena Vourla area on top of the Sub-Pelagonic zone sequences, Neogene sediments such as marls, clays, gravels sandstones and conglomerates have been unconformably deposited. On top of them alluvial deposits including clays, unconsolidated conglomerates, gravels and sands exist.

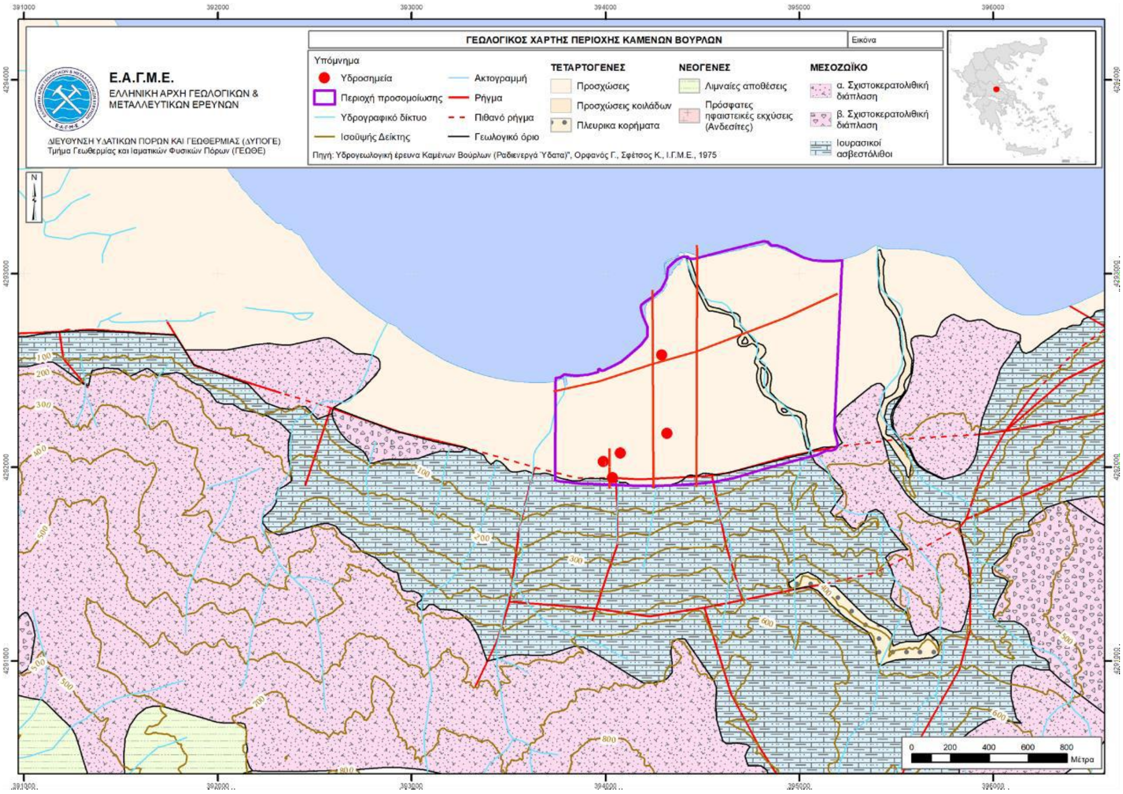


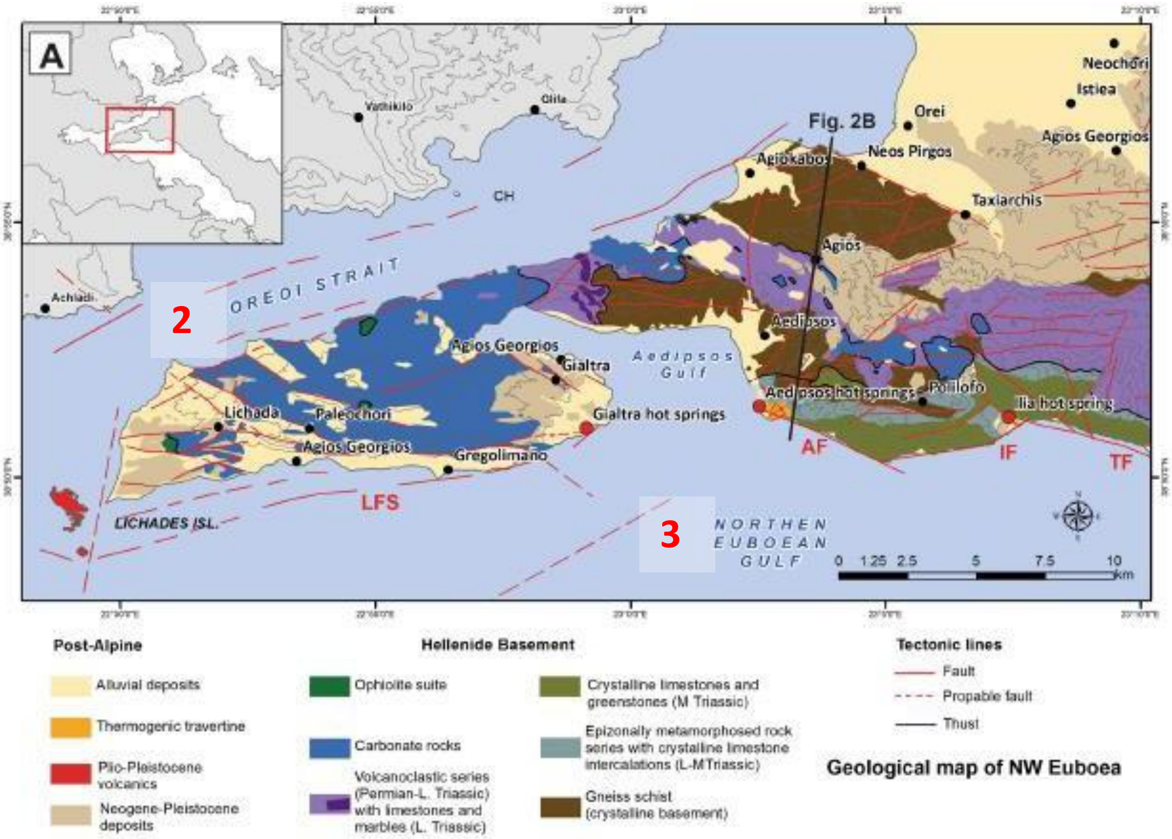
Figure7: Geological map of Kammena Vourla area hatched green= Jurassic Limestones , doted yellow=talus cones, pink(dots or triangles)=Shales-Cherts formations(fine or coarse material), hatched yellow=lacustrine deposits, yellow=alluvia deposits, red lines=faults, red dots=production wells (Vougioukalakis et al., 2023)

3 TECTONIC REGIME

The broader northern Euboea region exhibits significant brittle and shear deformation, with numerous faults shaping its morphology (Figure). Morphologically the greater area is characterized by the Northen Euboean gulf which is a part of 3 different graben system and the tectonic horst of Northen Euboea. This three-graben system includes:

1. **Spercheios graben:** Dominated by E–W to ESE–WNW normal faults.
2. **Oreoi strait (graben):** Characterized by NE–SW striking marginal faults.
3. **Northern Euboean gulf:** Bordered by SE–NW to E–W normal faults.

Number 1 is not shown in the below figure 8, because it is located further east (related to the Kammena Vourla area). Numbers 2 and 3 are clearly shown. As it has been suggested the westward propagation of the Anatolian fault (the well-known North Anatolian Fault system, NAF: one of the largest in length, continental, active strike-slip faults) has likely influenced this tectonic framework, with the Oreoi Strait aligning closely with its westwards projection (Caroir et al., 2024; Shaw and Jackson, 2010).



The Euboean gulf is further subdivided into 3 different sedimentary basins (Figure): western, central and southeastern as Sakellariou et al. (2007) have shown.

- **Western basin:** Dominated by the E-W projections of Spercheios basin faults and the NW-SE Arkitsa-Kammena Vourla fault zone.

- **Central basin:** Controlled by the Aidipsos-Kandili fault zone. The Euboean Gulf reaches its maximum depth of approximately -450 m below mean sea level (msl), which is associated with E-W and NW-SE trending fault systems. The Aidipsos area is situated at the margins of the western and central basin, with the deepest part of the gulf located directly offshore the town.
- **Southeastern basin**: Dominated by the Aidipsos-Kandili fault zone while the parallel zone of Melouna subdivides this basin into two different parts.

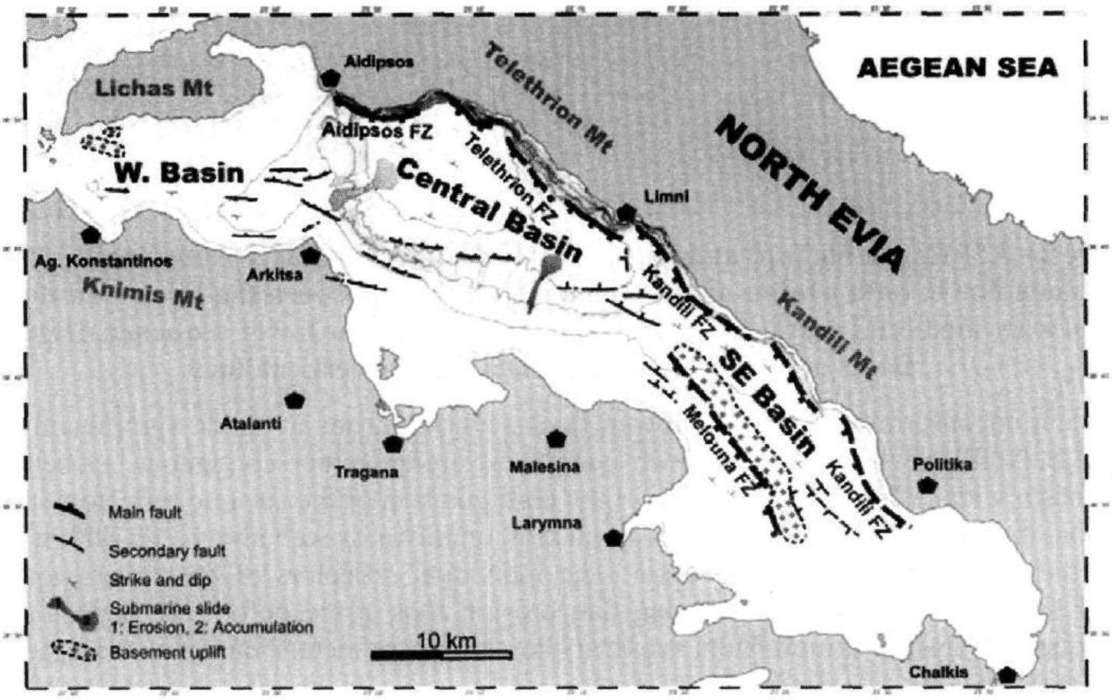


Figure 9: The 3 basins of north Euboean gulf (Sakellariou et al.,2007)

Finally, in the Euboean gulf we can find the volcanic cones at Monolia island and Asproneri (Figure). Karastathis et al. (2010; 2011) using microseismic and aeromagnetic data concluded that a possible magmatic chamber is situated at depths of ca. 8-12km below the Lichades (Quaternary volcanoes) and Asproneri areas.

These observations align well with earlier microseismic studies. Makris et al. (2001) determined that the depth of the Mohorovičić discontinuity beneath the North Euboean Gulf is approximately 19–20 km, whereas along the Oreoi Strait, it extends to about 30 km.

The extensional tectonic regime and the thinner crust in the North Euboean Gulf region can explain the significant geothermal activity observed in the broader area.

3.1 Aidipsos

At the closer area of Aidipsos normal faults of NNW-SSE to NW-SE, NNE-SSW to NE-SW and ENE-WSW to E-W directions are found. These 3 fault system intersects in Aidipsos hot spring area.

It is worth noting that following the earthquake of 426 BC, both Thucydides (in “History of the Peloponnesian War”) and Strabo (in “Geography”) recorded that the hot springs of Aidipsos dried up for 3 days, while parts of the nearby volcanic islands submerged. Afterwards, new springs emerged, albeit in locations different from the original ones. On top of that, in 1894 when Atalanti earthquake happened new springs appeared in Aidipsos area (Margomenou, Leonidopoulou, 1976).

3.2 Ilia

In the closest Ilia area, the NW-SE Telethrion fault and the E-W Ilia fault are crossing exactly in front of Ilia spring area.

3.3 Gialtra

In this area seems the E-W Lichades fault passes by the Gialtra hot springs while NE-SW faults could facilitate the fluid circulation as higher temperatures are found to follow a NE-SW direction.

3.4 Kammena Vourla

Two normal fault systems with E-W and ESE-WNW directions are found. These are the faults that created the Spercheios and Kallidromo basin as well as the tectonic horst of Knimis mountain during Miocene-Pliocene. The main fault zone is the E-W located at base of mountain Knimis and has created displacement of more than 1000m. Moreover, faults of NNW-SSE and NNE-SSW directions exist. (Papanikolaou, 1972)

4 THERMAL SPRINGS AND WELL LOCATIONS

It has been suggested that most thermal springs of Greece (Figure 10) are mainly located in areas with greater heat flow which originated a) from (subsurface) intense volcanic activity that took place in recent geological times, or b) are connected to deep tectonic structures –fault system- (such as the Spercheios depression). Low crustal thickness contributed as well to the area’s thermal springs manifestation.

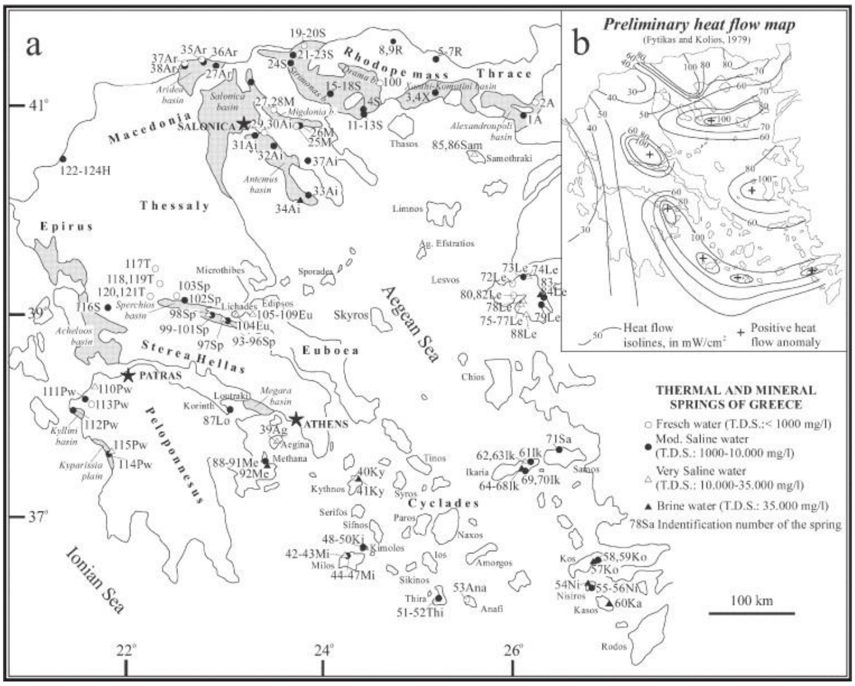


Figure 10: Main thermal waters of Greece (a: Labrakis & Kallergis, 2005) and the heat flow map (b: inlet) of Fytikas & Kolios (1979).

In northern Euboea the main geothermal reservoir hasn’t been discovered yet. This reservoir feeds through faults and fractures other shallower aquifers with geothermal fluids. Various exploration programs took place in Aidipsos, Gialta and Kammena Vourla detecting only the shallower aquifers accommodating the geothermal fluid.

4.1 Aidipsos

In Aidipsos area 17 thermal springs and 6 shallow production wells (maximum depth 40m) are located inside the limits of the village. As it can be seen from Figure most of the thermal springs emerge at the base of the mountain with significant discharging rates while many offshore hot springs exist. In Aidipsos area temperatures vary from 37°C to almost 83°C.

From the exploration project carried out by Chatzis et al. (2008), it can be assumed that the geothermal fluid is likely stored in a relatively shallow leaky carbonate rock aquifer, approximately 340 meters deep. Overlying schists serve as a caprock, confining the fluid. Although these schists are fractured and as a result fluid ascends to surface, creating the geothermal springs.

As it is depicted in Figure 11 thermal anomaly aligns with NE-SW faults implying that the main fluid circulation happens in this fractured zone. Moreover, the maximum temperature occurs at the intersection of all the 3 fault directions.

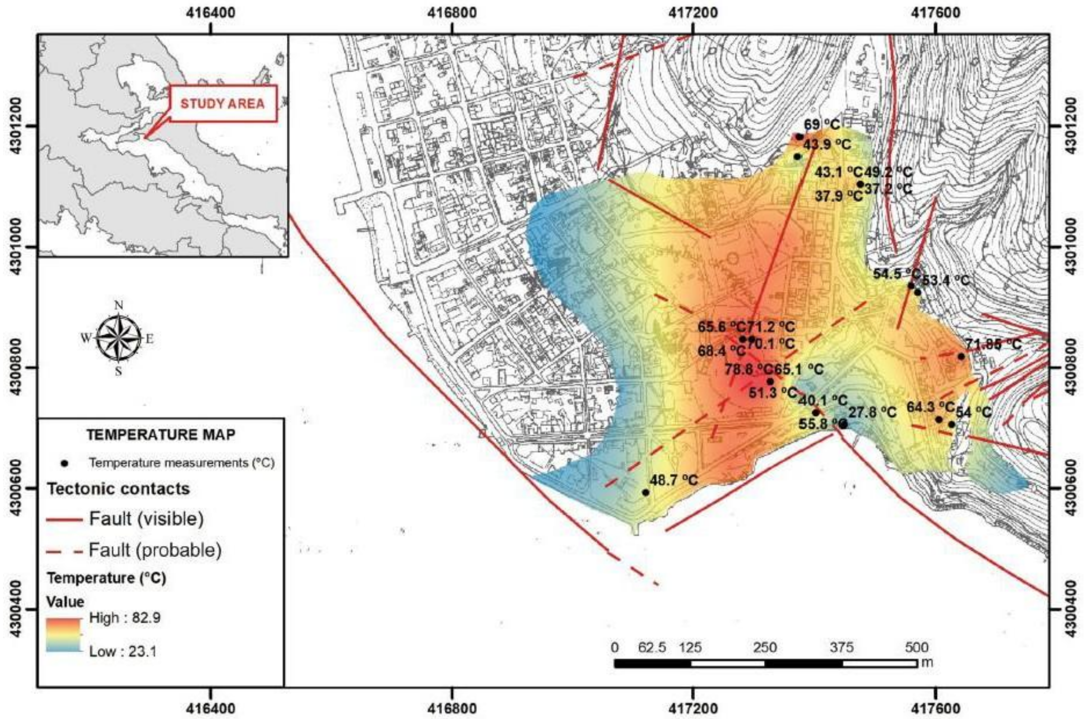


Figure 11: Temperature map of Aidipsos area (Kanellopoulos et al.,2020)

4.2 Ilia

In Ilia area only one hot spring and an artesian well exists. The fluid temperature is 64°C (Vakalopoulos et al., 2016). Ilia spring along with Aidipsos springs present the higher temperatures in the area. In Ilia geothermal fluid circulates similarly to Aidipsos.

4.3 Gialtra

In Gialtra area 3 exploration, 1 production wells and 2 hot springs exist. Temperatures range from 25 to 44°C with the springs presenting the highest temperatures. Springs are located nearby the coast across Aidipsos area, except this spring no artesian wells exist.

Based on the exploration project conducted by Chatzis et al. (2008), it can be inferred that the geothermal fluid is stored within carbonates and conglomerates. These formations form an inclined aquifer with a thickness of 30 to 50 meters, beginning at a depth of 90 to 120 meters and extending to 200 to 250 meters. They also created a temperature distribution for Gialtra area at the depth of 250m (Figure 12).

17.

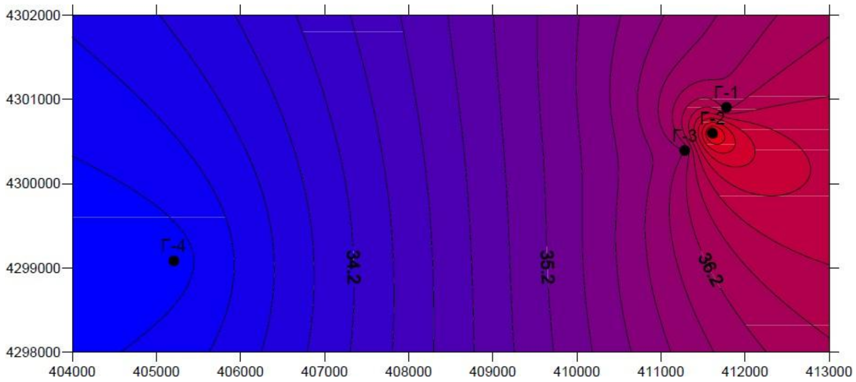


Figure 12: Temperature distribution at 250m depth (Chatzis et al.,2008)

4.4 Kammena Vourla

In Kammena Vourla area, a total of 23 exploration, 3 production wells and 3 hot springs are reported. Measured temperatures at the maximum depth of the wells found to range between 31^{O}C and 48^{O}C.

The geothermal fluid in Kammena Vourla is stored in a shallow unconfined reservoir deepening towards the sea (Orfanos et al., 1975). This reservoir is mainly constituted by Neogene sediments while the E-W fault that prevails, feeds it with enormous amounts of geothermal fluid. The highest temperatures are found near the base of the mountain Knimis following the E-W axis of the fault.

Vougioukalakis et al. (2023) developed a refined reservoir model of the unconfined aquifer and validated it by performing a history match against observed hydraulic head and temperature data. The model's initial temperature distribution at a depth of 20 meters is given in Figure 13. As in Aidipsos case, also here most of the wells were artesian. Unfortunately, almost all wells have been destroyed.

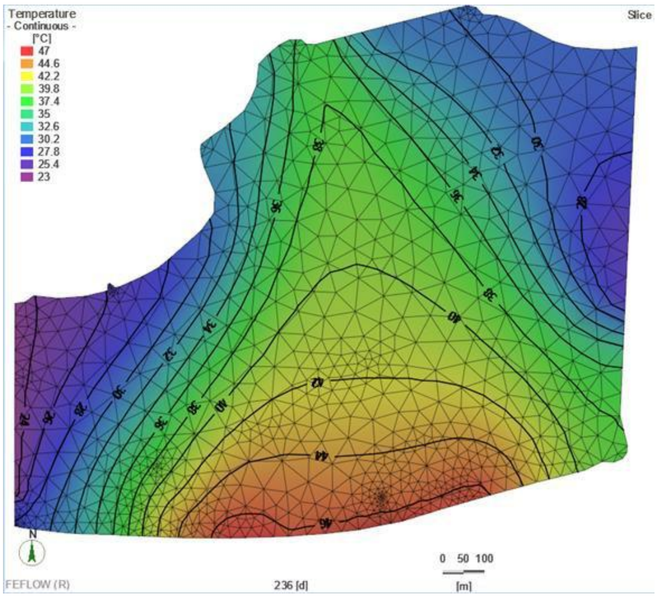
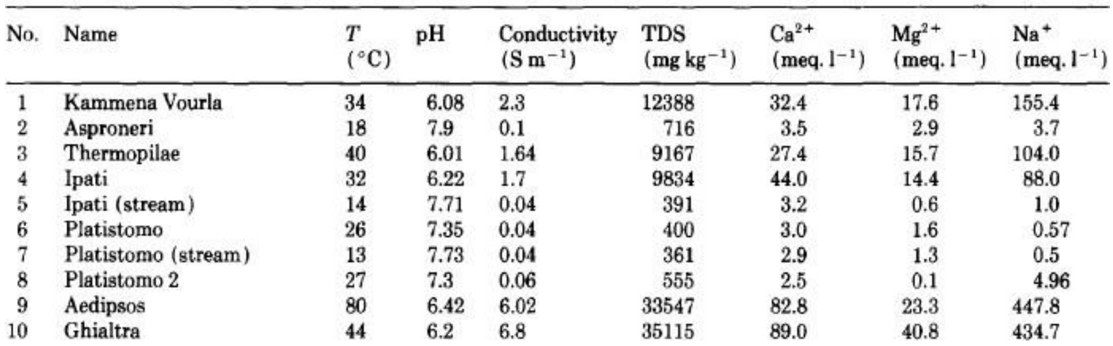


Figure 13: Model produced temperature distribution at 20m depth in Kammena Vourla area when the exploration wells were drilled (Vougioukalakis et al., 2023)

5 GEOCHEMISTRY

Geochemical characteristics of the continental Greek thermal springs (mainly samples from Aidipsos and Spercheios) have been systematically studied by Minissale et al. (1989; an example is shown in the below table). They concluded that the thermal manifestations of continental Greece can be fitted in a tectonic framework where high hydraulic gradients enable waters in hot deep aquifers to reach the surface rapidly along fault systems at the boundary of N-S- and E-W-trending Tertiary basins. The chemical composition of most thermal springs they analyzed was typical of deep Na-HCO3 rising hot waters which circulate in CO2-rich silicic formations, and which acquire progressively a Na-Cl composition by admixing of colder shallower saline connate waters housed in the rock matrix of marine post-orogenic Tertiary-Quaternary sediments. Moreover, the equilibration temperatures found to range between 80 and 120°C in the main storage zone. High N2 and low H2 and H2S content in gas emissions associated to water samples are consistent with temperatures assessed by using geothermometers in liquid phase.

Chemical composition of waters from continental Greece



No.	Name	T (°C)	pH	Conductivity (S m^{-1})	TDS (mg kg^{-1})	Ca^{2+} (meq. l^{-1})	Mg^{2+} (meq. l^{-1})	Na^{+} (meq. l^{-1})
1	Kammena Vourla	34	6.08	2.3	12388	32.4	17.6	155.4
2	Asproneri	18	7.9	0.1	716	3.5	2.9	3.7
3	Thermopilae	40	6.01	1.64	9167	27.4	15.7	104.0
4	Ipati	32	6.22	1.7	9834	44.0	14.4	88.0
5	Ipati (stream)	14	7.71	0.04	391	3.2	0.6	1.0
6	Platistomo	26	7.35	0.04	400	3.0	1.6	0.57
7	Platistomo (stream)	13	7.73	0.04	361	2.9	1.3	0.5
8	Platistomo 2	27	7.3	0.06	555	2.5	0.1	4.96
9	Aedipsos	80	6.42	6.02	33547	82.8	23.3	447.8
10	Ghialtra	44	6.2	6.8	35115	89.0	40.8	434.7

All four geothermal areas that are currently presented, exhibit water influenced by a combination of deep heat sources, surrounding rocks, and seawater to varying degrees of impact (Kanellopoulos et al.,2020). Researchers compare the chemical composition, based on its seawater contribution, to that found in springs located at the Aegean volcanic arc (Kelepertsis et al., 2009; Dotsika, 2015; Kanellopoulos et al., 2018).

The analyzed samples (few of them are presented in Table 1) showed a Na-Cl water type, were slightly acidic, and exhibited degassing of various gasses at the springs. In terms of radioactivity, most samples were classified as normally radioactive; however, Kammena Vourla data clearly deviated from the other ones (Kanellopoulos et al., 2020).

Researchers encountered challenges in applying geothermometers due to the high influence of seawater on fluid composition (Kelepertsis et al., 2009; Dotsika et al., 2015; Vakalopoulos et al., 2016; Diamantopoulos et al., 2018). Among the different methods the Na-K-Ca geothermometer proved to be more reliable.

5.1 Aidipsos

Aidipsos hot springs are characterized by high Ca concentrations and H_2S and CO_2 degassing (D’ Alessandro et al., 2014). This combination has led to the extensive formation of travertine deposits and the severe scaling of the wells.

The elevated Ca concentrations indicate that the geothermal fluid has interacted with carbonates dissolving them while the presence of other metals (such as Ni and Cu) suggests interaction with ophiolitic bodies (Dotsika et al., 2015; Kanellopoulos et al., 2018).

Researchers estimated the probable origin temperatures range between 140^{O}C (quartz geothermometer), 164^{O}C (Na-K-Ca geothermometer) and approximately 200^{O}C (isotope geothermometer) (Kelepertsis et al., 2009; Dotsika et al., 2015; Vakalopoulos et al., 2016; Diamantopoulos et al., 2018). In addition to these an estimation of the circulation depth was done by Kanellopoulos et al. (2020). They concluded that Aidipsos fluid circulate at depths between 700 and 830m.

Radioactivity analyses revealed normal radon (^{222}Rn) levels, while radium (^{226}Ra) concentrations were significantly high ranging from 0.2 to 8 Bq/lt, which are among the highest levels ever recorded in Greece (Vakalopoulos et al., 2016).

5.2 Ilia

Ilia hot spring water presents seasonal variation in water chemistry. During the dry season, the water is of Na-Cl type, while in the wet season, it transitions to Ca-Na-Cl (Kanellopoulos et al., 2020). The estimated circulation depth of geothermal fluids is between 1,200 and 1,300 m (Kanellopoulos et al., 2020). These springs degas CO_2 as the fluids ascend to the surface (D’Alessandro et al., 2014).

5.3 Gialtra

At Gialtra, the geothermal fluid circulation depth is estimated at 1,831 m (Kanellopoulos et al., 2020). Unlike other areas, these springs primarily degas nitrogen (N_2), which likely explains the absence of travertine formations (D’Alessandro et al., 2014).

5.4 Kammena Vourla

The estimated initial (deep) temperatures of Kammena Vourla geothermal fluids range from 120°C to 160°C (Dotsika et al., 2015). Kanellopoulos et al. (2018) reported a significantly shallower circulation depth of 255 m. The springs in this area, like those in Gialtra, primarily degas N_2 (D’Alessandro et al., 2014).

The high salinity of Kammena Vourla waters is not solely attributed to magmatic and seawater mixing. Instead, it is believed that the meteoric water plays a significant role, and therefore the high salinity is mainly attributed to rock-water interactions (Dotsika et al., 2015).

Radioactivity measurements indicate that the area is slightly radioactive, with radon (^{222}Rn) concentrations reaching up to 850 Bq/lt (Kanellopoulos et al., 2020).

5.5 Concluding Remarks

After evaluating the geochemistry of the well and springs geothermal fluids of northern Euboa in the areas of **Aidipsos, Ilia and Gialtra,** Kanellopoulos et al. (2016b; 2017a, b), show that all three present the same hydrochemical type i.e. Na-Cl.

- Based on the classification diagrams i.e. Cl-SO4-HCO3 and Na/1000-√Mg-K/100, they are characterized as near neutral chloride waters and mature waters respectively.
- The geothermal fluids from Euboea are presenting noticeable concentrations of several trace elements, such as up to 11000 μg/L Fe; up to 460 μg/L Cs; up to 340 μg/L Ba; 76 μg/L V; 67.5 mg/L Br; 65 μg/L Cu; 20 μg/L Cr;12 μg/L Ge; up to: 10 μg/L Ag.

Scientific work in the **Eastern Sperchios** area Hot springs, provided for the following geochemical characteristics:
Two main areas with hot spring activity occur in eastern Sperchios basin of continental central Greece, a) the Kammena Vourla and b) the Thermopylae.

- At **Kamena Vourla**, several hot springs occur, with temperatures ranging from 29.6 to 35.5 ^{O}C, and pH values between 5.9 and 6.2 (Kanellopoulos et al., 2017a). They are degassing mainly N_2 (D`Alessandro et al., 2014).
- The **Thermopylae** hot spring temperatures range from 32.8 to 33.5 ^{O}C and their recorded pH values are between 6 and 6.2 respectively (Kanellopoulos et al., 2017a). Degassing is mainly composed by CO_2 (D`Alessandro et al., 2014).

Similar to Euboea geothermal fluids, the geochemistry of eastern Sperchios geothermal fluids shows the same hydrochemical type i.e. Na-Cl.

- Based on classification diagrams (i.e. Cl-SO4-HCO3 and Na/1000-√Mg-K/100), they are characterized as near neutral chloride waters and mature waters respectively (Kanellopoulos et al., 2017a).
- Finally, the geothermal fluids from both, Kammena Vourla and Thermopylae present lower concentrations to almost all trace elements compared to those of Euboea, with only few exceptions, such as Co and Ni (Kanellopoulos et al., 2017a).

21.

Table 1: Sample chemical analyses from Aidipsos, Ilia and Gialtra all in Euboa island (Vakalopoulos et al.,2016)

Site	**Sampling date**	**Temperature (°C)**	**pH**	**Conducivity (µS/cm)**	**TDS (mg/l)**	**Ca**	**Mg**	**Na**	**K**	**CO3**
Ntamaria spring	20/5/2015	70.1	6.5	48630	32530	1642	321.3	10219	351	0
Artemis spring	20/5/2015	79.6	6.9	49580	33575	1650	321.5	10500	361	0
Therma Sylla	20/5/2015	48.7	6.6	47470	32330	1357	484.3	10133	354	0
Ilia well	19/5/2015	63.7	6.5	34410	22690	1571	233.3	6755	206	0
Gialtra spring	21/5/2015	43.4	6.8	50230	34685	1641	620.7	10541	337	0
	HCO3	**Cl**	**SO4**	**NO3**	**SiO2**	**Li**	**F**	**B**	**Fe**	**Sr**
Ntamaria spring	620	18722	950	5	17	1.37	4.7	5.28	2.5	11.3
Artemis spring	585	19290	1150	5	16.4	1.36	4.8	5.4	0.54	11.3
Therma Sylla	489	18298	1450	5	13.8	1.48	4.46	1.03	0.077	11.5
Ilia well	636	12765	800	5	47	3.36	3.8	9.2	13.3	24
Gialtra spring	265	19006	2400	5	8	0.79	3	0.547	0.79	0.12
	Ba	**Al**	**Br**	**As**	**Cu**	**Hg**	**U**	**NH4**	**NO2**	
Ntamaria spring	0.24	0.01	55	0.068	0.155	0.001	0.005	0.44	0.05	
Artemis spring	0.25	0.01	55.5	0.068	0.15	0.001	0.005	0.5	0.05	
Therma Sylla	0.13	0.01	50.6	0.072	0.19	0.001	0.005	0.26	0.005	

22.

Ilia well	0.21	0.01	38.1	0.15	0.13	0.001	0.005	0.57	0.05	
Gialtra spring	0.07	0.01	44.3	0.082	0.19	0.001	0.005	0.15	0.05	

6 SELECTED LITERATURE

Bellon, H., Jarrige, J.J., Sorel, D. (1979). Les activites magmatiques egeennes de l'Oligocene a nos jours et leurs cadres geodynamiques. Donnees nouvelles et synthese. *Revue de Géologique Dynamique et de Géographie Physique*,21, 41–55.

Caroir, F., Chanier, F., Gaullier, V., Sakellariou, D., Bailleul, J., Maillard, A., Paquet, F., Watremez, L., Averbuch, O., Graveleau, F., & Ferrière, J. (2024). Late Quaternary deformation in the western extension of the North Anatolian Fault (North Evia, Greece): Insights from very high-resolution seismic data (WATER surveys). *Tectonophysics*, *870*.

https://doi.org/10.1016/j.tecto.2023.230138

Chatzis, M., Kavouridis, T., Vakalopoulos, P., Xenakis, M. (2008, in Greek), Research and identification of geothermal fields in northern Euboea. I.G.M.E. (Internal Report), Athens.

D`Alessandro, W., Brusca, L., Kyriakopoulos, K., Bellomo, S., Calabrese, S. (2014). A geochemical traverse along the “Sperchios Basin e Evoikos Gulf” graben (Central Greece): Origin and evolution of the emitted fluids. *Marine and Petroleum Geology*, 55: 295-308. https://doi.org/10.1016/j.marpetgeo.2014.02.009

Diamantopoulos, G., Poutoukis, D., Raco, B., Arvanitis, A., & Dotsika, E. (2018). Hydro Chemical Assessment of Aidipsos Geothermal Area, Greece. *Proceedings of the International Workshop on Environmental Management, Science and Engineering* (IWEMSE 2018), pp. 253-259, ISBN: 978-989-758-344-5

Dotsika E. (2015). H-O-C-S isotope and geochemical assessment of the geothermal area of Central Greece. *Journal of Geochemical Exploration,* 150: 1–15.

https://doi.org/10.1016/j.gexplo.2014.11.008

Fytikas M, Kolios N (1979). Preliminary heat flow map of Greece. In: Cermak, V., Rybach, L. (eds): Terrestrial heat flow in Europe, pp 197–205; Springer-Verlag, Berlin-Heidelberg- New York.

Fytikas, M., Giuliani, O., Innocenti, F., Marinelli, G., Mazzuoli, R. (1976). Geochronological data on recent magmatism of the Aegean Sea. *Tectonophysics*, 31: T29-T34.

https://doi.org/10.1016/0040-1951(76)90161-X

Kanellopoulos, C., Lamprinou, V., Mitropoulos, P., Voudouris, P. (2016). Thermogenic travertine deposits in Thermopylae hot springs (Greece) in association with cyanobacterial microflora. *Carbonates and Evaporites Journal*, 31(3): 239–248

Kanellopoulos, C., Mitropoulos, P., Valsami-Jones, E., Voudouris, P. (2017a). Fluid characteristics and mineralizing processes of an Active Low-Sulfidation Epithermal (geothermal) system of Northern Euboea and Eastern Central Greece. *Journal of Geochemical Exploration*, 179: 9-24.

Kanellopoulos, C., Stouraiti, C., Xenakis, M., Vakalopoulos, P., Vougioukalakis, G. (2017b). The geothermal system of Northwestern Euboea island and eastern

Sperchios areas, Greece: Geological characteristics and suggested direct use applications. *11th International Hydrogeological Congress of Greece*, 2017, Conference Proceedings, pp. 263-273; Athens.

Kanellopoulos, C., Mitropoulos, P., Argyraki, A. (2018). Radiological and hydrochemical study of thermal and fresh groundwater samples of northern Euboea and Sperchios areas, Greece: insights into groundwater natural radioactivity and geology. *Environ. Monit. Assess. J.*, 190: 265. https://doi.org/10.1007/s10661-018-6643-1

Kanellopoulos, C., Vougioukalakis, G., Mavrogonatos, C., Megremi, I., Iliopoulos, I., (2019). Mineralogical, Petrological and Geochemical Study of the Agios Ioannis Volcanic Rocks, Kamena Vourla Area, Greece. *Bulletin Geological Society of Greece*, 55, 274-289. https://doi.org/10.12681/bgsg.21128

Kanellopoulos, C., Xenakis, M., Vakalopoulos, P., Kranis, H., Christopoulou, M., & Vougioukalakis, G. (2020). Seawater-dominated, tectonically controlled and volcanic related geothermal systems: the case of the geothermal area in the northwest of the island of Euboea (Evia), Greece. *International Journal of Earth Sciences*, *109*(6), 2081–2112. https://doi.org/10.1007/s00531-020-01889-7

Katsikatsos, G., Mettos, A., Vidakis, M. (1984). Geological map of Greece, Sheet of Istiea, scale 1: 50,000. Institute of Geological and Mineral Exploration (I.G.M.E.), Athens.

Karastathis, V. K., Papoulia, J., di Fiore, B., Makris, J., Tsambas, A., Stampolidis, A., & Papadopoulos, G. A. (2011). Deep structure investigations of the geothermal field of the North Euboean Gulf, Greece, using 3-D local earthquake tomography and Curie Point Depth analysis. *Journal of Volcanology and Geothermal Research*, 206 (3–4): 106–120.

https://doi.org/10.1016/j.jvolgeores.2011.06.008

Karastathis, V., Papoulia, J., Fiore, B. di, & Makris, J. (2010). Exploration of the Deep Structure of the Central Greece Geothermal Field by Passive Seismic and Curie Depth Analysis. *72nd EAGE Conference and Exhibition*, Barcelona, Spain, 14-17 June 2010, (P012)

https://doi.org/10.13140/2.1.1621.9521

Kelepertsis, A., Tziritis, E., Kelepertzis, E., Leontakianakos, G., & Pallas, K. (2009). Hydrogeochemical characteristics and genetic implications of Aidipsos thermal springs, north Euboea, Greece. *Central European Journal of Geosciences*, *1*(3): 241–250. https://doi.org/10.2478/v10085-009-0019-2

Lambrakis, N., Kallergis, G. (2005). Contribution to the study of Greek thermal springs:hydro-geological and hydrochemical characteristics and origin of thermal waters.

Hydrogeology Journal, 13: 506-521.

Makris, J., Papoulia, J., Papanikolaou, D., & Stavrakakis, G. (2001). Thinned continental crust below northern Evoikos Gulf, central Greece, detected from deep seismic soundings. *Tectonophysics,* 341**:** 225–236 https://doi.org/10.1016/S0040-1951(01)00186

Margomenou, G. and Leonidopoulou, G., 1976. Preliminary report on the research of

Aedipsos thermometallic waters. *Proceedings International Workshop on Thermal Waters Geothermal Energy and Volcanism of the Mediterranean Area*. Athens, Oct. 1976, Vol. 2, pp. 340-351.

Minissale, A., Duchi, V., Kolios, N., Totaro, G. (1989). Geochemical characteristics of Greek thermal springs. *Journal of Volcanology and Geothermal Research*, 39(1): 1-16.

https://doi.org/10.1016/0377-0273(89)90017-6

Mountrakis D., 1985. Geology of Greece; Book; Publications of A.U.TH.

Papanikolaou, N., (1972). Geophysical survey in Kammena Vourla area. I.G.E.Y. (Internal Report), Athens.

Orfanos, G., Sfetsos, K. (1975), Hydrogeological survey of Kammeni Vourla, I.Γ.M.E. (Internal Report), Athens.

Sakellariou, D., Rousakis, G., Kaberi, H., Kapsimalis, V., Georgiou, P., Kanellopoulos, T., & Lykousis, V. (2007). Tectono-sedimentary structure and Late Quaternary evolution of the North Evia Gulf Basin, Central Greece: Preliminary results. *Bulletin of the Geological Society of Greece*, *40*(1): 451–462. https://doi.org/10.12681/bgsg.16644

Shaw, B. and Jackson, J. (2010). Earthquake mechanisms and active tectonics of the Hellenic subduction zone. *Geophys. J. Int.* 181: 966–984

Vakalopoulos, P., Xenakis, M., Vougioukalakis, G., Kanellopoulos, C., Christopoulou, M., Statha, F., 2016. Medium – high enthalpy geothermal exploration in Aidipsos area. I.G.M.E., NSRF (National Strategic Reference Framework) 2007-2013 / Operational Programme «Competitiveness and Entrepreneurship» / Project "*Geothermal energy exploration in selected areas, in order to reduce energy dependency and environmental impacts. Assessment of hot groundwater and geothermal resource potential (GEOTHEN)*", Athens.

Vougioukalakis, G., Arvanitis, A., Trimi, P., Xenakis, M., Amvrazis, M., Stefanou, E., Seferli, M., Mylonas, C., Vakalopoulos, P., Athanasoulis, K., (2023). Final study of the long-term monitoring of the country's thermal natural resources and geothermal fields.

H.S.G.M.E. (Internal Reports), Athens.

26.

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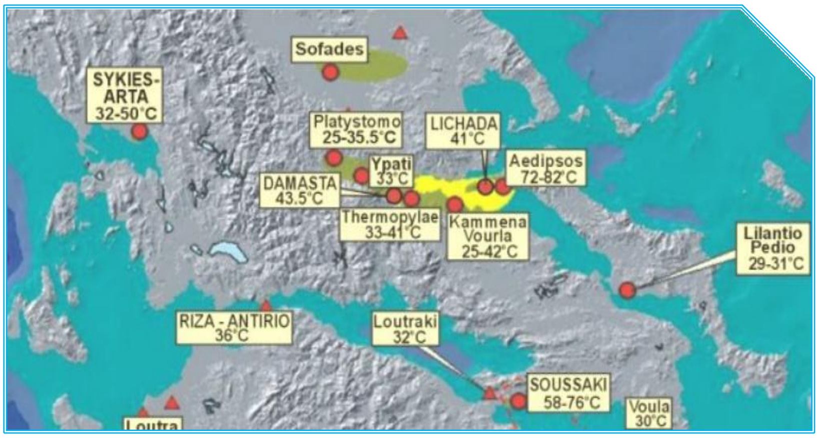

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The above geothermal map is the central part of the known recognized geothermal fields and areas of Greece, compiled by EAGME (f. IGME)