Structural Elements and Petroleum Exploration on the Apulian Platform, Hellenic Fold and Thrust Belt, Zakynthos Island (western Greece)*

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Abstract

The Fold and Thrust Belt in the western part of the Hellenic foreland, has been examined with respect to its geotectonic evolution and source rock potential. The upper Miocene to Pliocene clastic sedimentary sequence provides a great opportunity to reconstruct the regional Fold and Thrust development and to estimate its oil and gas generation potential. The occurrence of a late Oligocene in age, slumped interval suggests intense slope instability. This interval was initially accumulated in a deep water depositional environment, as evidenced by the common occurrence of both complete and incomplete Bouma sequences and is most likely related to the Ionian thrust activity. It is thus envisaged that the Ionian thrust should be positioned further westwards of the Zakynthos Island. The former Ionian thrust should most likely correspond to a younger, smaller scale and of local influence tectonic event. A total number of twenty seven mudstone samples were analyzed using Rock-Eval pyrolysis method. Organic geochemical data indicate that the containing organic matter is present in sufficient abundance and with good enough quality to be regarded as potential source rocks. The present Rock-Eval pyrolytic yields and calculated values of hydrogen and oxygen indexes imply that the recent organic matter is of Types II and III kerogen. The observed kerogen types suggest both gas and oil generation potential. The thermal maturity assessed from Tmax suggests an immature stage of the organic material along with the occurrence of layers having reached the very early mature stage.

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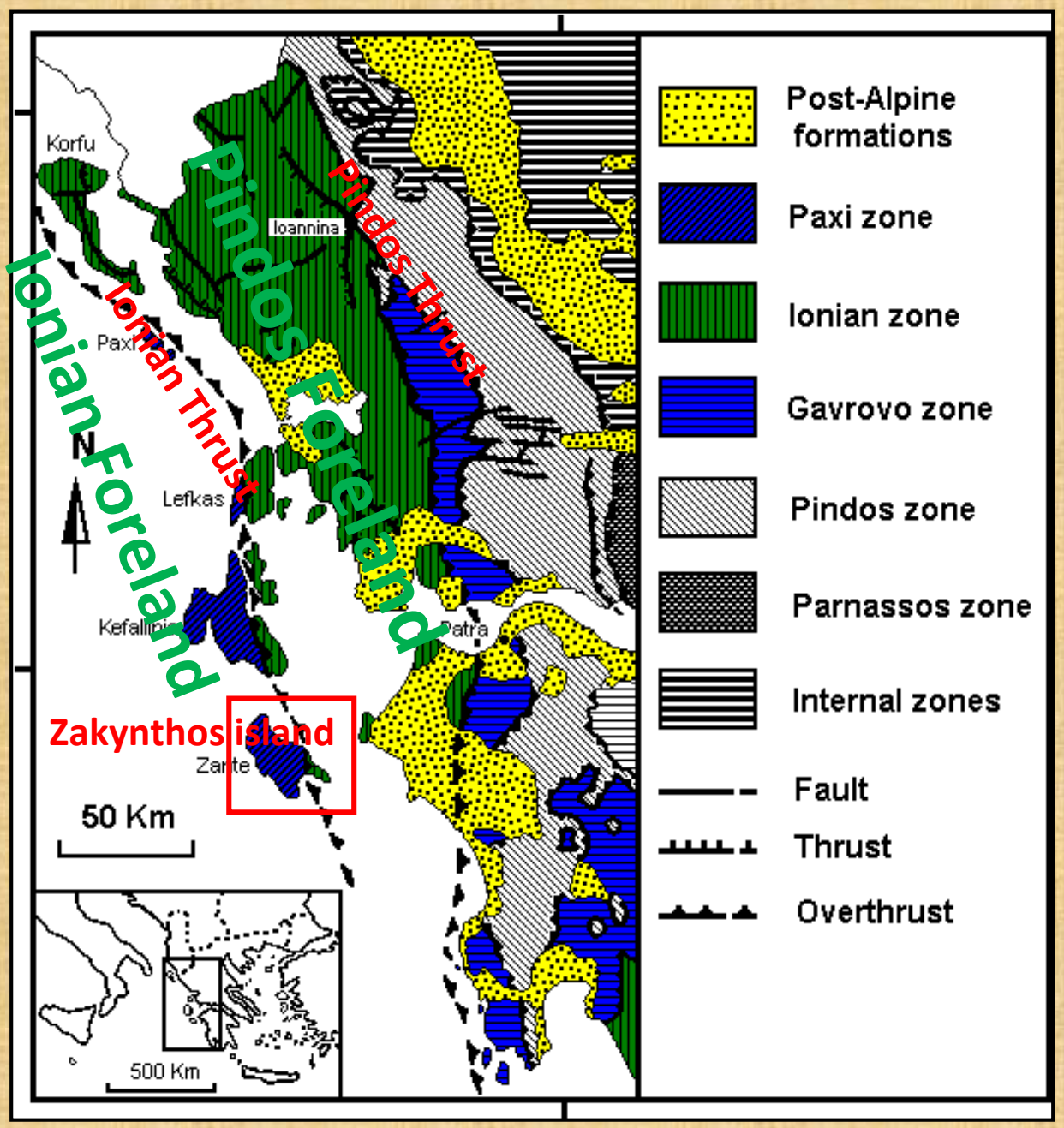
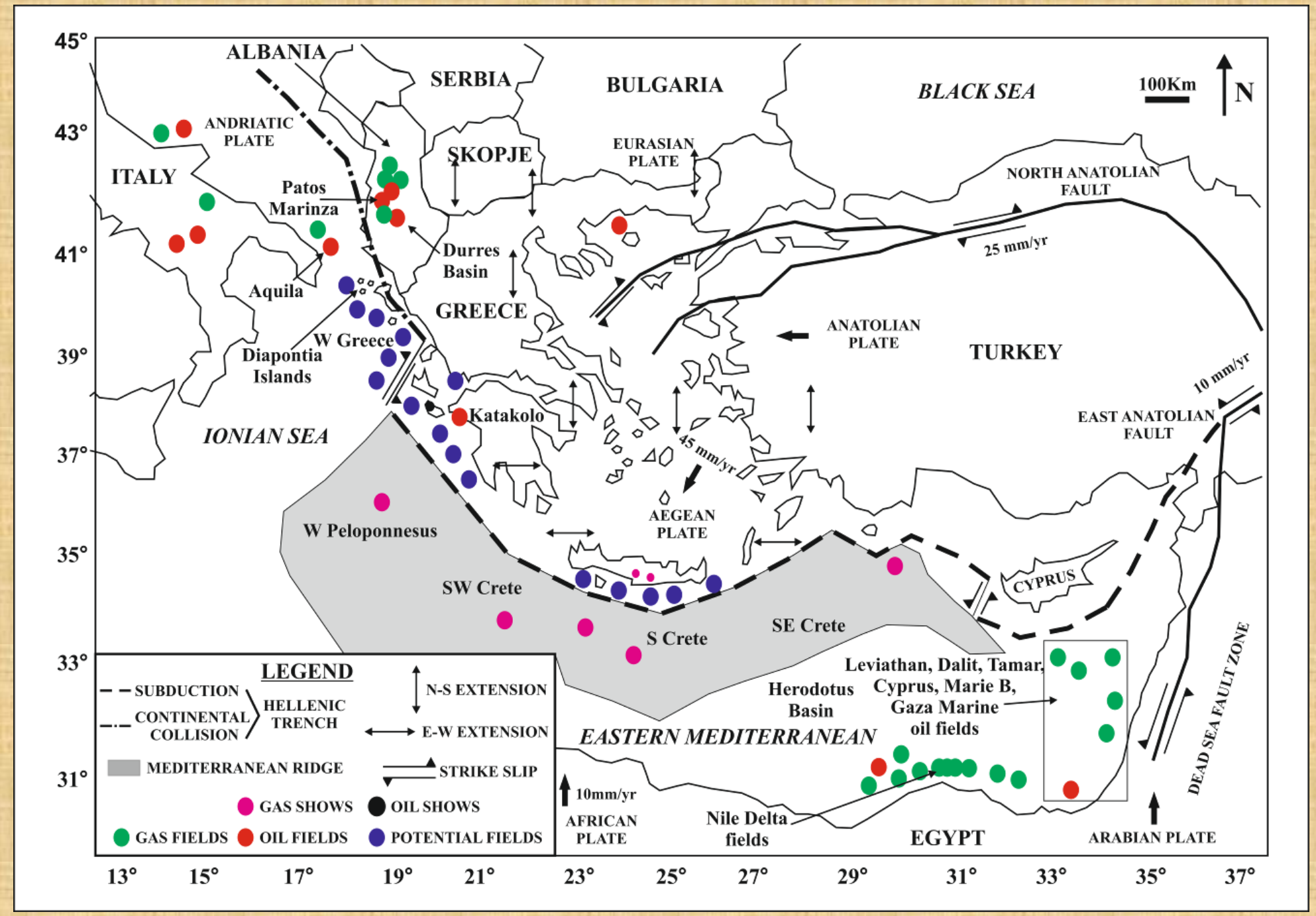


✓Western Greece represents the southern edge of the Alpine orogenic system of the Periadriatic chains.

✓Developed by the relative motion of the African and Eurasian tectonic Plates since the Mesozoic.

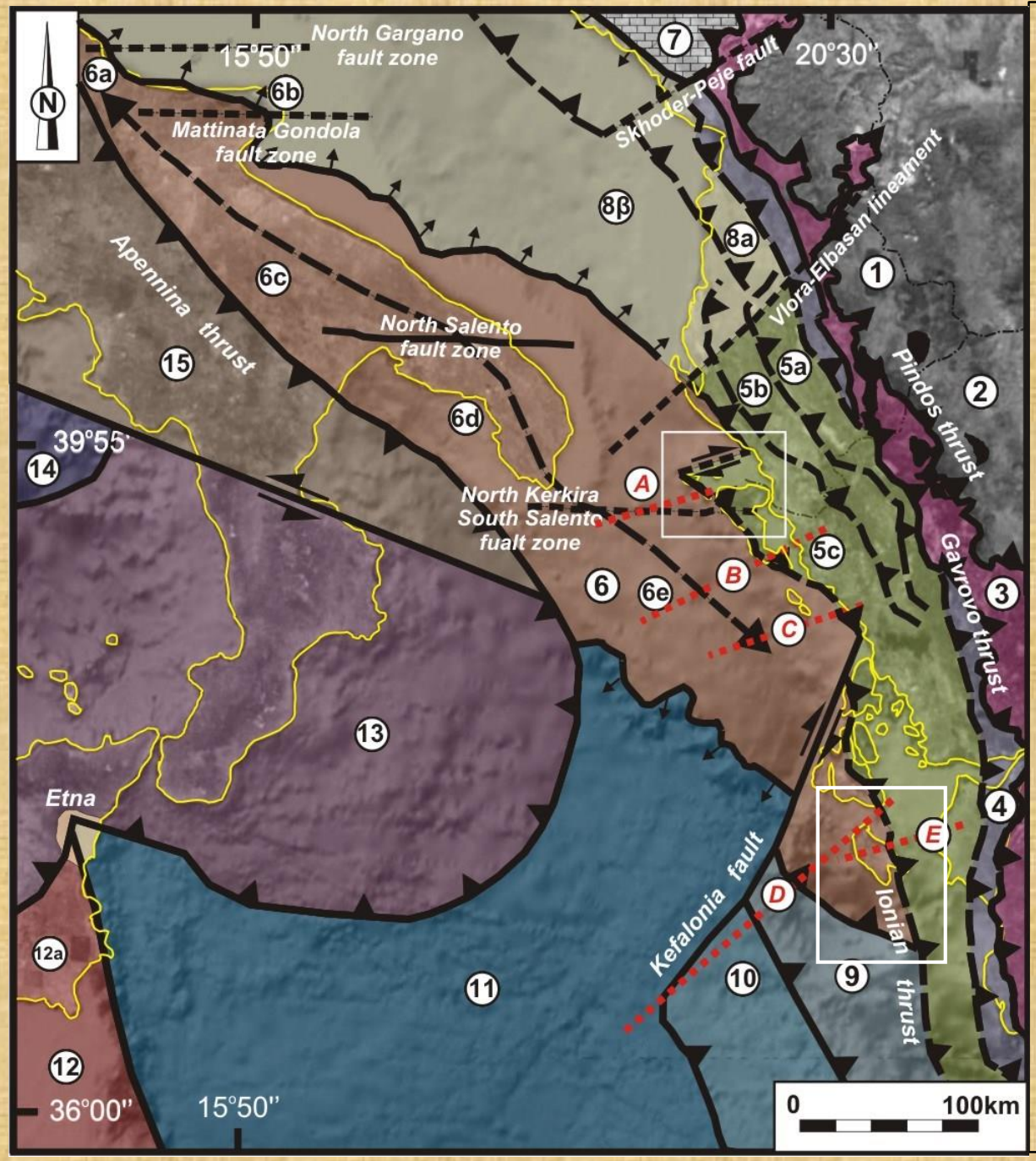
✓It is composed of the most external zones of the Hellenic FTB namely, Gavrovo, Ionian and pre-Apulian zones.


ALBANIA
SERBIA
BULGARIA
BLACK SEA
100Km
N
ANDRIATIC PLATE
ITALY
SKOPJE
EURASIAN PLATE
NORTH ANATOLIAN FAULT
25 mm/yr
Patos Marinza
Durres Basin
Aquila
GREECE
ANATOLIAN PLATE
TURKEY
W Greece
Diapontia Islands
Katakolo
IONIAN SEA
10 mm/yr
EAST ANATOLIAN FAULT
45 mm/yr
AEGEAN PLATE
W Peloponnesus
CYPRUS
SW Crete
S Crete
SE Crete
Leviathan, Dalit, Tamar, Cyprus, Marie B, Gaza Marine oil fields
Herodotus Basin
EASTERN MEDITERRANEAN
DEAD SEA FAULT ZONE
10mm/yr
AFRICAN PLATE
Nile Delta fields
EGYPT
ARABIAN PLATE
LEGEND
SUBDUCTION
CONTINENTAL COLLISION
HELLENIC TRENCH
N-S EXTENSION
E-W EXTENSION
MEDITERRANEAN RIDGE
STRIKE SLIP
GAS SHOWS
OIL SHOWS
GAS FIELDS
OIL FIELDS
POTENTIAL FIELDS
45°
43°
41°
39°
37°
35°
33°
31°
13°
15°
17°
19°
21°
23°
25°
27°
29°
31°
33°
35°
37°

✓Pre-Apulian zone is bounded to the west by the Apulian platform while eastwards it is bounded by the Ionian Zone.

✓Pre-Apulian zone is extended from the southwestern Albania, is exposed in the Ionian Islands and do not extend much further south than Zakynthos Island.

✓Ionian zone is exposed from southwestern Albania to the southern parts of Greece.



The red dashed lines are seismic lines.

The yellow line is the coastline.

1. Internal Albanides,
2. Internal Helenides,
3. Pindos zone (Krasta),
4. Gavrovo zone (Kruja),

5a. Internal Ionian zone,

5b. Middle Ionian zone,

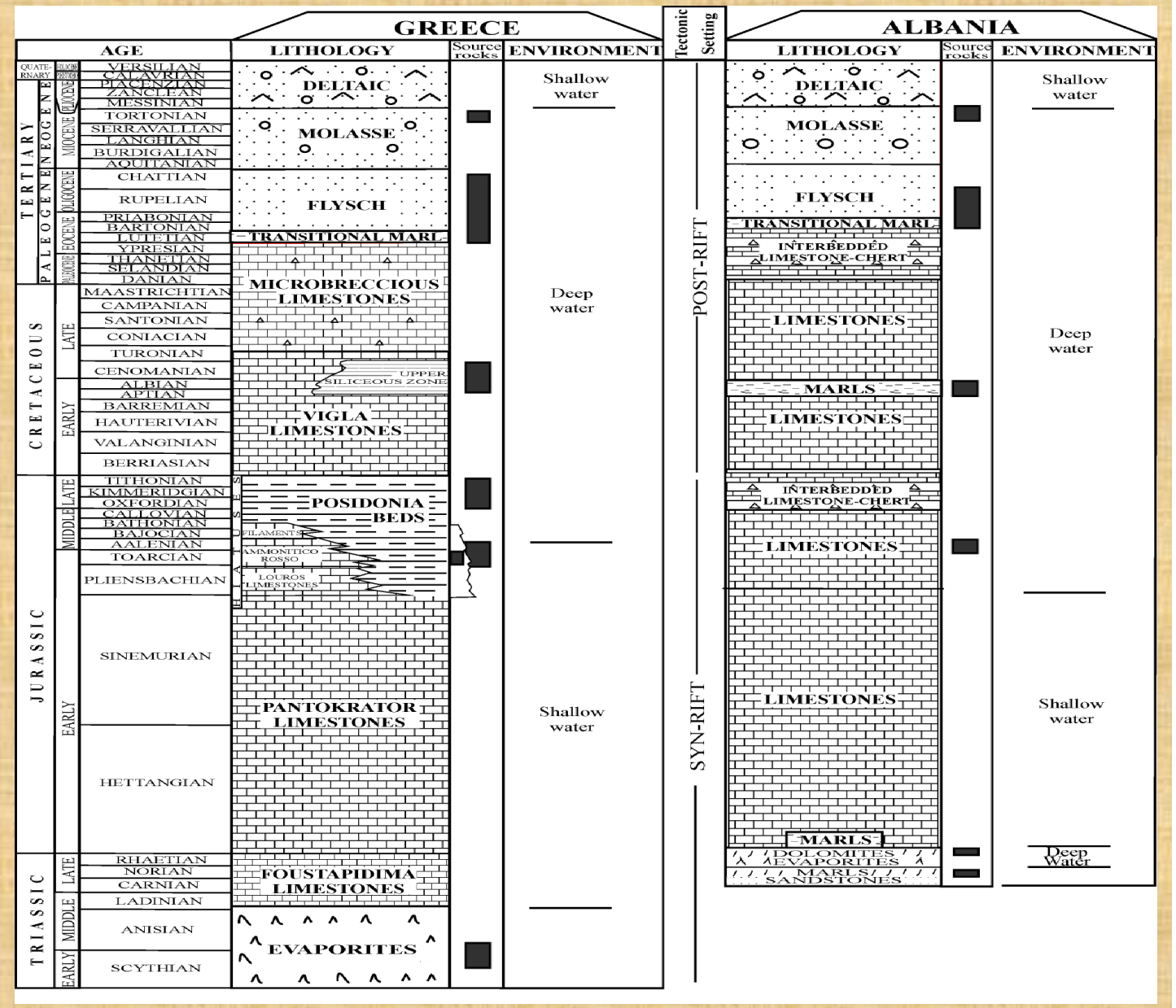
5c. External Ionian zone,

6. Apulian platform:
   - 6a. Plateau Rospo,
   - 6b. Gargano promontory,
   - 6c. Murge ridge,
   - 6d. Salento peninsula,
   - 6e. Apulia plateau,

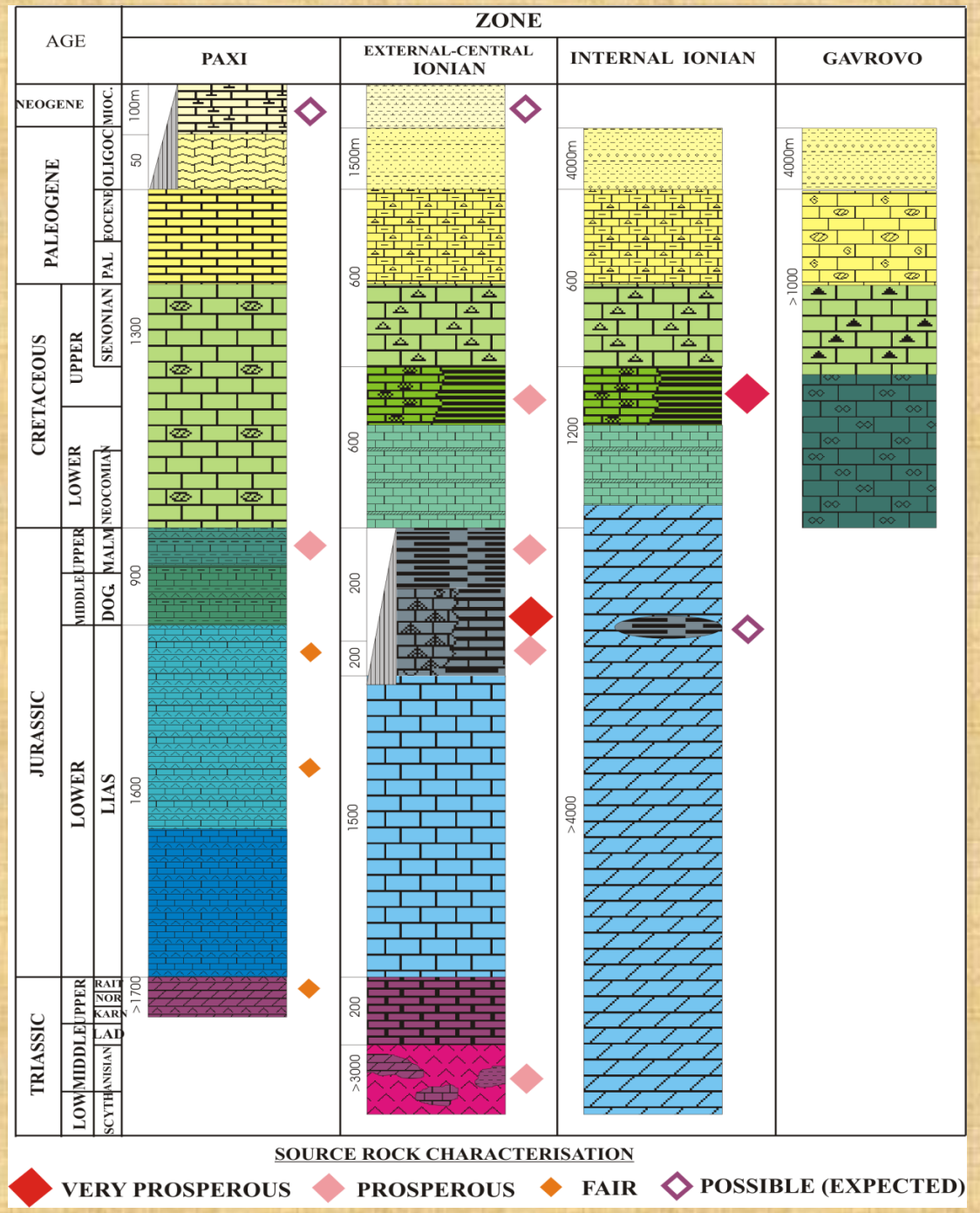
7. Albanian Alps,

8a. Dures basin, 8b. Ionian-Albania basin,

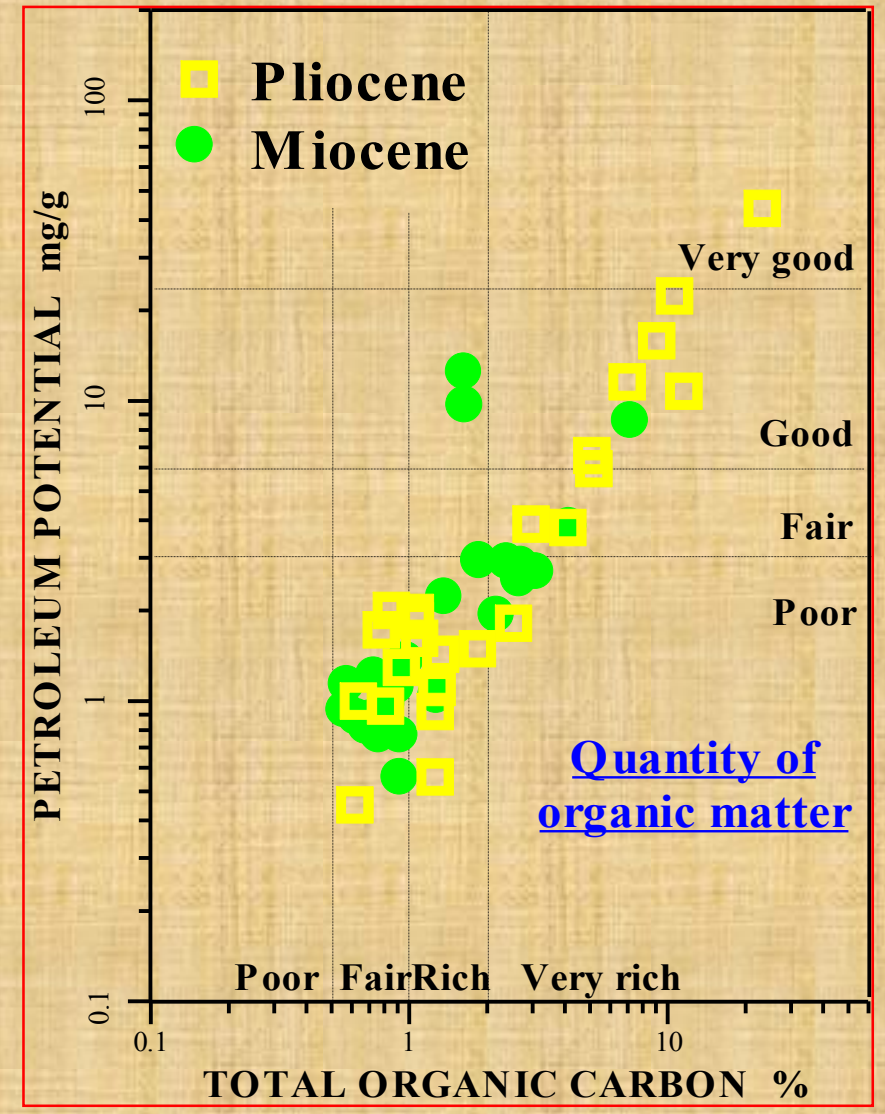
9. Hellenic trench,
10. Mediterranean ridge,
11. Ionian abyssal plain,
12. Africa, 12a. Hyblean plateau,
13. Calabrian arc,
14. South Tyrrhenian sea,
15. South Apennine.

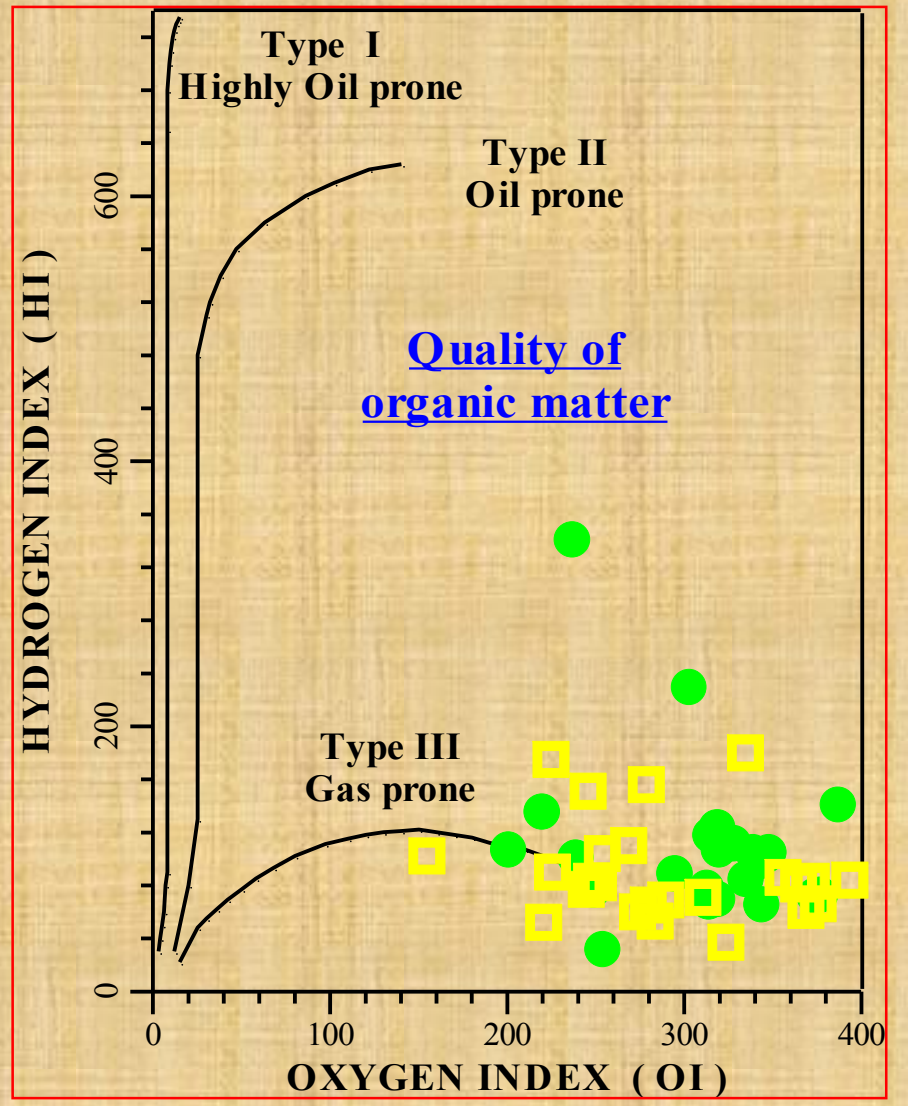


Stratigraphy of Ionian zone Zelilidis et al., 2003

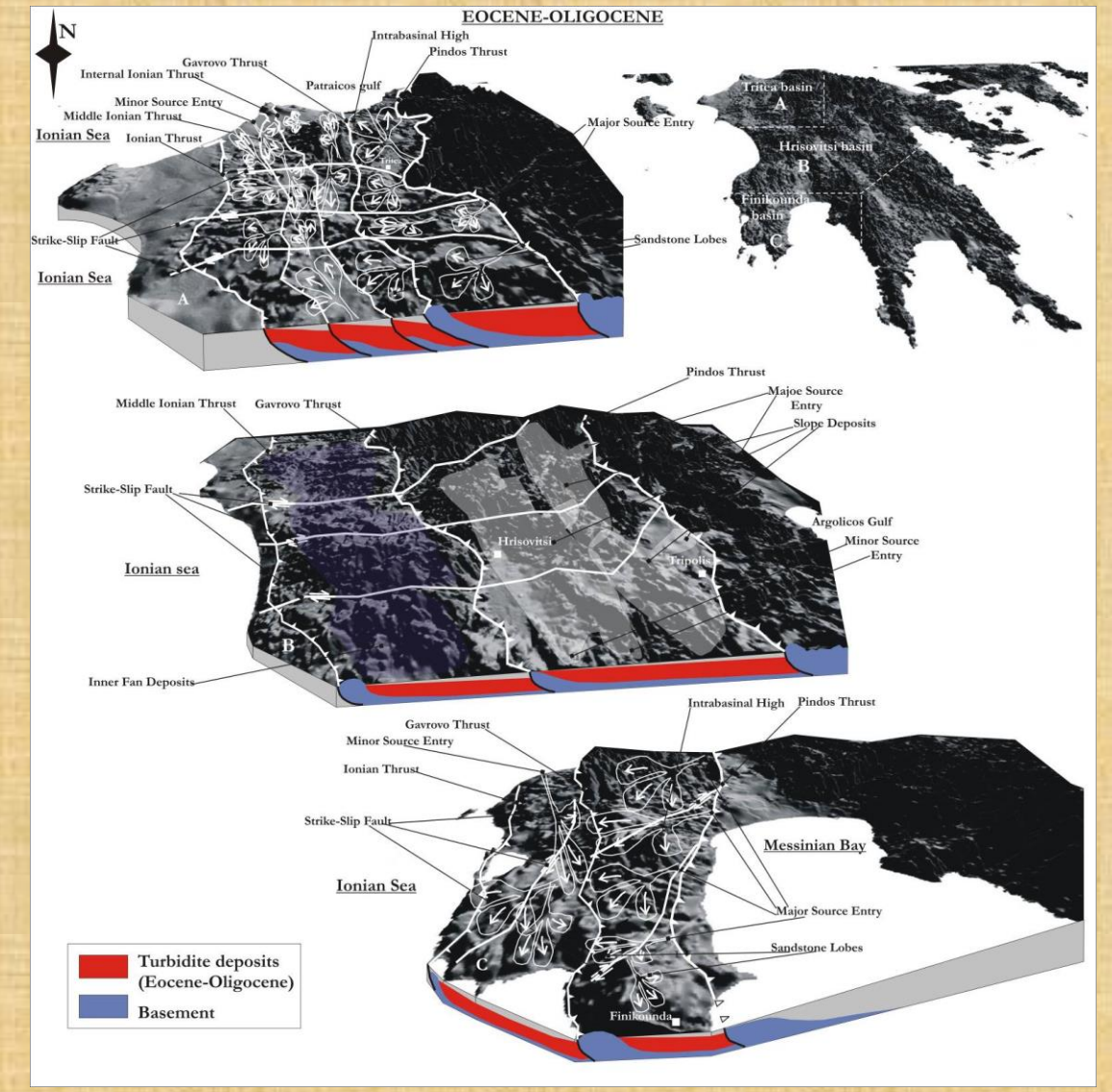


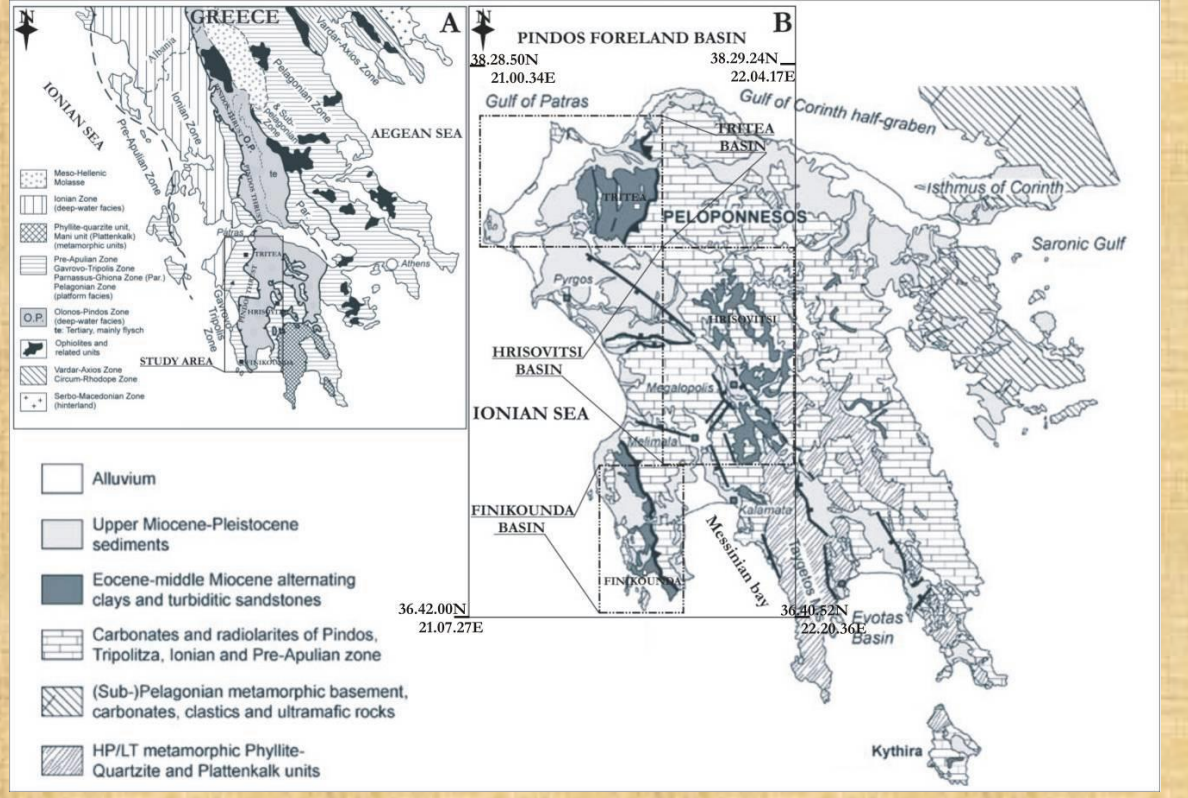
Clastic deposits of Miocene and Pliocene

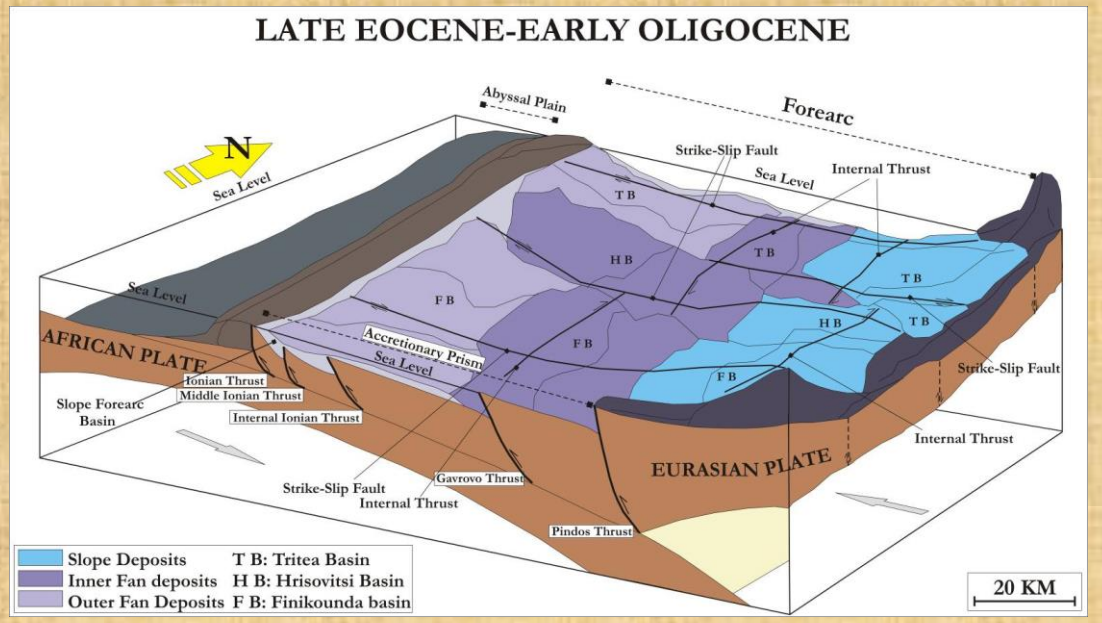




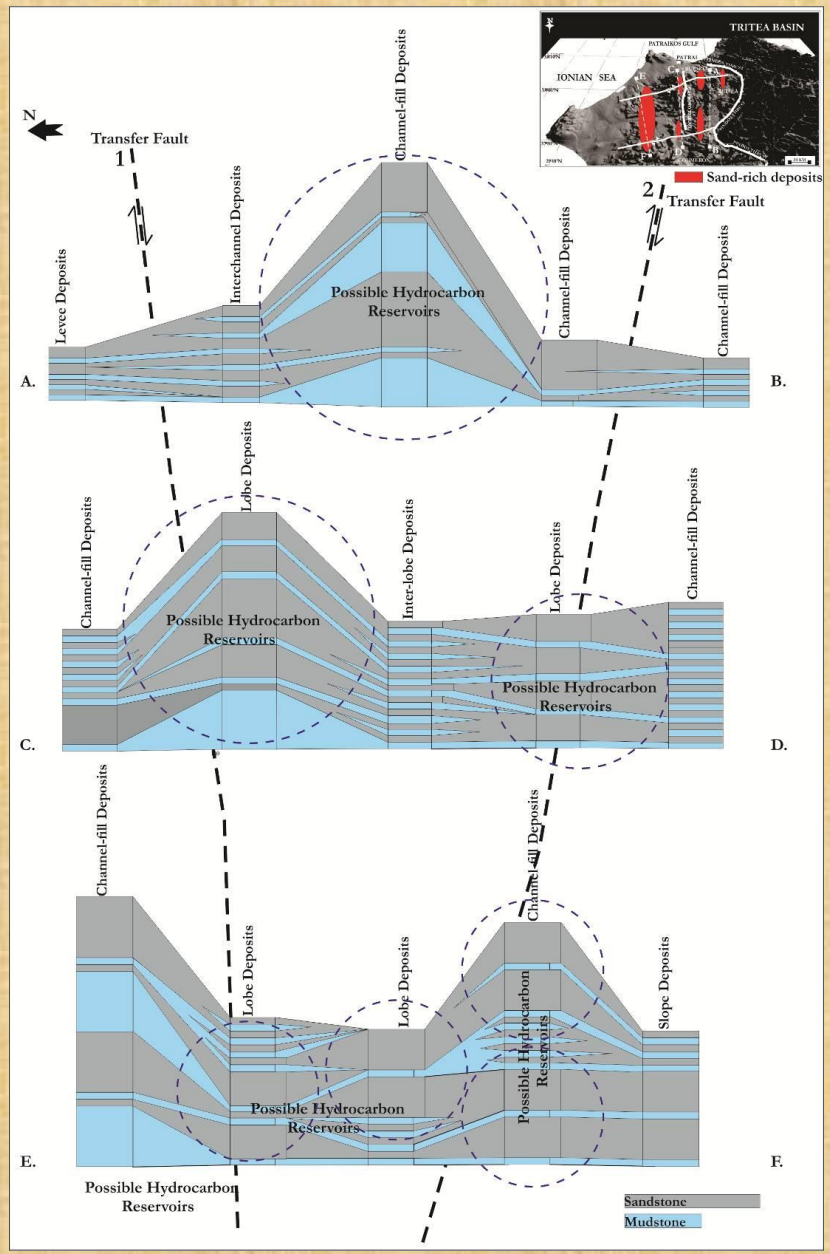
Karakitsios & Rigakis 2007







Konstantopoulos & Zelilidis, 2012


TRITEA BASIN
PATRAIKOS GULF
IONIAN SEA
Sand-rich deposits
N
Transfer Fault
1
2
Transfer Fault
Channel-fill Deposits
Levee Deposits
Interchannel Deposits
Possible Hydrocarbon Reservoirs
Channel-fill Deposits
Channel-fill Deposits
A.
B.
Channel-fill Deposits
Lobe Deposits
Inter-lobe Deposits
Lobe Deposits
Channel-fill Deposits
Possible Hydrocarbon Reservoirs
Possible Hydrocarbon Reservoirs
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Channel-fill Deposits
Channel-fill Deposits
Lobe Deposits
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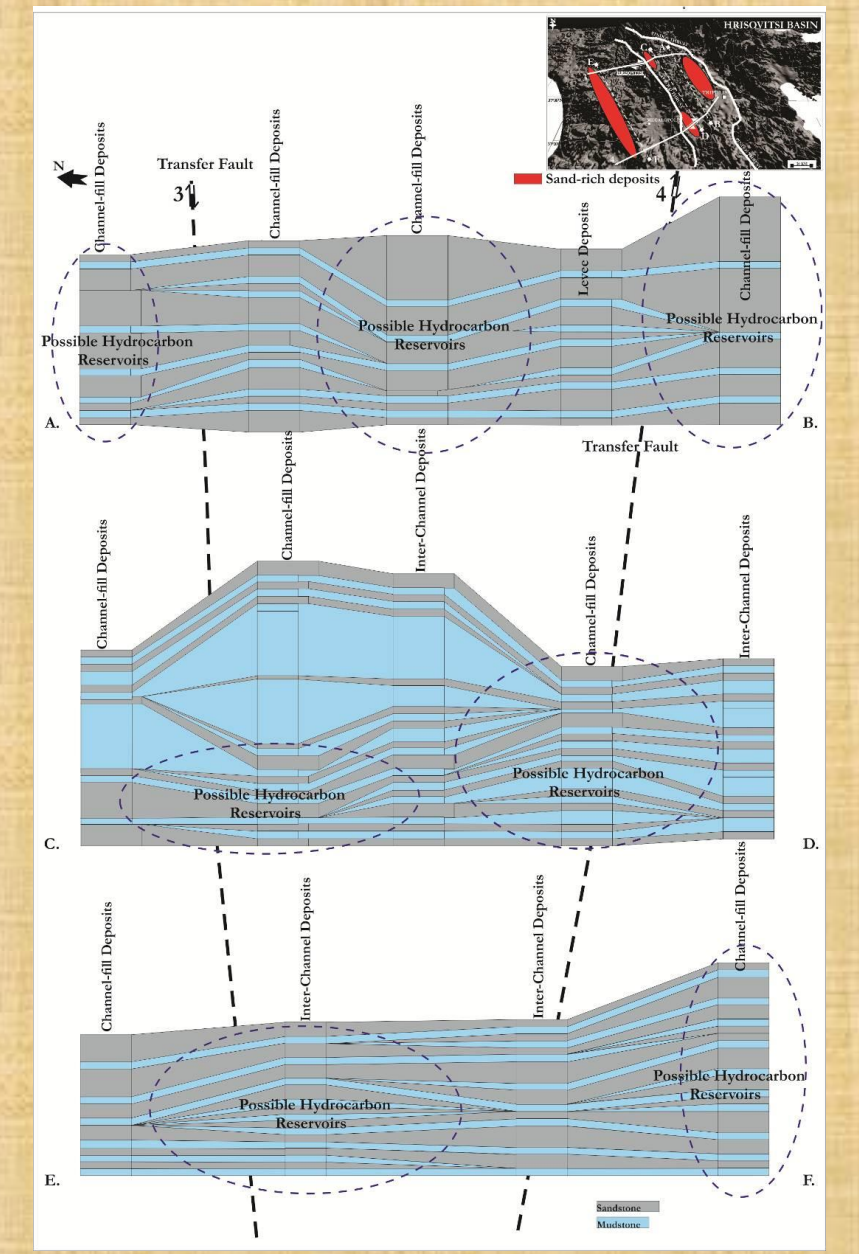
E.
F.
Sandstone
Mudstone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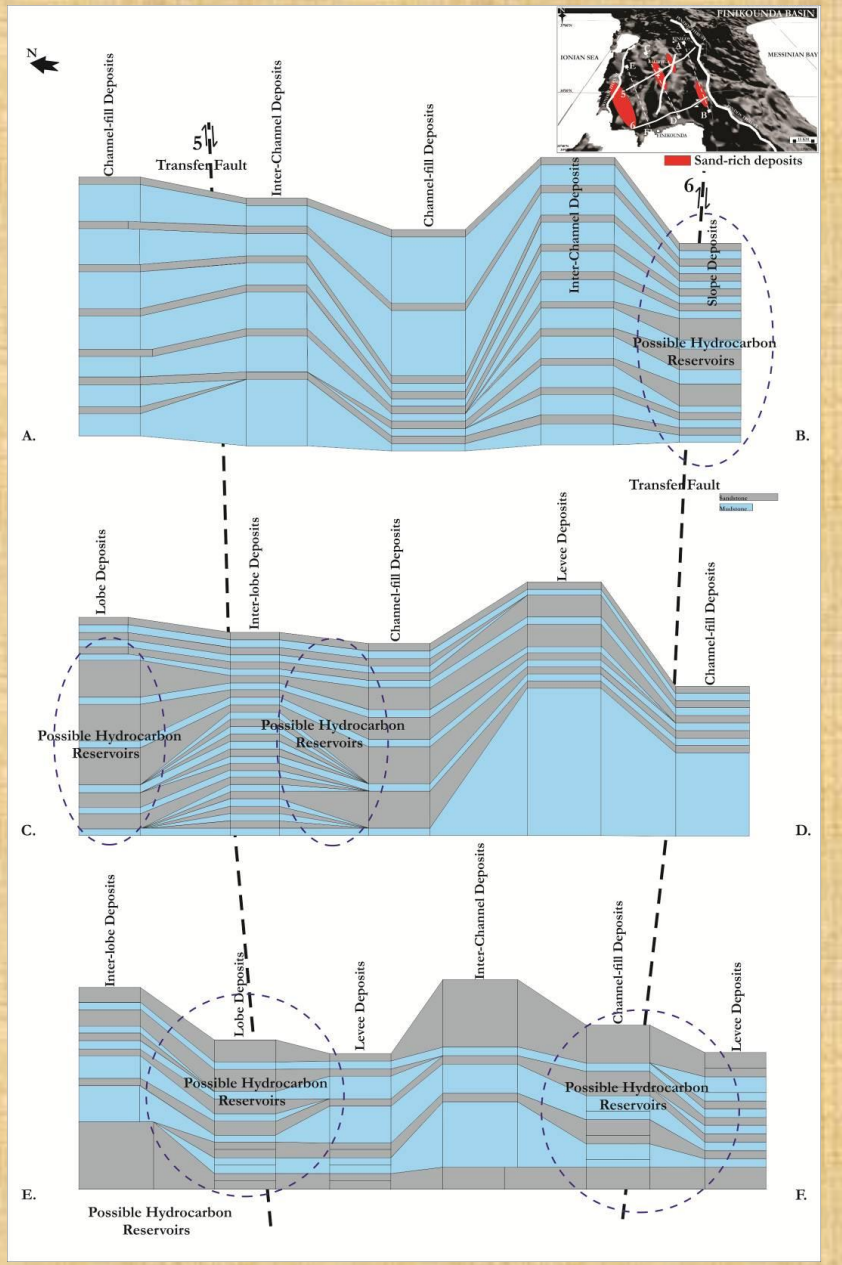
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Inter-lobe Deposits
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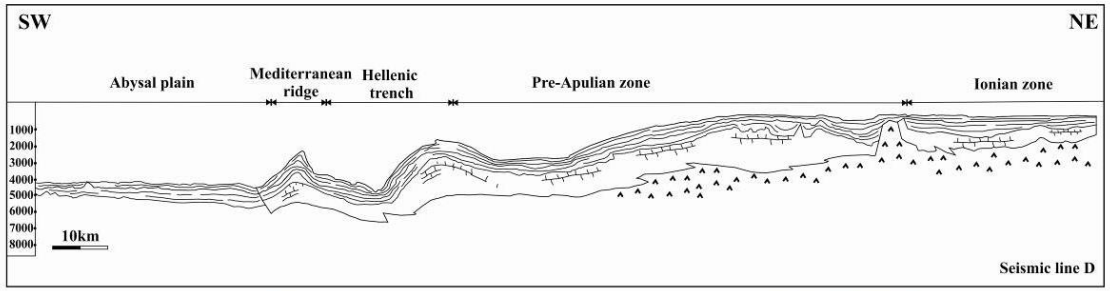
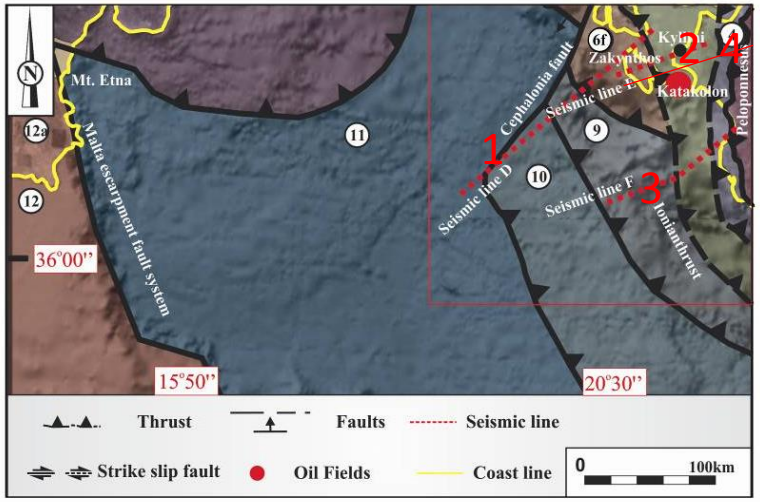
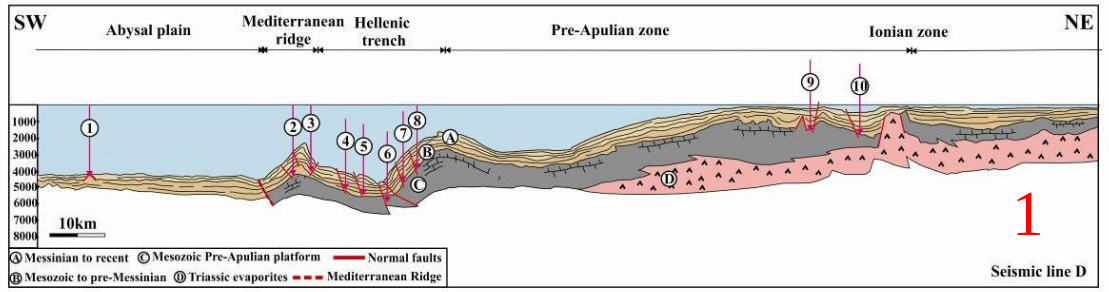
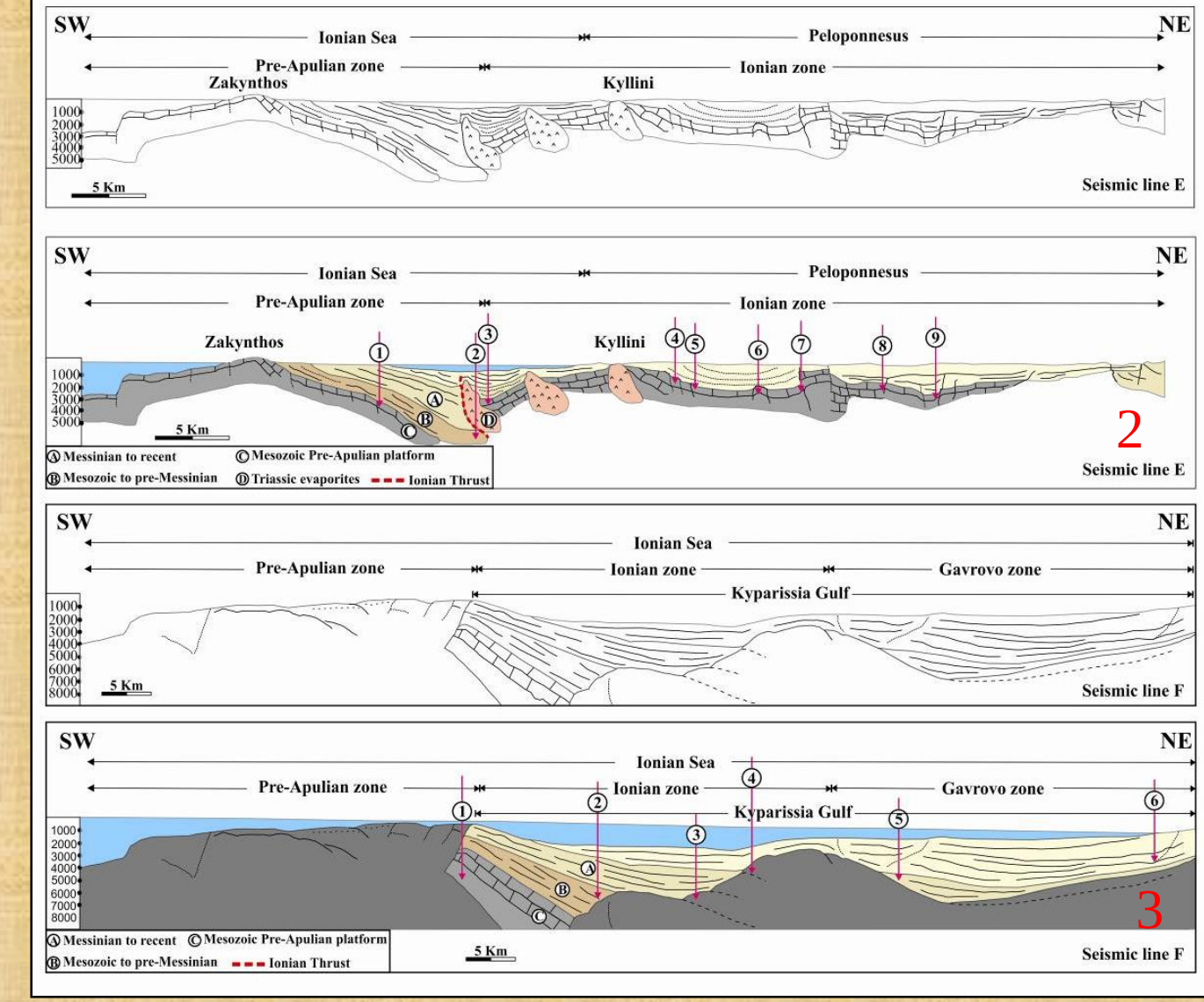


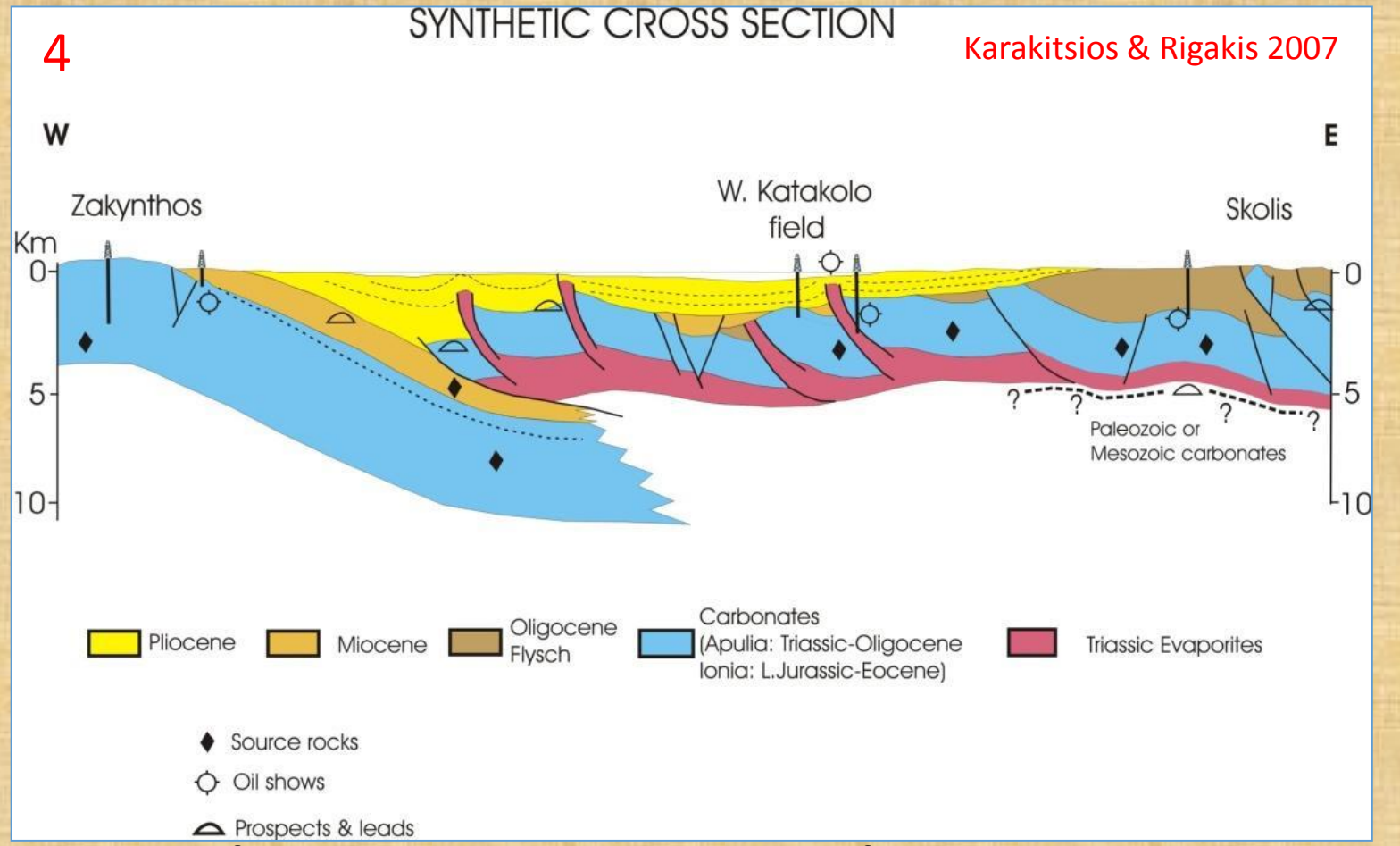




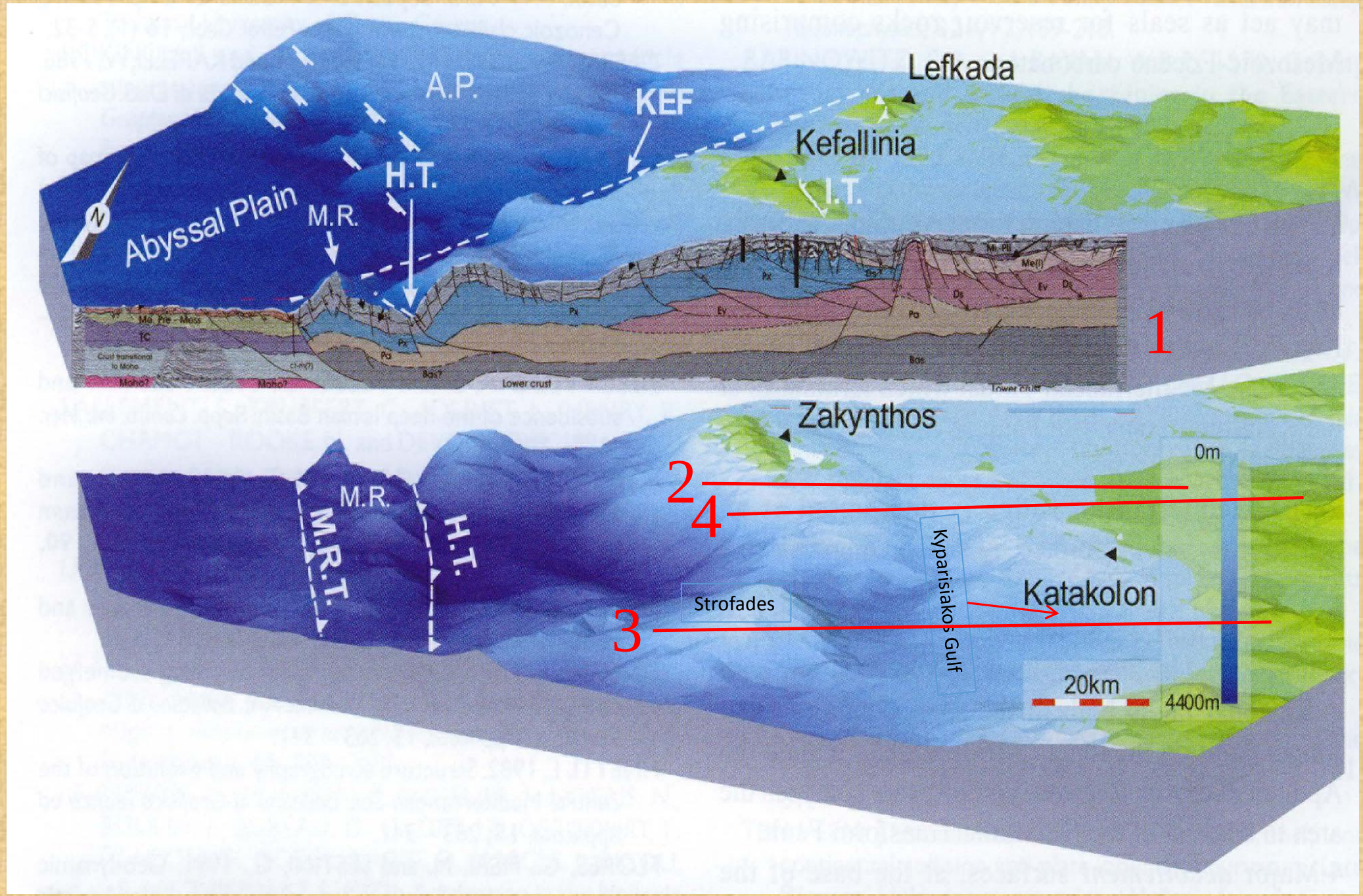


Maravelis et. al., 2012

4



- Gas flow: 11-12 million cubic meter/day for each zone
- Oil flow: 1000-1500 barrels/day
- Reservoir depth: 2400-2600m
- Water depth: 200-350m
- Distance from the land: 3.5km
- 2D seismic data: 6000km
- 3D seismic data: 100 square km


A.P.
KEF
Lefkada
Kefallinia
I.T.
H.T.
M.R.
Abyssal Plain
1
Zakynthos
2
4
3
M.R.
M.R.T.
H.T.
Strofades
Kyparisiakos Gulf
Katakolon
0m
20km
4400m

Geological Setting

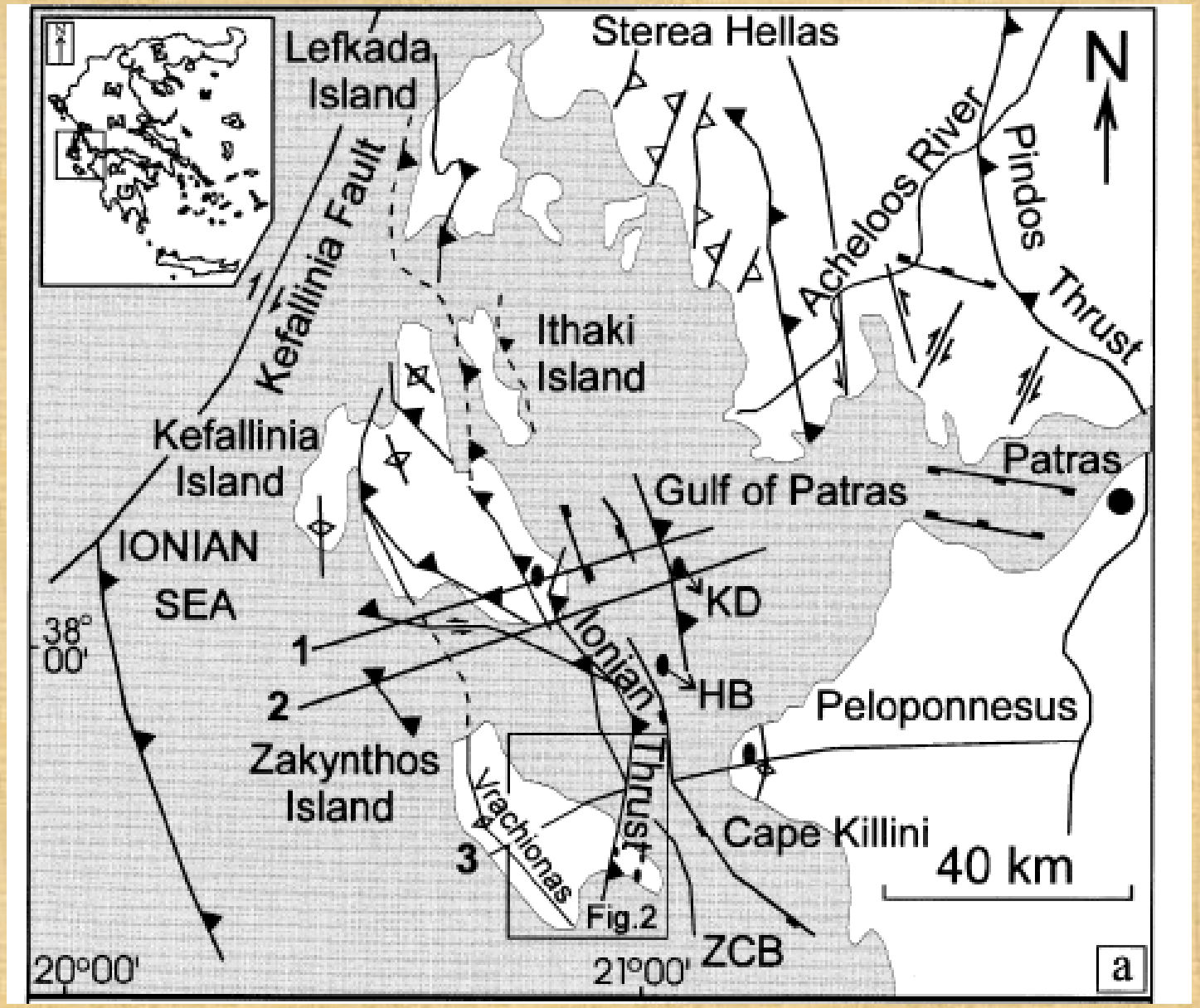
The study area is situated at the western part of Greece, at the southern edge of the Dinarides-Albanides-Hellenides active margin.

It has been influenced by both a compressional and an extensional tectonic regime.

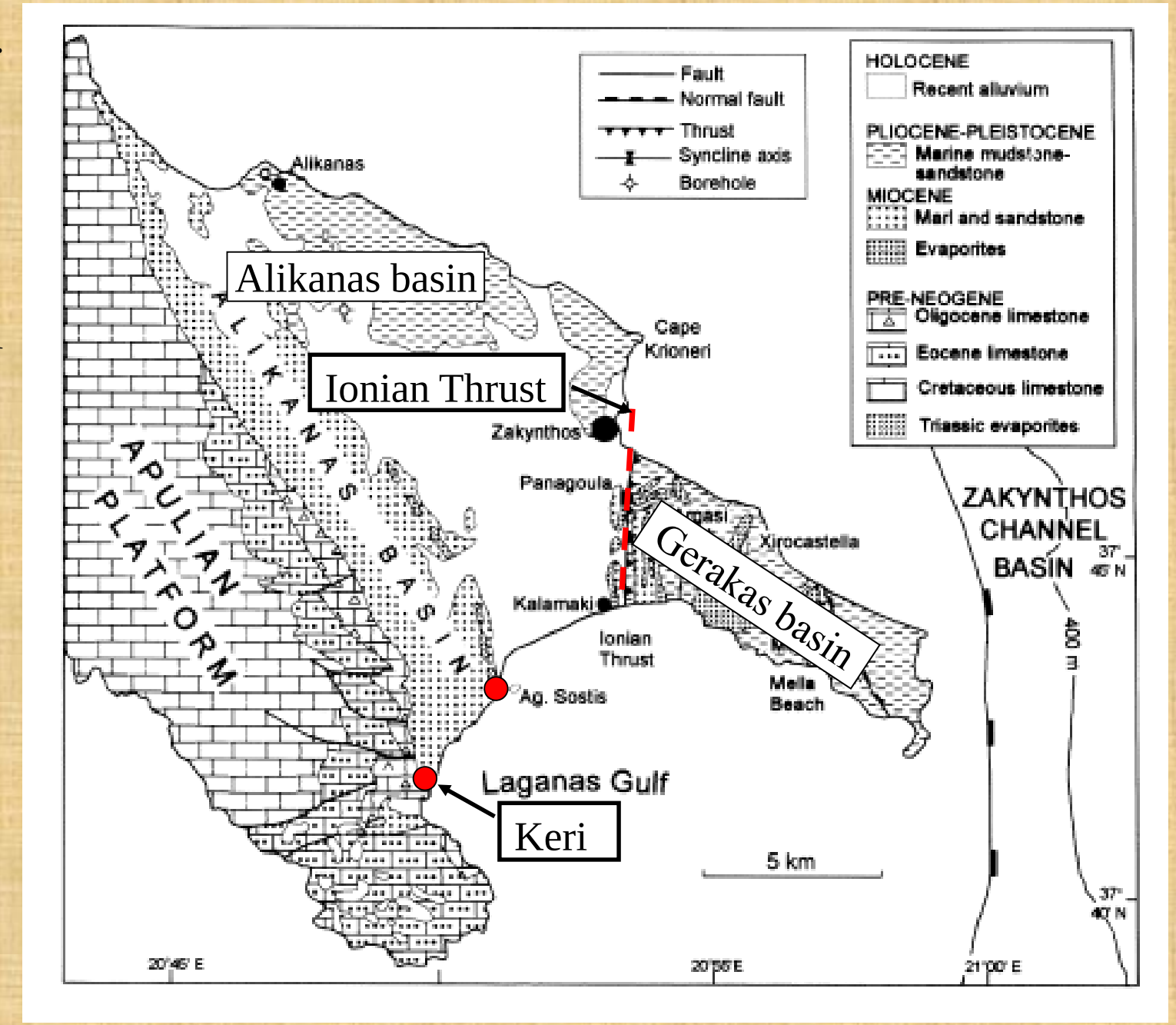
Zakynthos Island is part of the parautochthonus Apulian lithospheric plate of Hellenic mountain belt and contains rocks of two different geotectonic zones

-the western Pre-Apulian zone and

-the eastern Ionian zone



- The region under study was influenced by the Ionian thrust during the early Pliocene. As a result, the area was fragmented and separated into two discrete sedimentary basins, the westward Alikanas foreland basin **(**hosting the oldest rocks seen in the area**)** and the eastward Gerakas piggy-back basin.
- The study area was served as a continental shelf during Tortonian and thus, mudstones that contain rare sandstone beds were accumulated (Keri area).
- Messinian evaporites have been also identified (Agios Sostis area). Such salts evolve into a depositional sequence that contains evaporitic beds of turbiditic origin and further upslope, early Pliocene deep-sea sands.
- The sedimentation develops with the deposition of shelf deposits with hummocky cross-stratification. This depositional environment is represented by “trubi” marly limestone.



Tectonostratigraphy

- The activity of the Ionian thrust during the early Pliocene is the most important tectonic event that affected the study area. This orogenic event separated the main basin into two discrete sub-basins, a westward foreland and an eastward piggy-back basin .
- The foreland basin is typified by major NNW – SSE anticline, which is crossed-cut by both eastward and westward directed faults. Vrachionas anticline was developed during the Pliocene as part of the foreland-propagating fold and thrust system within Pre-Apulian zone.
- The Pre-Apoulian zone is characterized by a compression regime, after Miocene time, followed by a Pliocene extension regime.
- Nowadays, there is a shift in the tectonic regime and the study area is typified by a NNE – SSW directed regime.
- Finally, palaeomagnetic measurements indicate a late Pleistocene 25^{o} clockwise rotation.


Section 5
Section 4
Section 3
Section 2
Section 1
Image © 2012 TerraMetrics
Image © 2012 GeoEye
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Image © 2012 DigitalGlobe
Google earth

Section one:

This section is cited at the southern end of Keri gulf.

It is 8 m in total thickness and is composed of at least eight coarsening upward sedimentary cycles.

Each cycle is up to 1m in total thickness and is represented by a basal mudstone that evolves upslope into coaly beds.

Coals are with 30cm in total thickness.

Section two:

This section corresponds to the laterally equivalent of section one is located at Keri gulf and is presented with up to 6 meters total thickness.

This outcrop consists of a basal grey/brown mudstone up to 25cm thick interbedded with thin-bedded sandstones.

There is an upward increase in mudstone-sandstone ratio.

Section three:

This section is located northeast of the section two between the Keri gulf and Agios Sostis peninsula.

In this area a sedimentary succession with up to 65m in total thickness is exposed.

This sequence is characterized by a thick slump horizon, placed at the top and with 25m in total thickness.

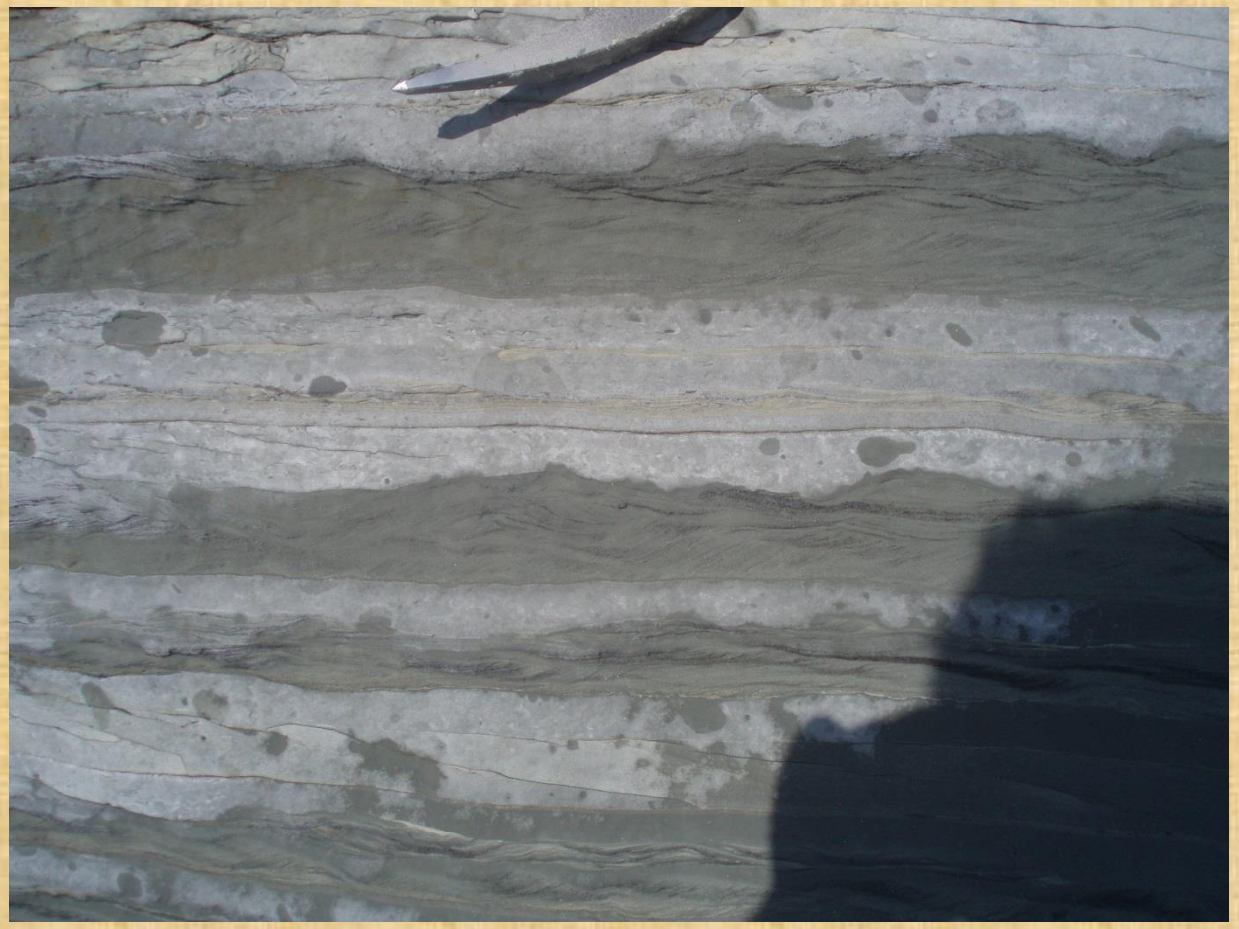
This slump horizon overlies sandstone beds, one meter thick with no evidence of deformation.

The deformation unit underlies undisturbed mudstone strata.

Throughout the sedimentary sequence Bouma subdivision are the dominant sedimentary features.

The western margins of Pindos foreland during the last stage of sedimentation, when the foreland basin changed to piggy-back basin

Thick slumped Oligocene turbiditic deposits within Miocene shelf deposits



Sedimentary structures within slumped horizon

Section four:

This section represents the upper parts of the studied stratigraphy.

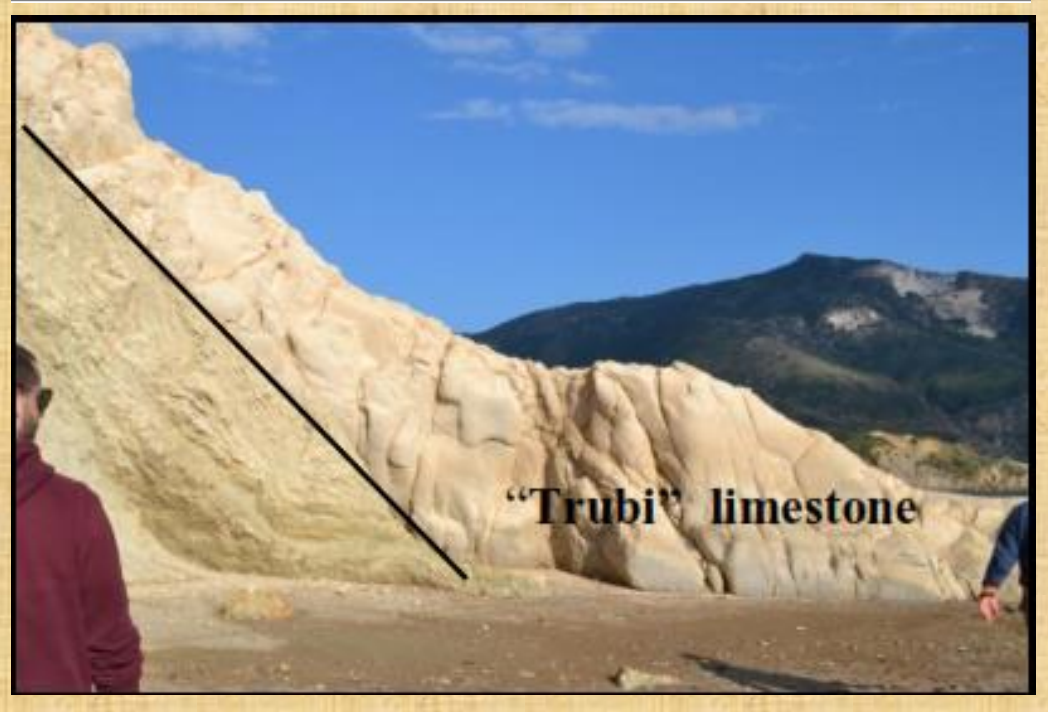
In the current research samples were collected at the base of the section.

The upper parts of both sections four and five are represented by carbonates.

The “Trubi” marly limestones are considered as the typical early Pliocene sedimentary facies of the Mediterranean.

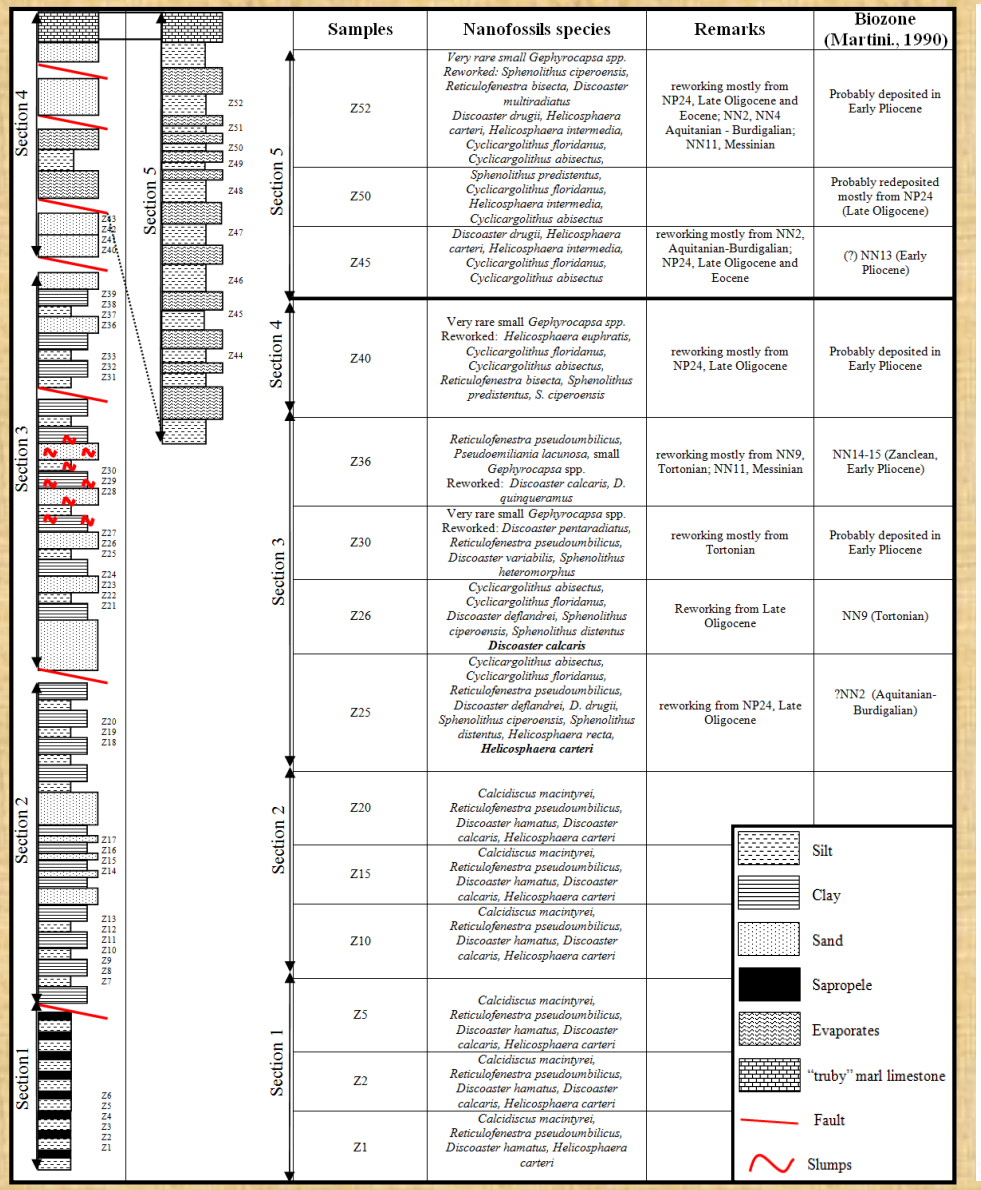
Such facies are overlain the turbiditic sequence, which contains sandstone and re-sedimented evaporitic turbidites.

Both the upper part of the studied section four (overlying the stratigraphic column of this work), and the upper part of the Kalamaki cross-section (Section five) consist of the typical for the Mediterranean environment during the Early Pliocene, "trubi" marly limestone, formed over Pliocene turbiditic sequence, with sandstone and resedimented evaporitic clasts turbidites.

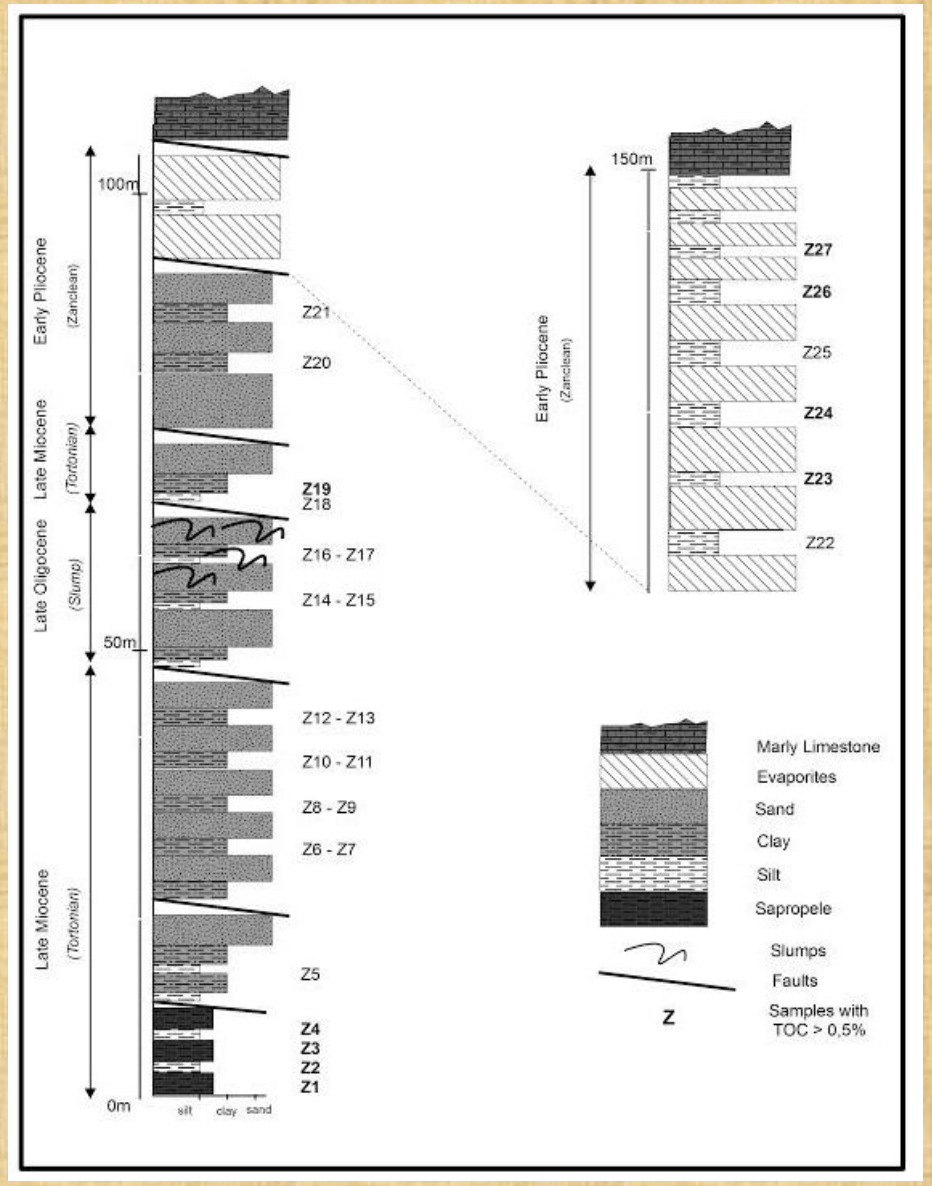


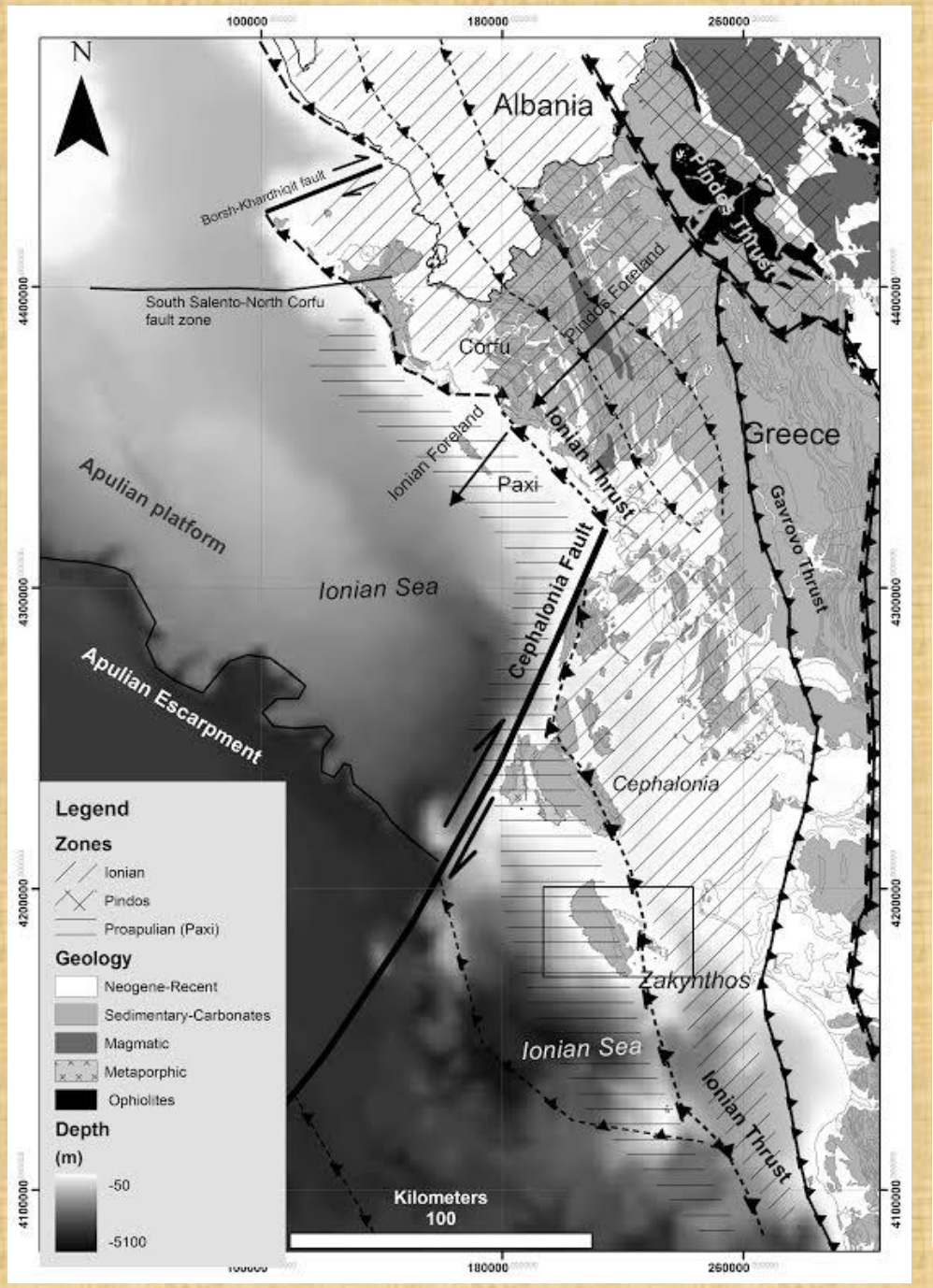
One cycle of section four at Agios Sostis and fourteen cycles of section five in Kalamaki display the influence of the Ionian thrust during the depositional evolution.

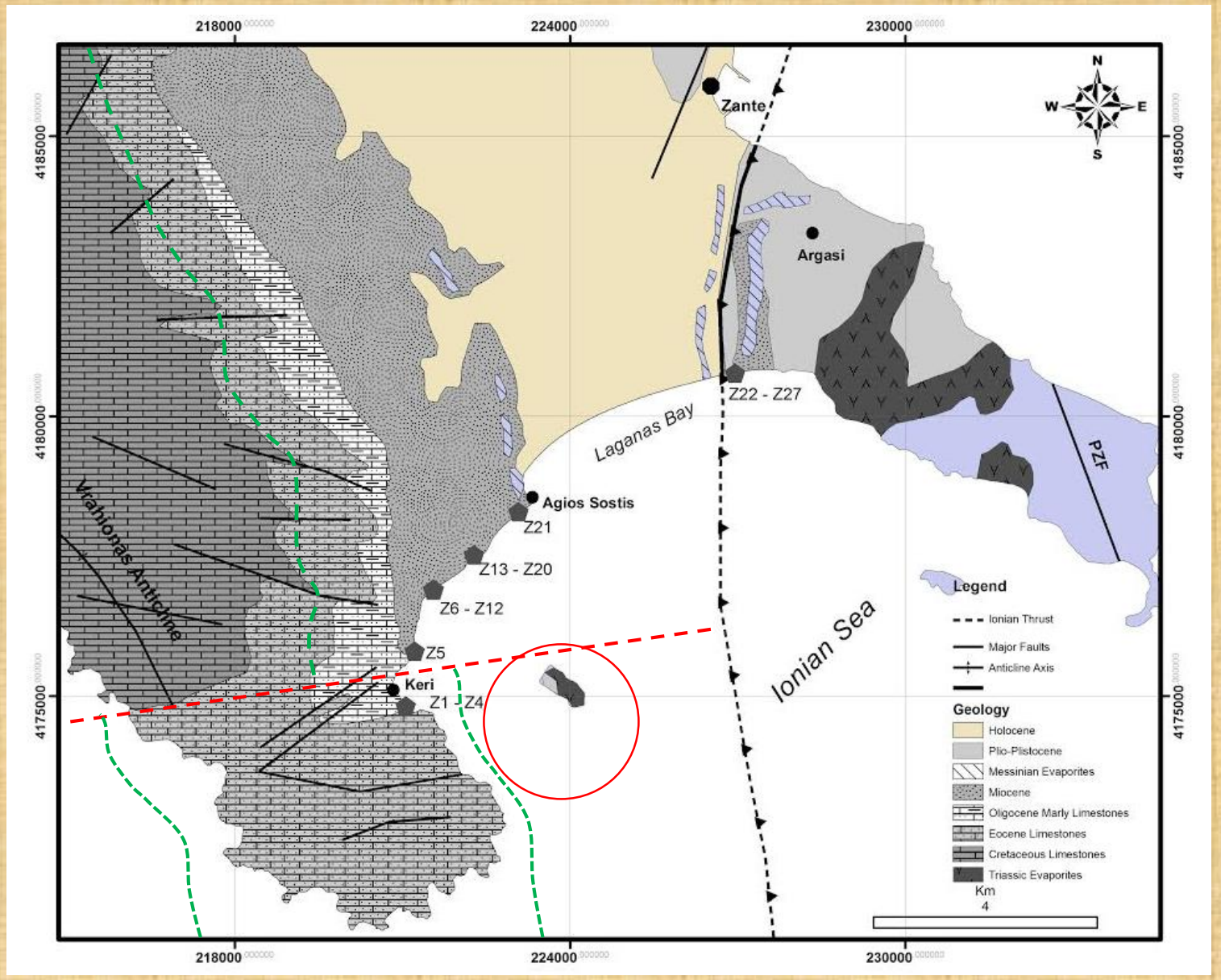
The section five is intimately related to the activity of the Ionian thrust because of its proximity to the thrust front whereas; the remotely positioned section four is little influenced by the thrust activity.



Samples	Nanofossils species	Remarks	Biozone (Martini., 1990)
Z52	*Very rare small Gephyrocapsa spp. Reworked: Sphenolithus ciperoensis, Reticulofenestra bisecta, Discoaster multiradiatus Discoaster drugii, Helicosphaera carteri, Helicosphaera intermedia, Cyclicargolithus floridanus, Cyclicargolithus abisectus,*	reworking mostly from NP24, Late Oligocene and Eocene; NN2, NN4 Aquitanian - Burdigalian; NN11, Messinian	Probably deposited in Early Pliocene
Z50	*Sphenolithus predistentus, Cyclicargolithus floridanus, Helicosphaera intermedia, Cyclicargolithus abisectus*		Probably redeposited mostly from NP24 (Late Oligocene)
Z45	*Discoaster drugii, Helicosphaera carteri, Helicosphaera intermedia, Cyclicargolithus floridanus, Cyclicargolithus abisectus*	reworking mostly from NN2, Aquitanian-Burdigalian; NP24, Late Oligocene and Eocene	(?) NN13 (Early Pliocene)
Z40	Very rare small *Gephyrocapsa spp.* Reworked: *Helicosphaera euphratis, Cyclicargolithus floridanus, Cyclicargolithus abisectus, Reticulofenestra bisecta, Sphenolithus predistentus, S. ciperoensis*	reworking mostly from NP24, Late Oligocene	Probably deposited in Early Pliocene
Z36	*Reticulofenestra pseudoumbilicus, Pseudoemiliania lacunosa,* small *Gephyrocapsa spp.* Reworked: *Discoaster calcaris, D. quinqueramus*	reworking mostly from NN9, Tortonian; NN11, Messinian	NN14-15 (Zanclean, Early Pliocene)
Z30	Very rare small *Gephyrocapsa spp.* Reworked: *Discoaster pentaradiatus, Reticulofenestra pseudoumbilicus, Discoaster variabilis, Sphenolithus heteromorphus*	reworking mostly from Tortonian	Probably deposited in Early Pliocene
Z26	*Cyclicargolithus abisectus, Cyclicargolithus floridanus, Discoaster deflandrei, Sphenolithus ciperoensis, Sphenolithus distentus* ***Discoaster calcaris***	Reworking from Late Oligocene	NN9 (Tortonian)
Z25	*Cyclicargolithus abisectus, Cyclicargolithus floridanus, Reticulofenestra pseudoumbilicus, Discoaster deflandrei, D. drugii, Sphenolithus ciperoensis, Sphenolithus distentus, Helicosphaera recta,* ***Helicosphaera carteri***	reworking from NP24, Late Oligocene	?NN2 (Aquitanian-Burdigalian)
Z20	*Calcidiscus macintyrei, Reticulofenestra pseudoumbilicus, Discoaster hamatus, Discoaster calcaris, Helicosphaera carteri*		
Z15	*Calcidiscus macintyrei, Reticulofenestra pseudoumbilicus, Discoaster hamatus, Discoaster calcaris, Helicosphaera carteri*		
Z10	*Calcidiscus macintyrei, Reticulofenestra pseudoumbilicus, Discoaster hamatus, Discoaster calcaris, Helicosphaera carteri*		
Z5	*Calcidiscus macintyrei, Reticulofenestra pseudoumbilicus, Discoaster hamatus, Discoaster calcaris, Helicosphaera carteri*		
Z2	*Calcidiscus macintyrei, Reticulofenestra pseudoumbilicus, Discoaster hamatus, Discoaster calcaris, Helicosphaera carteri*		
Z1	*Calcidiscus macintyrei, Reticulofenestra pseudoumbilicus, Discoaster hamatus, Helicosphaera carteri*		




N
Albania
Borsh-Khardhiqit fault
South Salento-North Corfu fault zone
Corfu
Pindos Foreland
Pindos Thrust
Greece
Ionian Foreland
Ionian Thrust
Paxi
Apulian platform
Ionian Sea
Gavrovo Thrust
Cephalonia Fault
Apulian Escarpment
Cephalonia
Zakynthos
Ionian Sea
Ionian Thrust
Legend
Zones
Ionian
Pindos
Proapulian (Paxi)
Geology
Neogene-Recent
Sedimentary-Carbonates
Magmatic
Metaporphic
Ophiolites
Depth
(m)
-50
-5100
Kilometers
100


218000
224000
230000
4185000
4180000
4175000
N
W
E
S
Zante
Argasi
Z22 - Z27
Laganas Bay
PZF
Agios Sostis
Z21
Z13 - Z20
Z6 - Z12
Z5
Keri
Z1 - Z4
Vrahionas Anticline
Ionian Sea
Legend
Ionian Thrust
Major Faults
Anticline Axis
Geology
Holocene
Plio-Pliostocene
Messinian Evaporites
Miocene
Oligocene Marly Limestones
Eocene Limestones
Cretaceous Limestones
Triassic Evaporites
Km
4

SOURCE ROCK RESERVOIR ROCK

APULIAN PLATFORM

AGE		LITHOLOGY
NEOGENE	MIOCENE	Anhydrite with rare thin-bedded marls Grey marl with whitish thin-bedded mudstone Marly limestones and marls Grey wackestone locally marly
PALEOGENE	OLIGOCENE	Sandstones and mudstones
	EOCENE	Marly wackestone/packstone, often dolomitized with benthic macroforaminifera
	PALEOCENE	
CRETACEOUS	LATE	Wackestone/packstone with rudists white,chalky, with clastic (breccia) levels
	EARLY	Alternating packstone/grainstone, breccias (boundstone clasts), marl

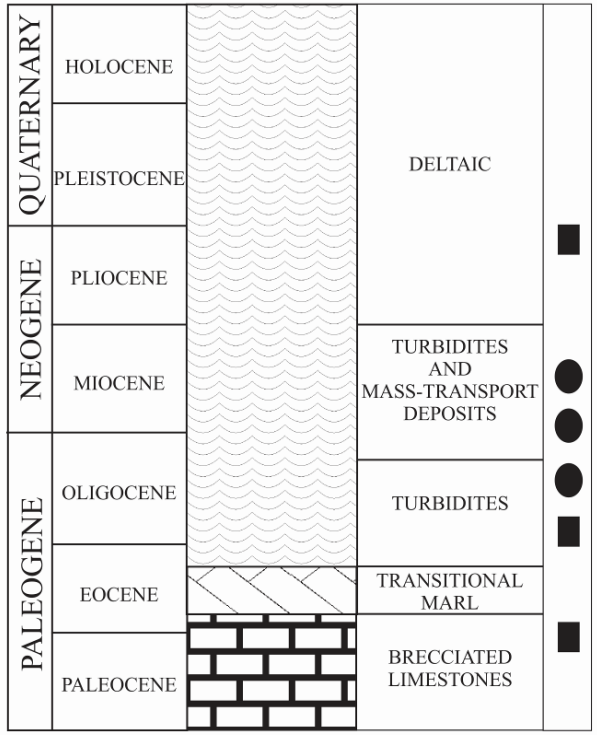
PRE APULIAN (OR PAXOI) ZONE

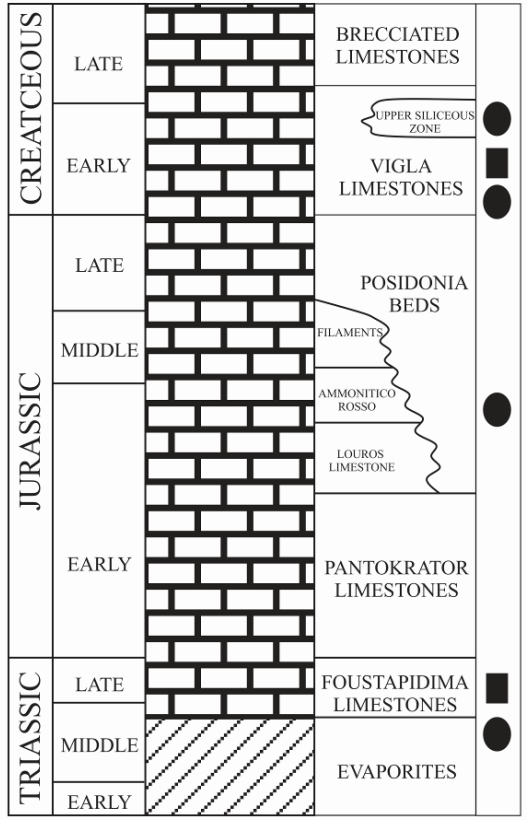
AGE		LITHOLOGY
QUATERNARY	PLEISTOCENE	Marine marls
NEOGENE	PLIOCENE	marine marls and sands
	MIOCENE	marls marly limestones, marls
PALEOGENE	OLIGOCENE	Often marly pelagic limestones with breccias, extensive hiatuses
	EOCENE	Pelagic limestones, breccias limestones
	PALEOCENE	
CRETACEOUS	LATE	Undifferentiated, brecciated upwards limestones which cherts, hiatuses
	EARLY	
JURASSIC	LATE	Limestones, marly limestones, marls, occasionally hiatuses
	MIDDLE	Limestones with cherts, marly limestones, marls, anhydrites
	EARLY	Limestones, dolomitic limestones, anhydrites, shale intercalations
TRIASSIC	LATE	evaporites, dolomites, shale intercalations
	MIDDLE	
	EARLY	????????

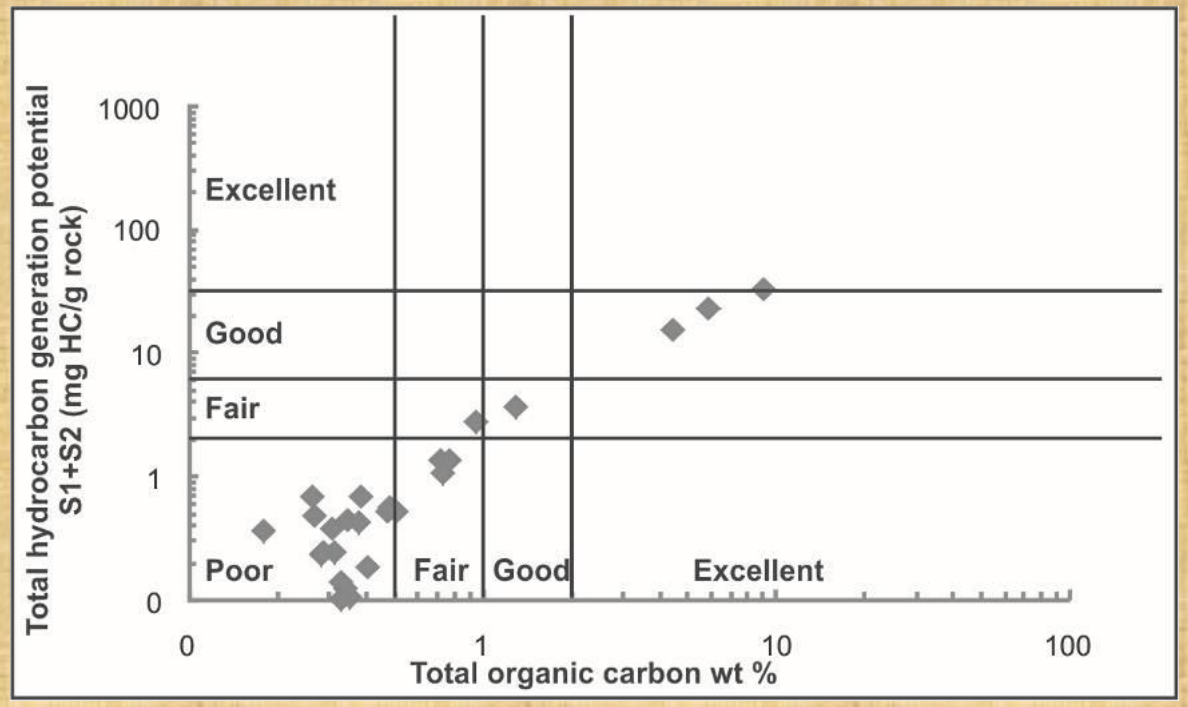
SOURCE ROCK CLASTICS CARBONATES

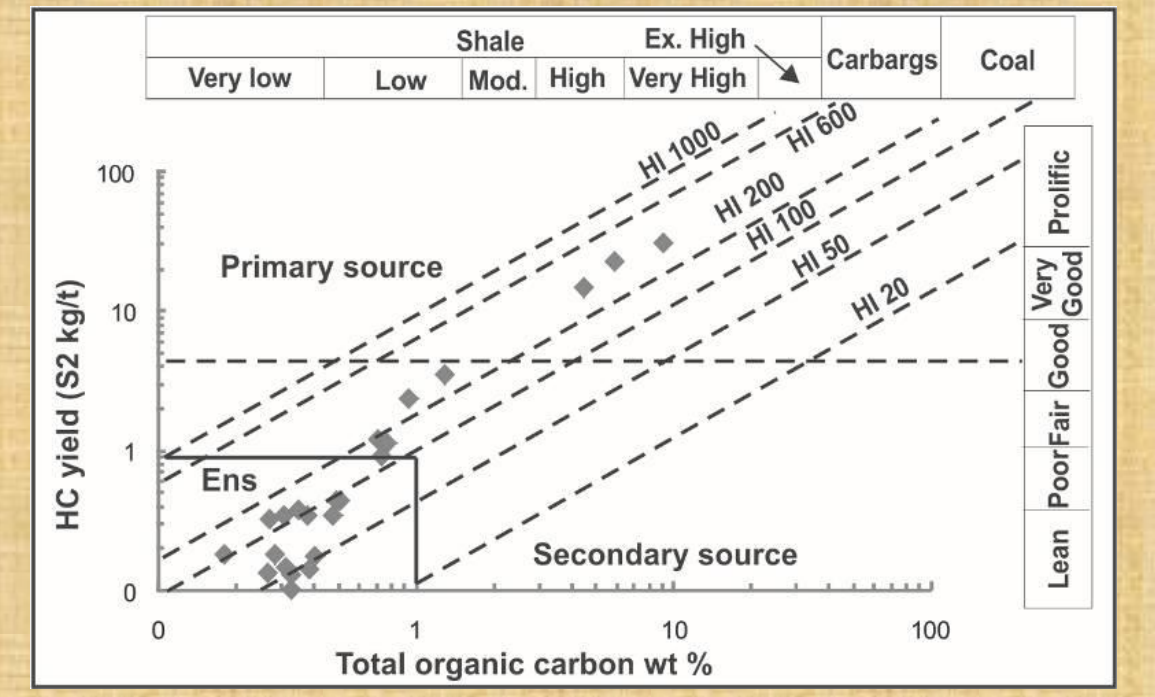
RESERVOIR ROCK TRANSITIONAL

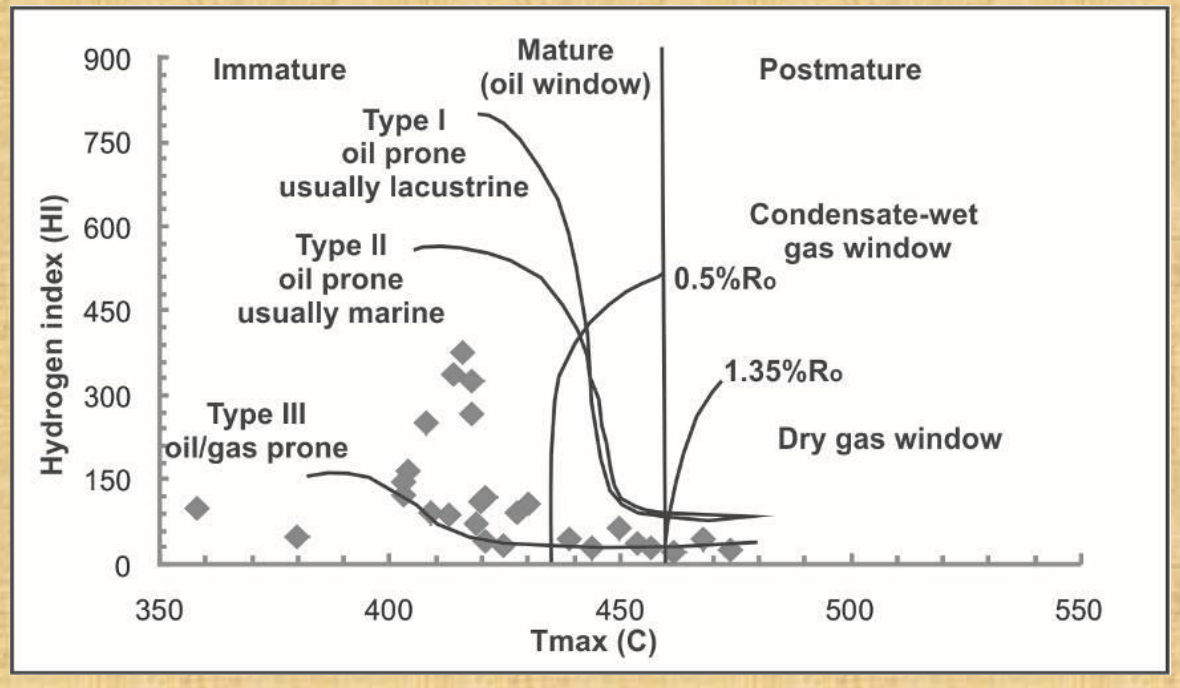
IONIAN ZONE

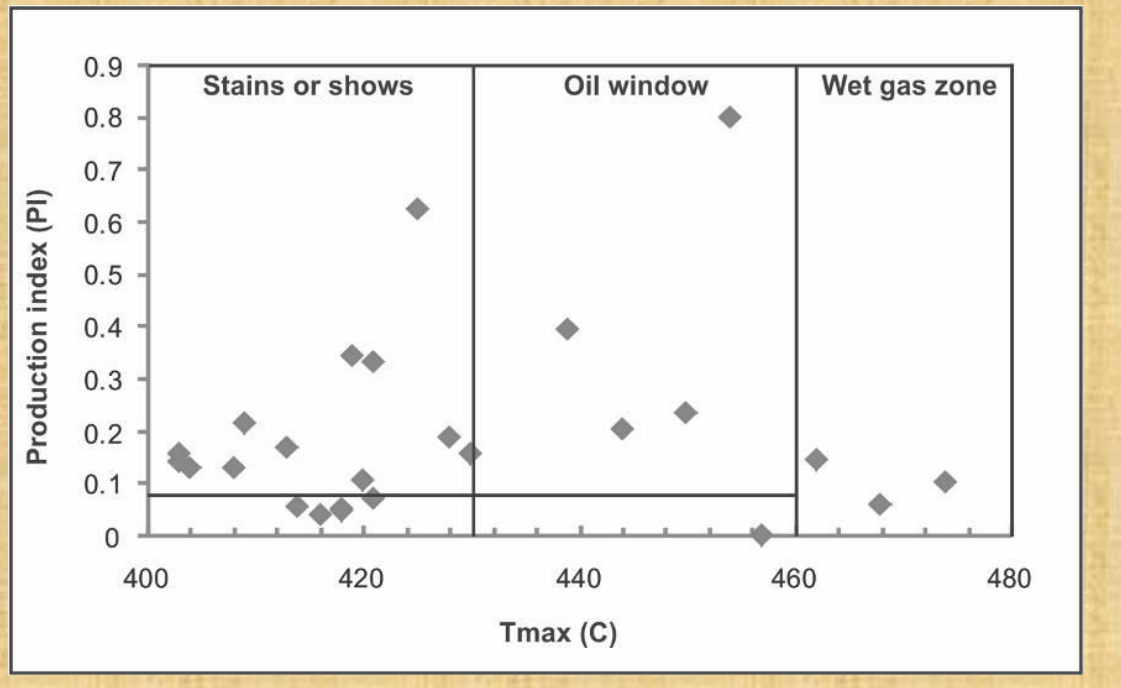


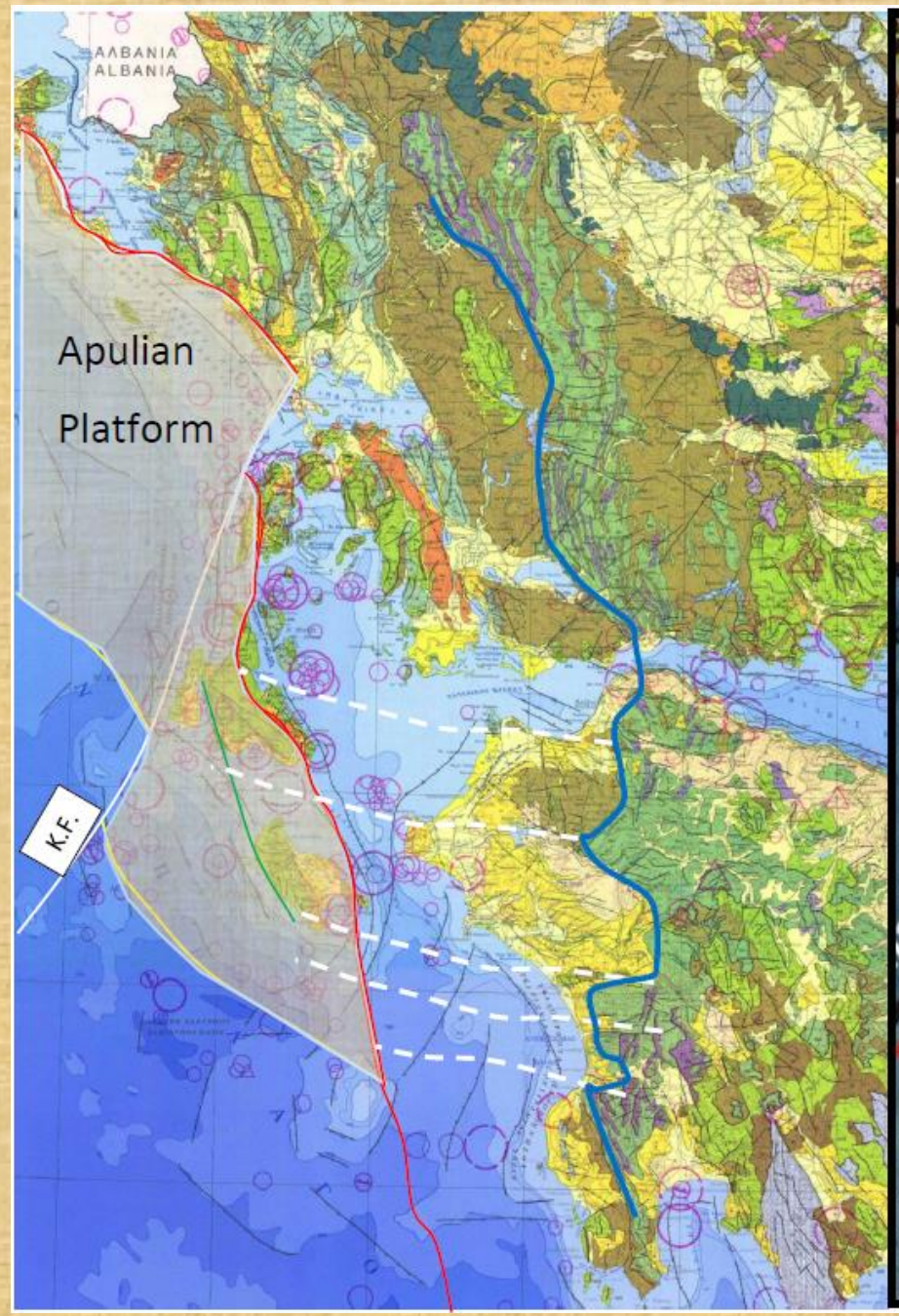


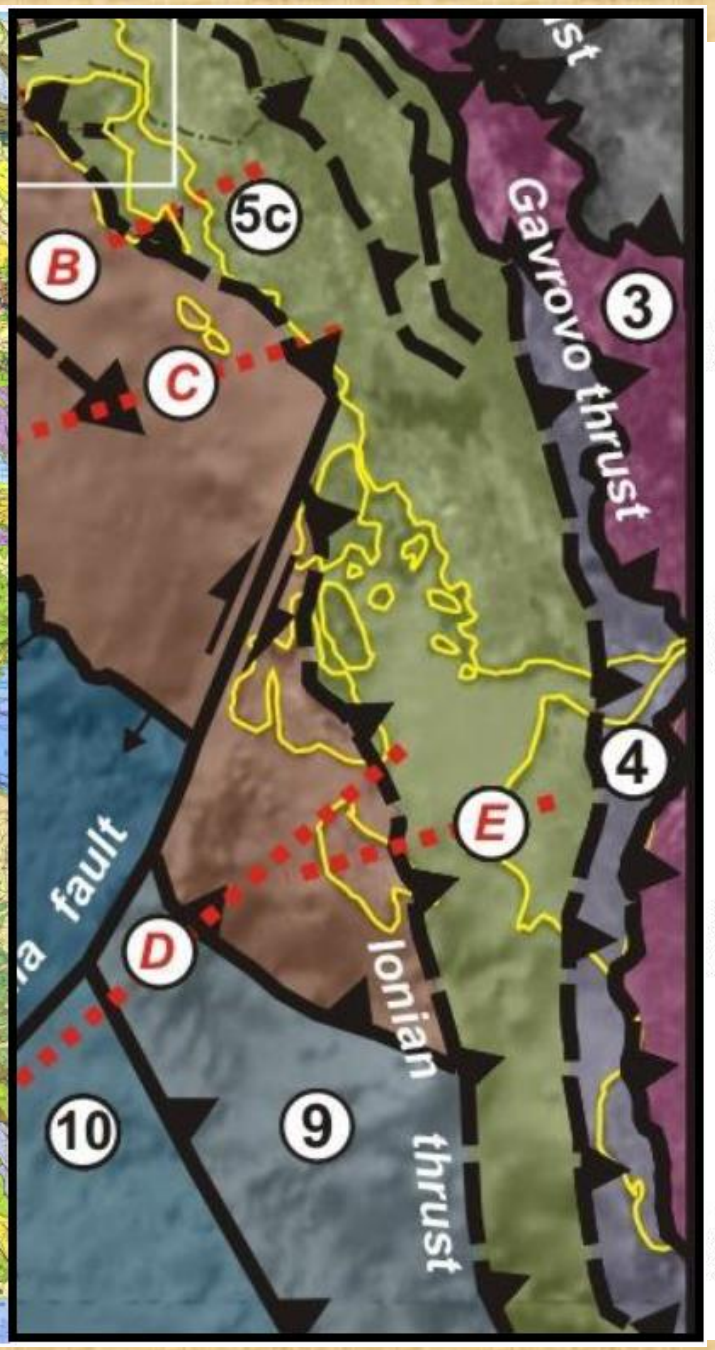

Total hydrocarbon generation potential
S1+S2 (mg HC/g rock)
1000
100
10
1
0
Excellent
Good
Fair
Poor
Fair
Good
Excellent
0
1
10
100
Total organic carbon wt %

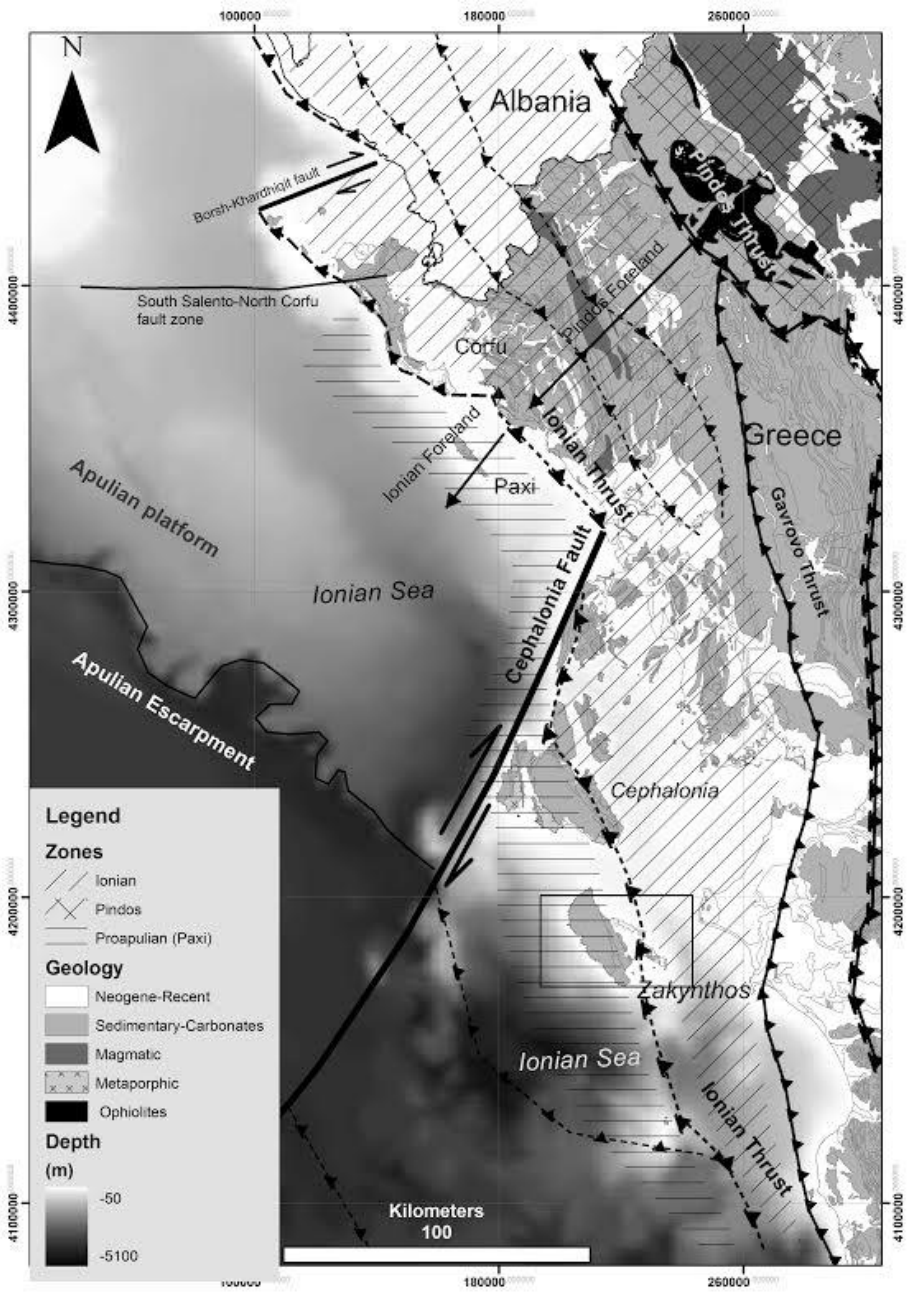

Shale
Ex. High
Very low
Low
Mod.
High
Very High
Carbargs
Coal
HI 1000
HI 600
HI 200
HI 100
HI 50
HI 20
100
10
1
0
HC yield (S2 kg/t)
Primary source
Ens
Secondary source
Prolific
Very Good
Good
Fair
Poor
Lean
0
1
10
100
Total organic carbon wt %


900
750
600
450
300
150
0
Hydrogen index (HI)
Immature
Mature
(oil window)
Postmature
Type I
oil prone
usually lacustrine
Type II
oil prone
usually marine
Type III
oil/gas prone
Condensate-wet
gas window
0.5%Ro
1.35%Ro
Dry gas window
350
400
450
500
550
Tmax (C)


0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Production index (PI)
Stains or shows
Oil window
Wet gas zone
400
420
440
460
480
Tmax (C)


ΑΛΒΑΝΙΑ
ALBANIA
Apulian
Platform
K.F.


5c
B
C
Gavrovo thrust
3
4
E
D
fault
Ionian thrust
10
9


N
100000
180000
260000
4400000
4300000
4200000
4100000
Albania
Borsh-Khardhiqi fault
Pindos Thrust
South Salento-North Corfu
fault zone
Corfu
Pindos Foreland
Greece
Ionian Foreland
Paxi
Ionian Thrust
Gavrovo Thrust
Apulian platform
Ionian Sea
Cephalonia Fault
Apulian Escarpment
Cephalonia
Zakynthos
Ionian Sea
Ionian Thrust
Legend
Zones
Ionian
Pindos
Proapulian (Paxi)
Geology
Neogene-Recent
Sedimentary-Carbonates
Magmatic
Metaporphic
Ophiolites
Depth
(m)
-50
-5100
Kilometers
100

Publications for this region from our lab

1. Kontopoulos, N., **Zelilidis, A.,** Piper, D.J.W. & Mudie, P.J. 1997: Messinian evaporites in Zakynthos, Greece. -*Palaeog., palaeocl., palaeoec*, 129, 361-367.

2. Zelilidis, A., Kontopoulos, N., Piper, D.J.W. & Avramidis, P. 1998: Tectonic and sedimentological evolution of the Pliocene-Quaternary basins of Zakynthos island, Greece: Case study of the transition from compressional to extensional tectonics. - *Basin Research*, 10, 393-408.

3. Zelilidis, A., Piper, DJW., Vakalas, J., Avramidis, P. & Getsos, K. 2003: Oil and gas plays in Albania: do equivalent plays exist in Greece? – *Journal of Petroleum Geology*, 26, 1, 29-48.

4. Kokinou, E., Kamberis, E., Vafidis, A., Monopolis, D., Ananiadis, G. & **Zelilidis, A.** 2005: Deep seismic reflection data from offshore western Greece: a new crustal model for the Ionian Sea. – *Journal of Petroleum Geology*, 28, 81-98.

5. Konstantopoulos, P. & **Zelilidis, A.** 2012: The geodynamic evolution of Pindos foreland basin in SW Greece: Tectonic and sedimentary evolution. *Episodes, v.35, no4, 501-512.*

6. Maravelis, A., Makrodimitras, G. & **Zelilidis, A.** 2012: Hydrocarbon prospectivity in western Greece. *Oil and Gas European Magazine*, 38, 2, 64-89.

7. Konstantopoulos, P. & Zelilidis, A. 2013: Sedimentation of submarine fan deposits in the Pindos foreland basin, from late Eocene to early Oligocene, west Peloponnesus peninsula, SW Greece. *Geological journal*, 48(4), 335-362.

8. Konstantopoulos, P. & Zelilidis, A., 2013: Provenance analysis of Eocene-Oligocene turbidite deposits in Pindos foreland basin, fold and thrust belt of SW Greece: Constraints from framework petrography and bulk-rock geochemistry. *Arabian Journal of Geosciences, 6(12), 4671-4700.*

9. Konstantopoulos, P., Maravelis, A. & Zelilidis, A. 2013: The implication of transfer faults in foreland basin evolution: Application on Pindos Foreland Basin, West Peloponnesus, Greece. *Terra Nova 25(4), 323-336.*

10. Maravelis, A., Makrodimitras, G., Pasadakis, N., & Zelilidis, A. (2014). Stratigraphic evolution and source rock potential of a Lower Oligocene to Lower–Middle Miocene continental slope system, Hellenic Fold and Thrust Belt, Ionian Sea, northwest Greece. *Geological Magazine, 151*(03), 394-413.

11. Mpotziolis, Ch., Kostopoulou, S., Triantaphyllou, M. & Zelilidis A. 2013. Depositional environments and hydrocarbon potential of the Miocene deposits of Zakynthos island. *Bull. Geol. Soc. Greece*, v. XLIII/.

Thank you for your attention