Fault geometry and kinematics of the broader Santorini area in relation to seismic activity and volcanism

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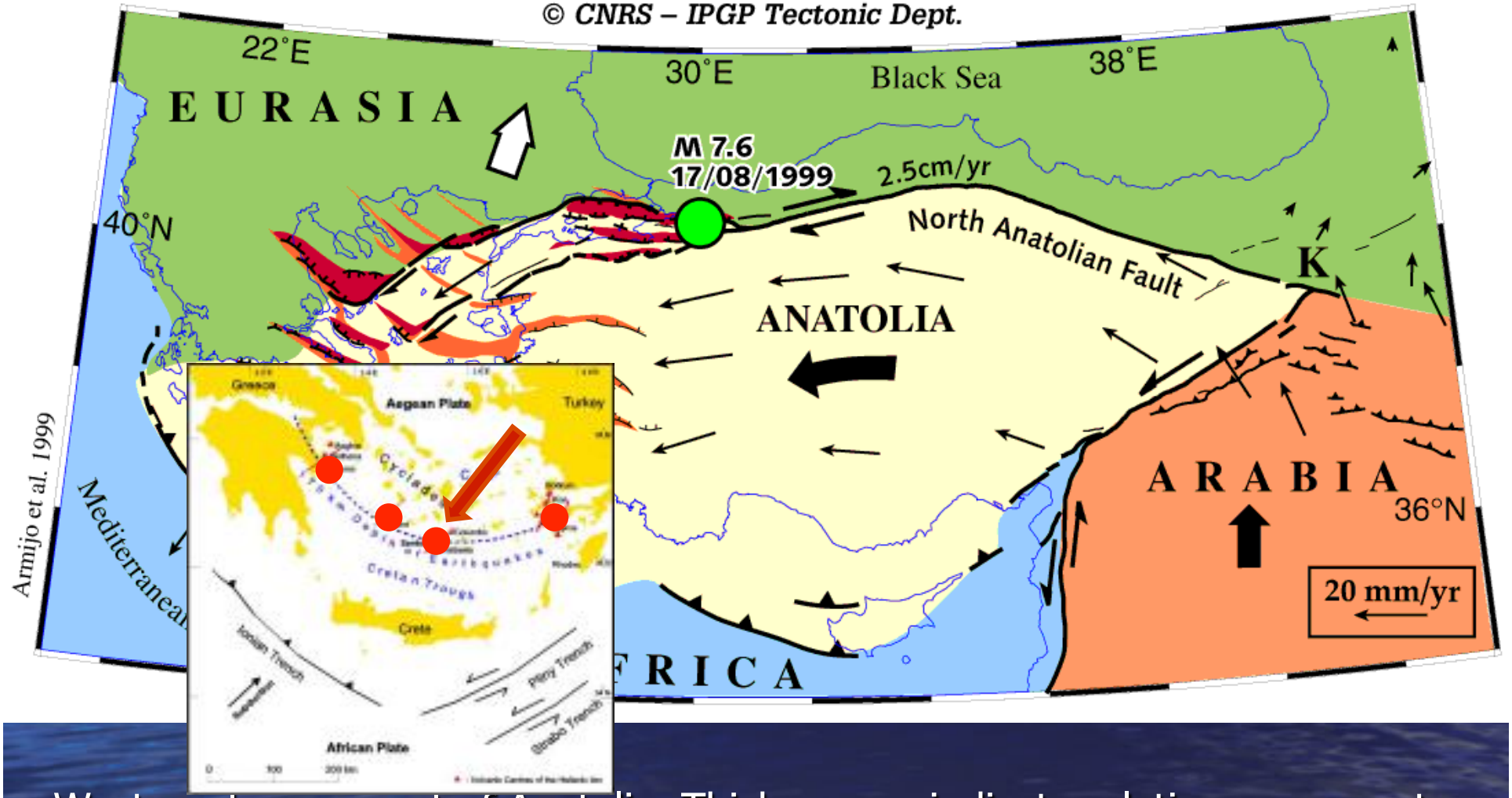
1866 eruption

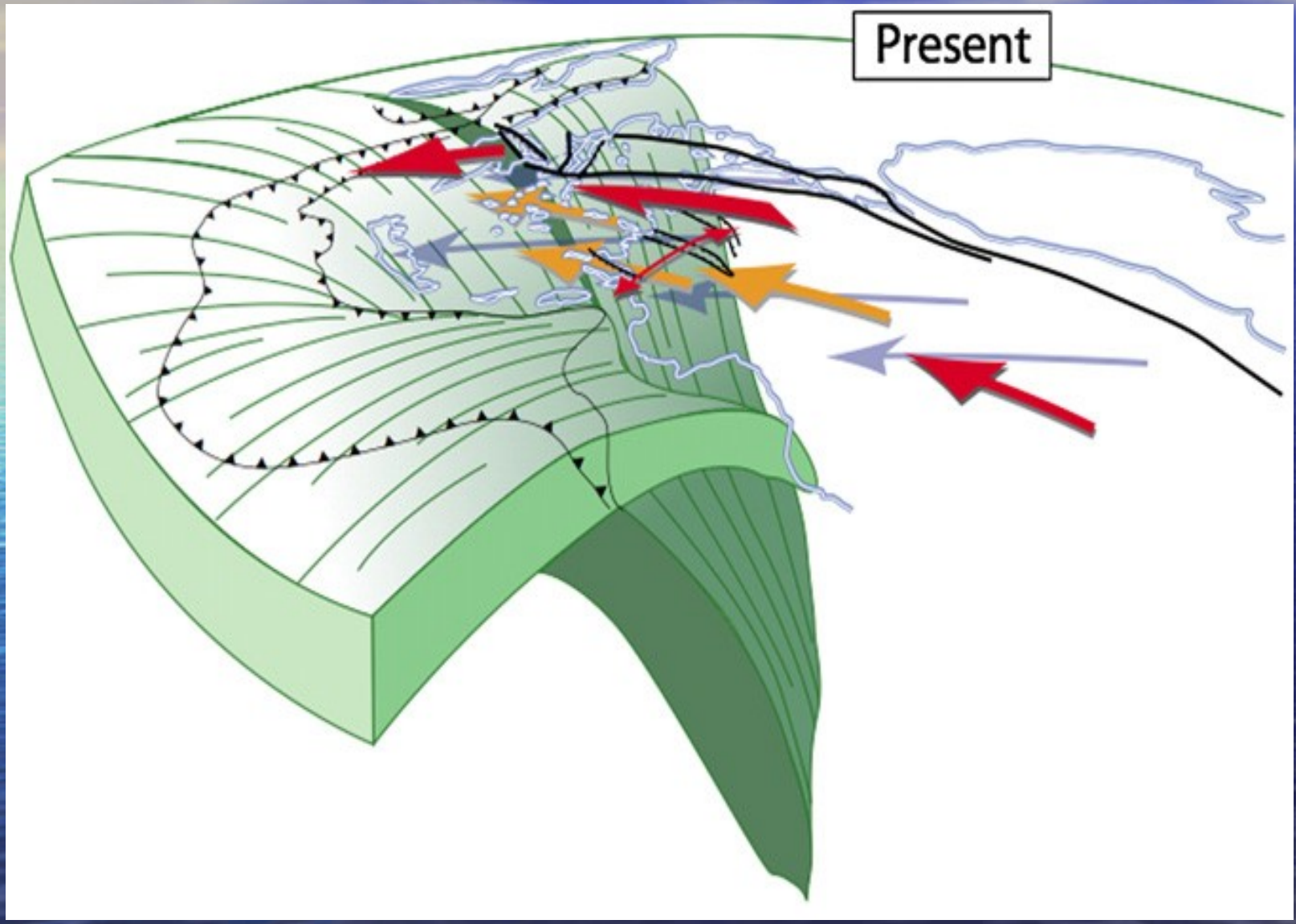
GEODYNAMIC MODEL OF ANATOLIA-AEGEAN (Armijo et al 1996)

The volcanic arc is about 500 km long and 20 to 40 km wide and extends from the mainland of Greece through the islands of Aegina, Methana, Poros, Milos, Santorini, Kos, Yali, Nisyros and the Bodrum peninsula in Turkey

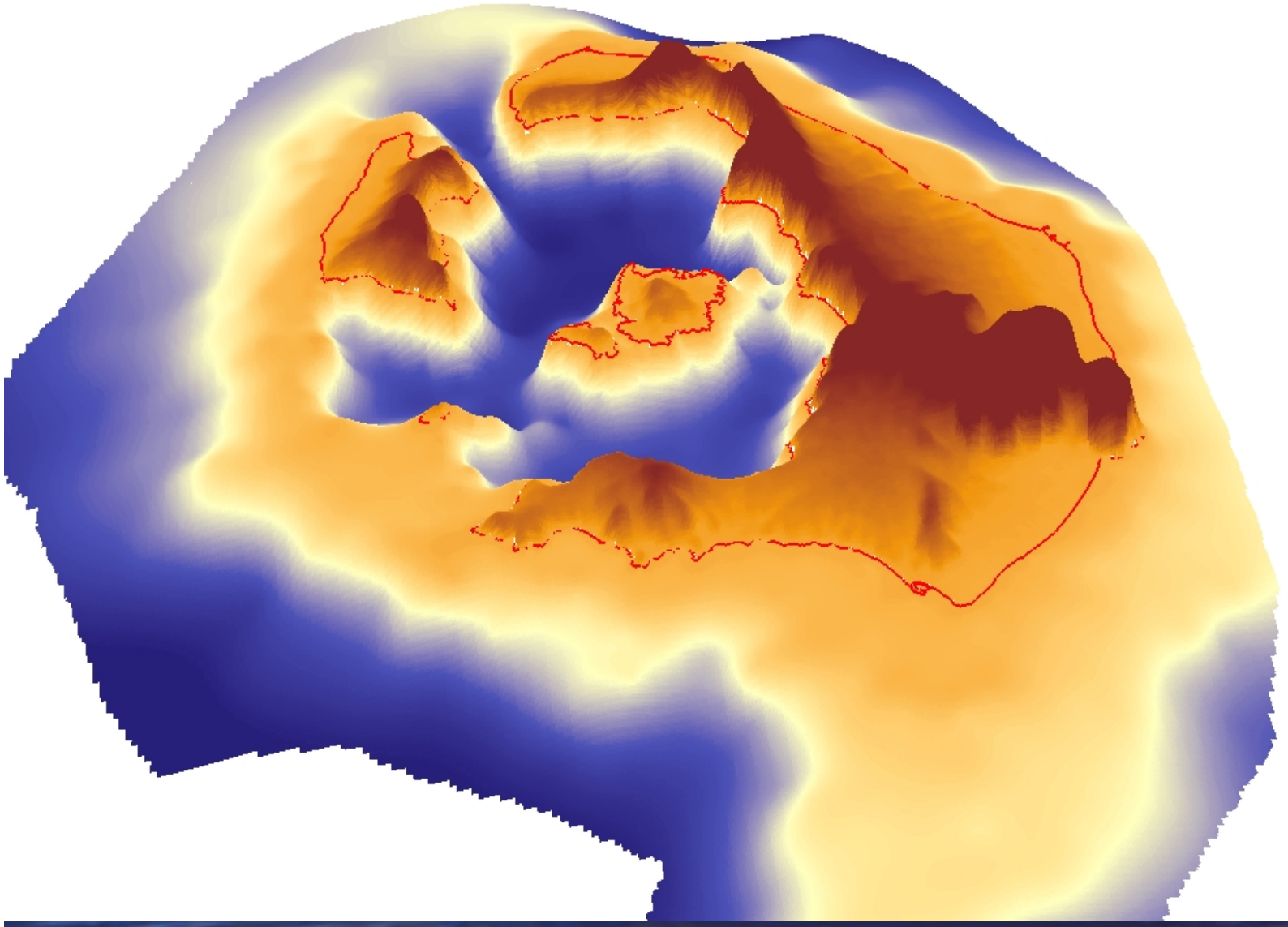


Westward movement of Anatolia. Thick arrows indicate relative movements, while thin ones indicate displacement vectors. (Armijo et al., 1996)

SUBDUCTION
African Plate beneath Aegean

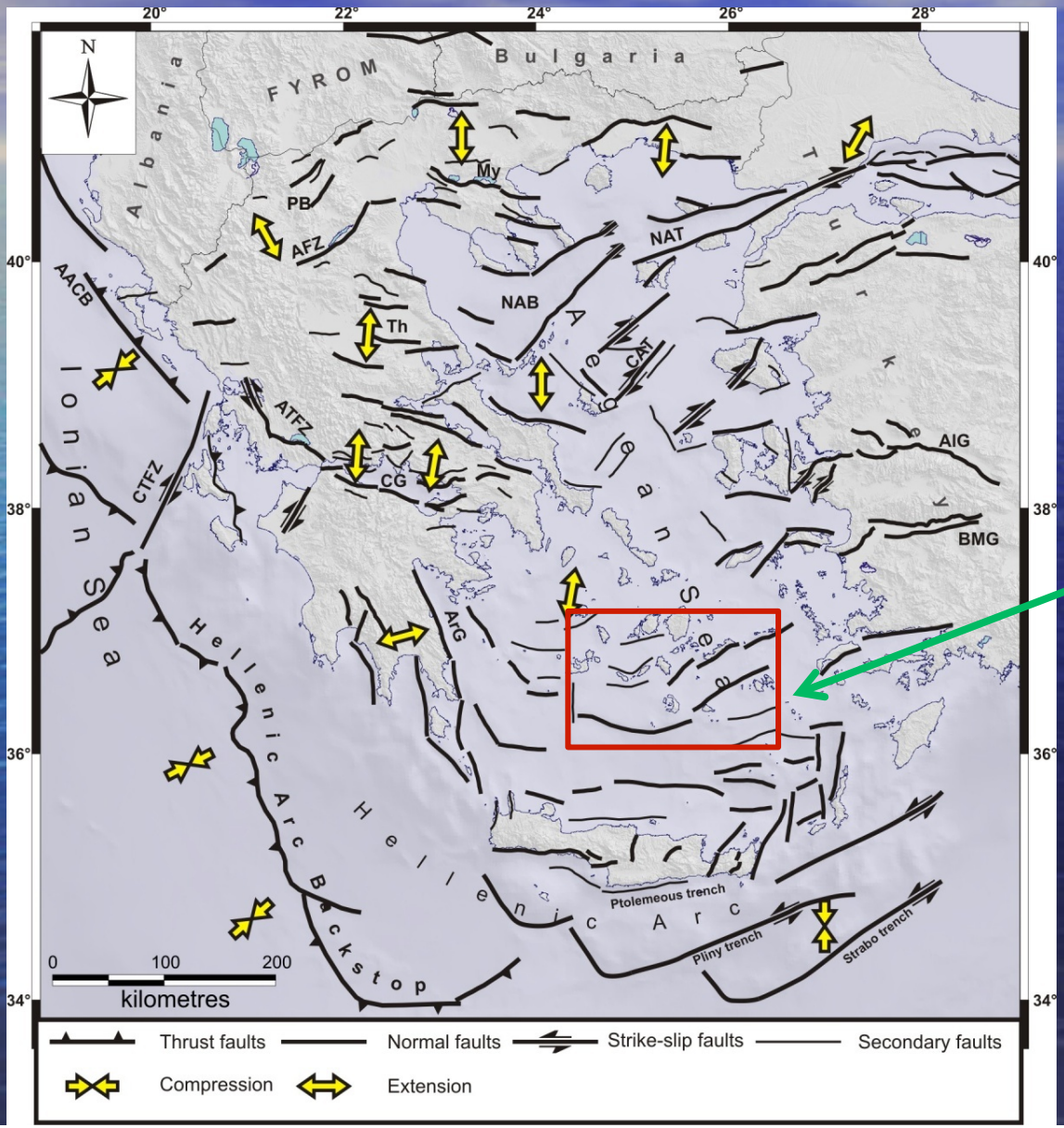


Jolivet et al 2012

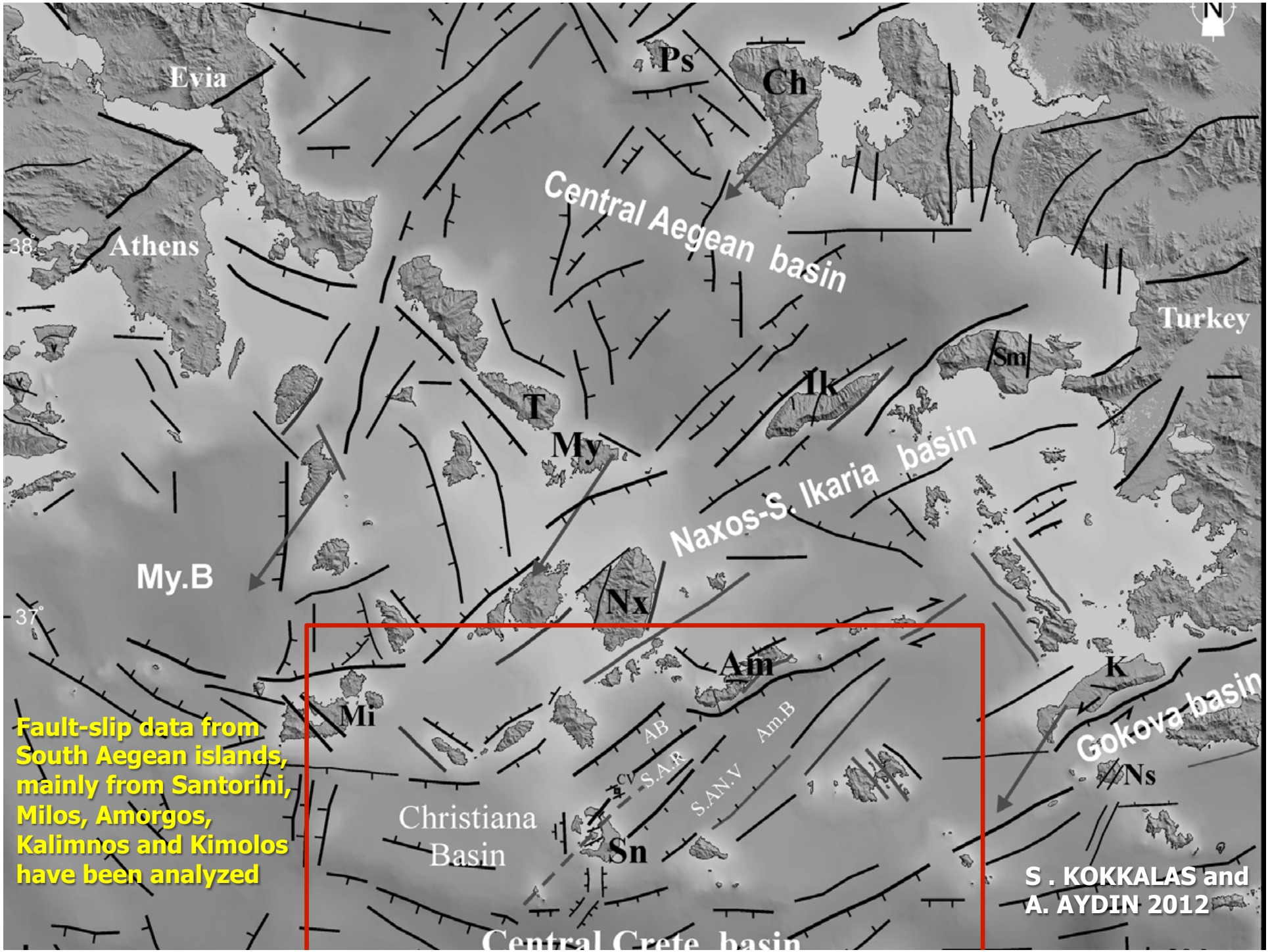


The new DEM of Santorini Volcano edifice, created by ASTER/GDEM (land), sea-floor topographic map (sea-floor depth) and Google Earth (present shoreline).

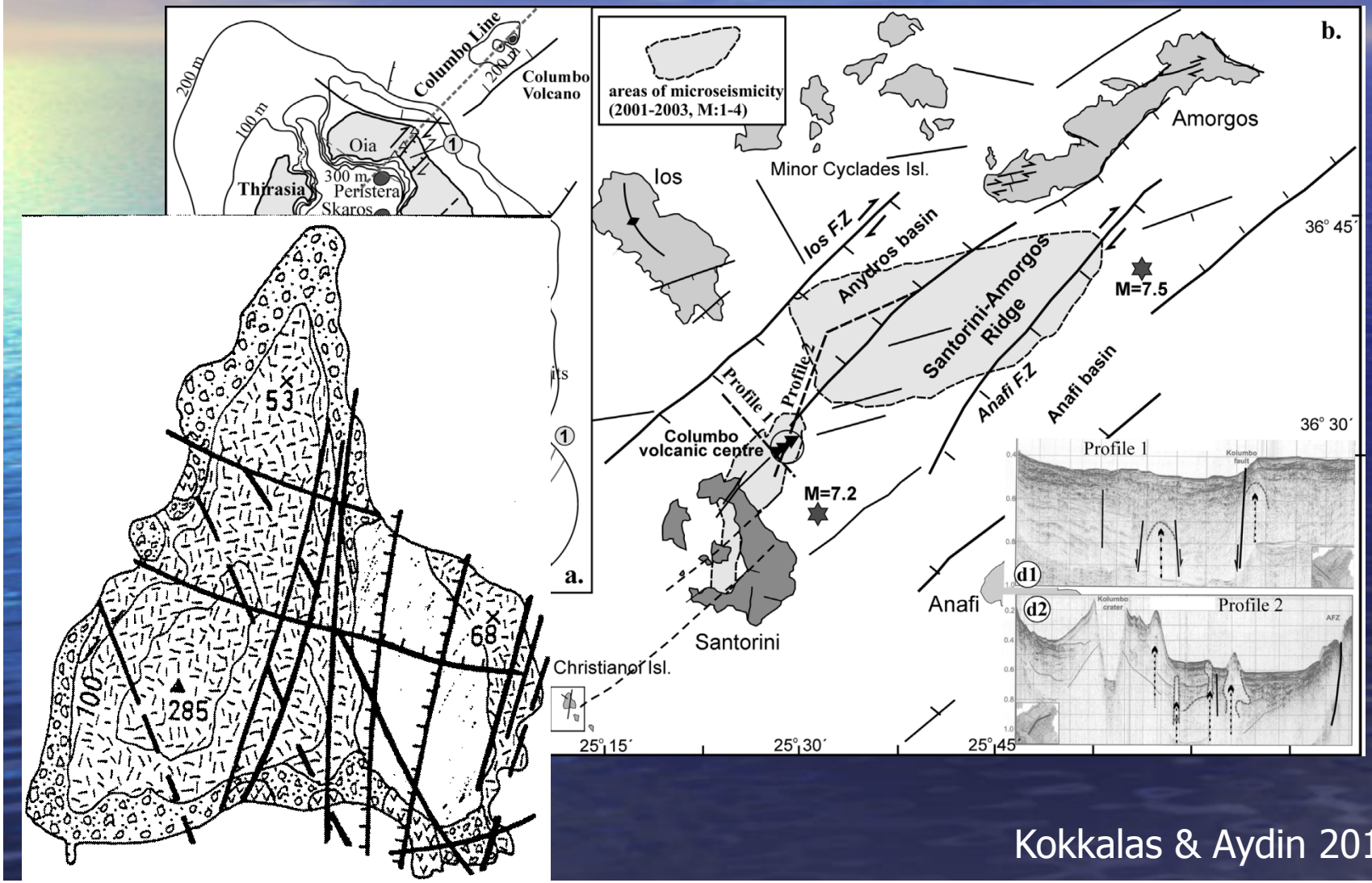
N-S trending σ3 axis in the Aegean region



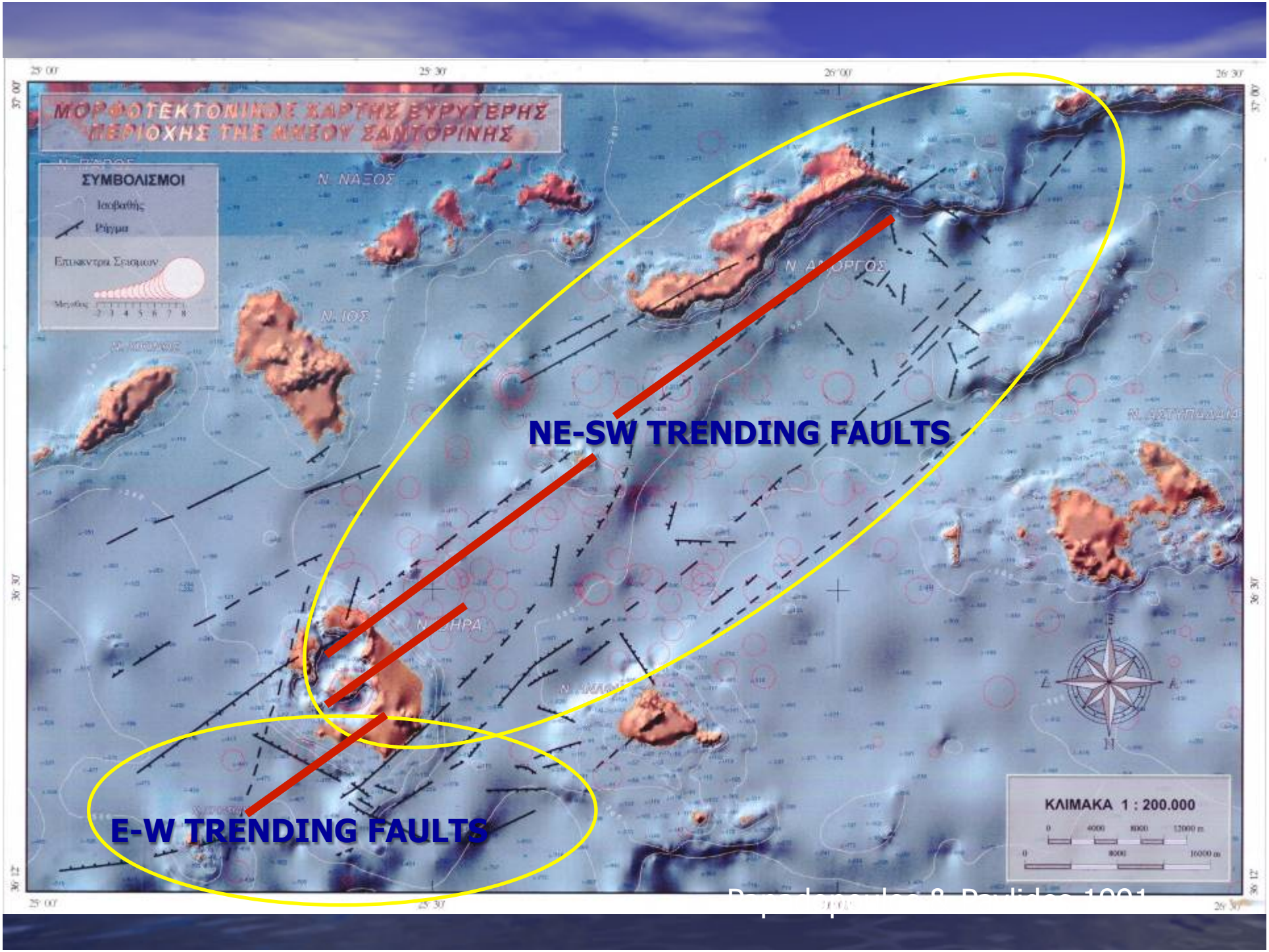
STUDY AREA


Evia
Ps
Ch
Central Aegean basin
38°
Athens
Turkey
Sm
Ik
T
My
Naxos-S. Ikaria basin
My.B
Nx
37°
Am
K
Mi
AB
Am.B
CV
S.A.R
S.AN.V
Gokova basin
Ns
Christiana
Basin
Sn
Central Crete basin
Fault-slip data from
South Aegean islands,
mainly from Santorini,
Milos, Amorgos,
Kalimnos and Kimolos
have been analyzed
S . KOKKALAS and
A. AYDIN 2012

(a) Simplified tectonic map of the Santorini volcanic centre showing the distribution of dacite domes, cinder cones and submarine volcanoes with regard to the volcano-tectonic lineaments. Stereonet 1 displays fault slip data in the northern part of the island close to the Columbo line. (b) Map of the Santorini–Amorgos Fault Zone. Areas of higher earthquake activity (microseismicity) are marked by the two light grey shaded areas with dashed outline. (c) Inset shows fault pattern in the Christianoi Islands (modified from Mountrakis *et al. 1998). (d1) Seismic reflection profile (profile 1 on* map) across the Columbo submarine volcano (taken from Sakellariou *et al. 2010). (d2) Composite seismic profile (profile 2 on map) along the Columbo volcano and Anydros basin (from Sakellariou et al. 2010). The bright spot area below volcano caldera suggests the presence of fluids or gas about 200 m beneath the caldera.*

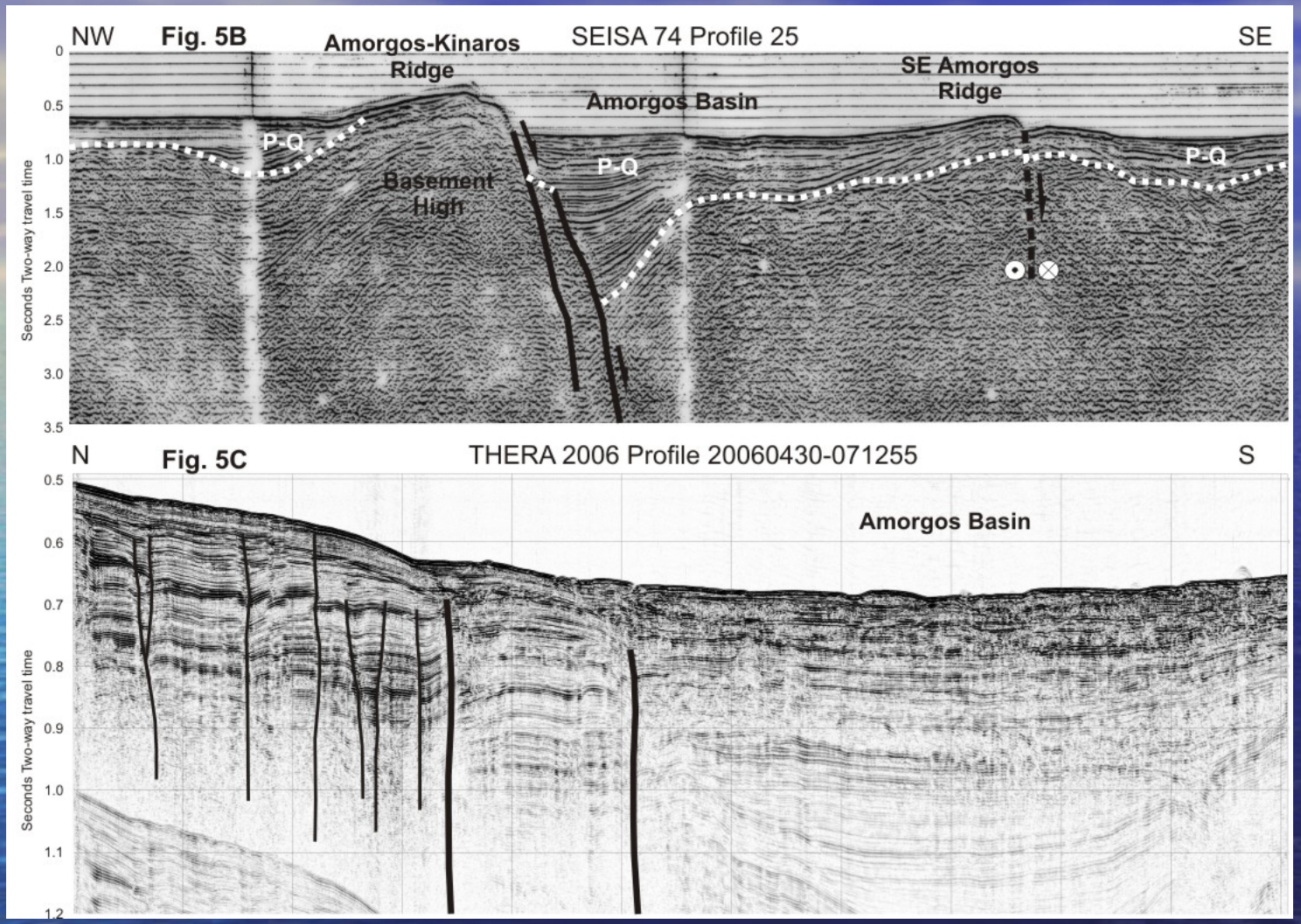


Kokkalas & Aydin 2012

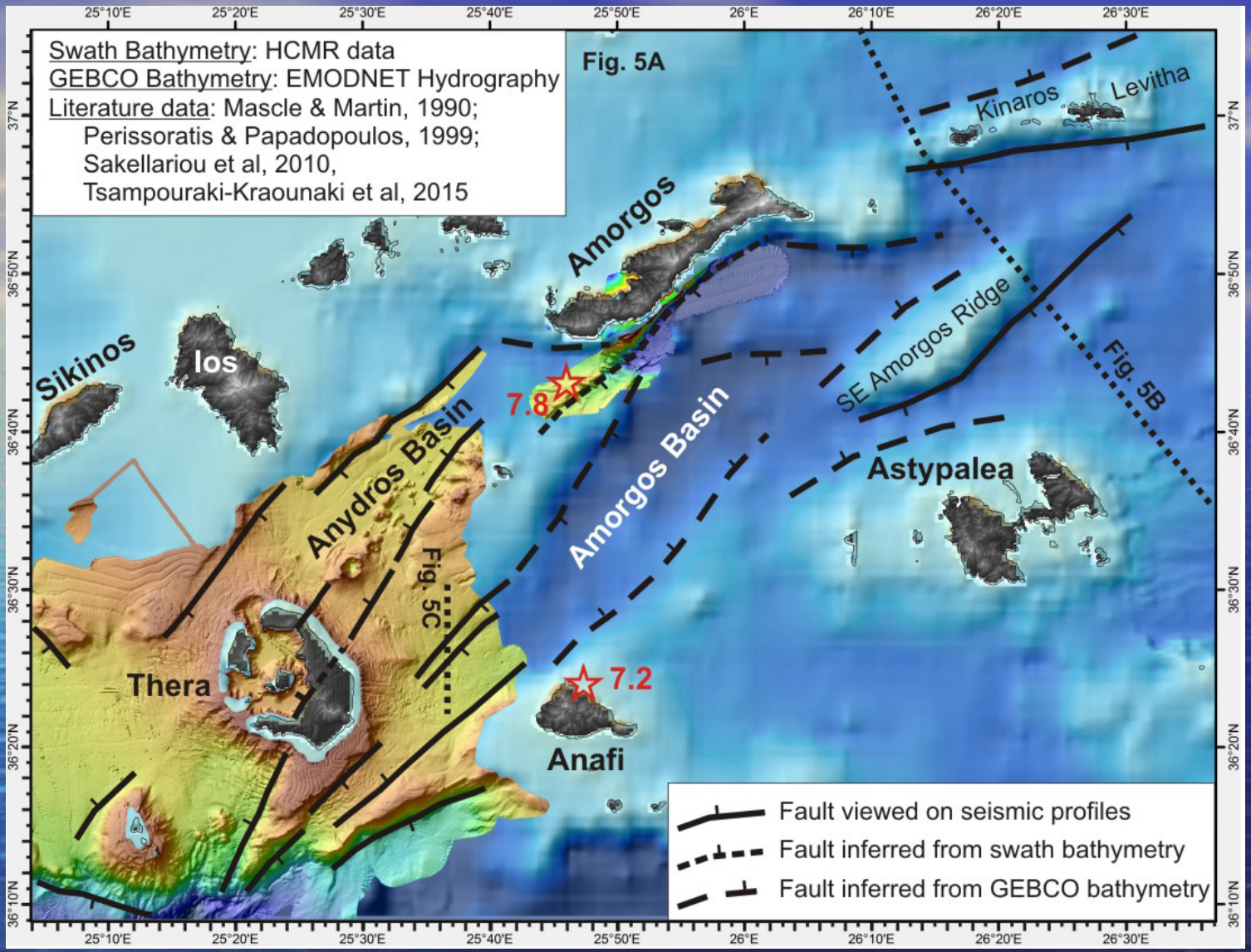

ΜΟΡΦΟΤΕΚΤΟΝΙΚΗ ΧΑΡΤΗΣ ΕΥΡΥΤΕΡΗΣ ΠΕΡΙΟΧΗΣ ΤΗΣ ΝΗΣΟΥ ΣΑΝΤΟΡΙΝΗΣ
ΣΥΜΒΟΛΙΣΜΟΙ
Ισοβαθής
Ρήγμα
Επικεντρα Σεισμων
Μεγεθος
Ν. ΝΑΞΟΣ
Ν. ΙΟΣ
NE-SW TRENDING FAULTS
E-W TRENDING FAULTS
ΚΛΙΜΑΚΑ 1 : 200.000
25° 00'
25° 30'
26° 00'
26° 30'
37° 00'
36° 30'
36° 12'

AMORGOS fault

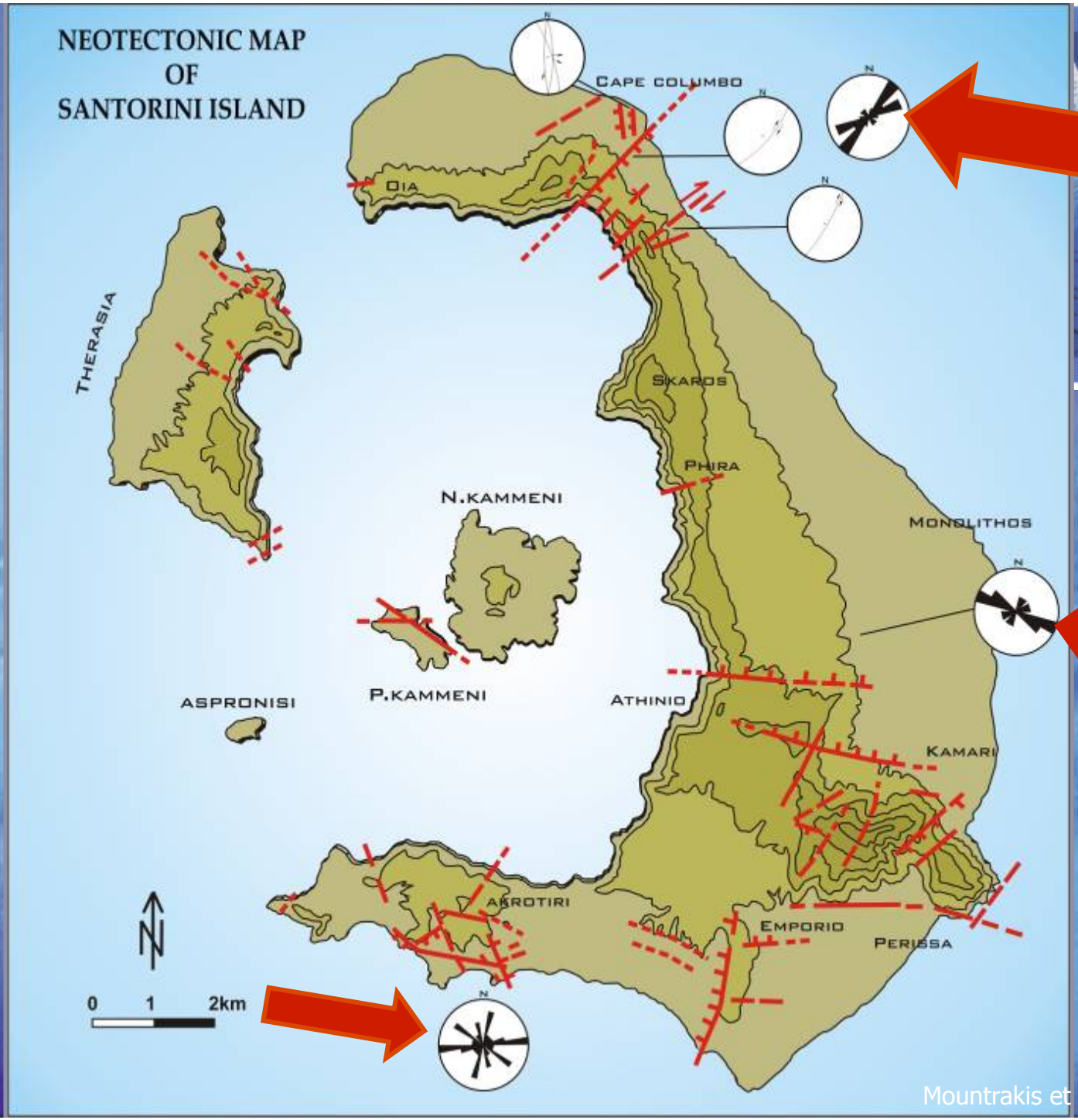
Hozoviotissa monastery on the fault surface (wall)



SEISA multi-channel Line 25 (Mascle & Martin, 1990).
C: Single channel HCMR profile (Sakellariou et al, 2010).



DEM and faults of Santorini-Amorgos area. Red stars show the epicenters of the 1956 Amorgos earthquakes. (*Sakellariou D and Tsampouraki-Kraounaki 2016*)



Submarine Columbo volcano

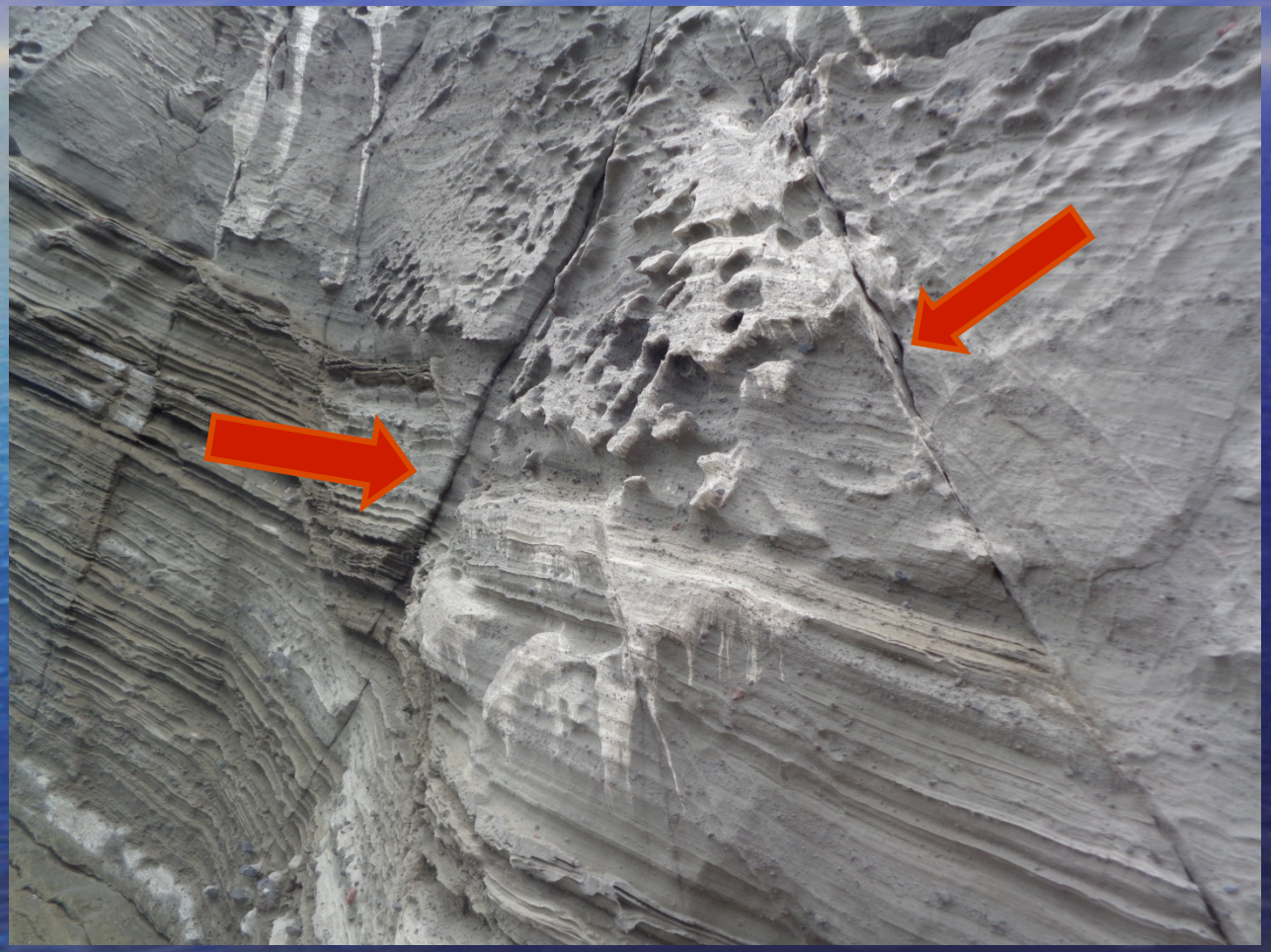
Three-dimensional model of he current morphology of the Kolumbo volcano

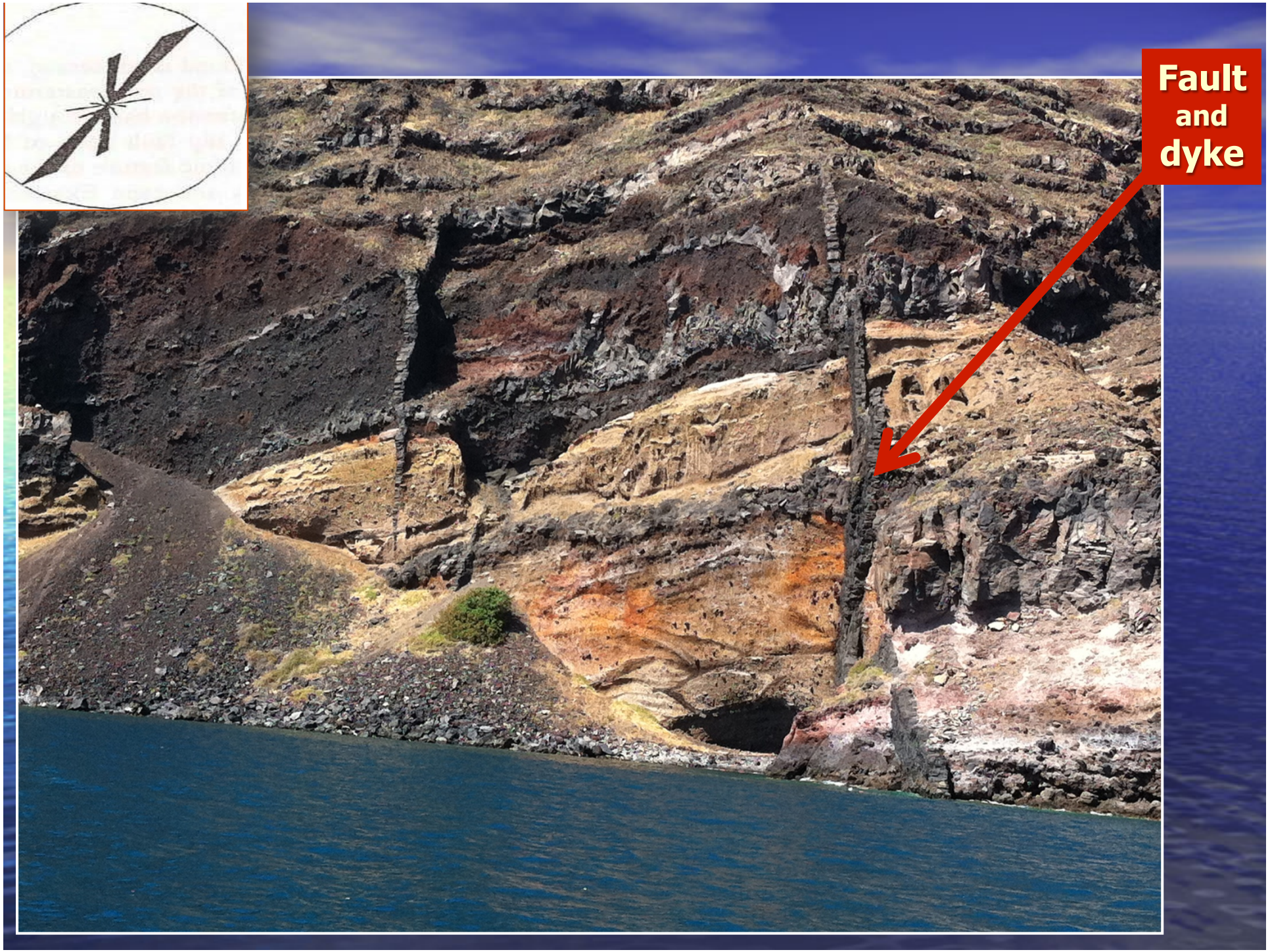
500 m-deep crater, 18 m below sea level

Santorini, Thera or Strogyle island complex

Mountrakis et al., 1995

Columbo conjugate normal faults

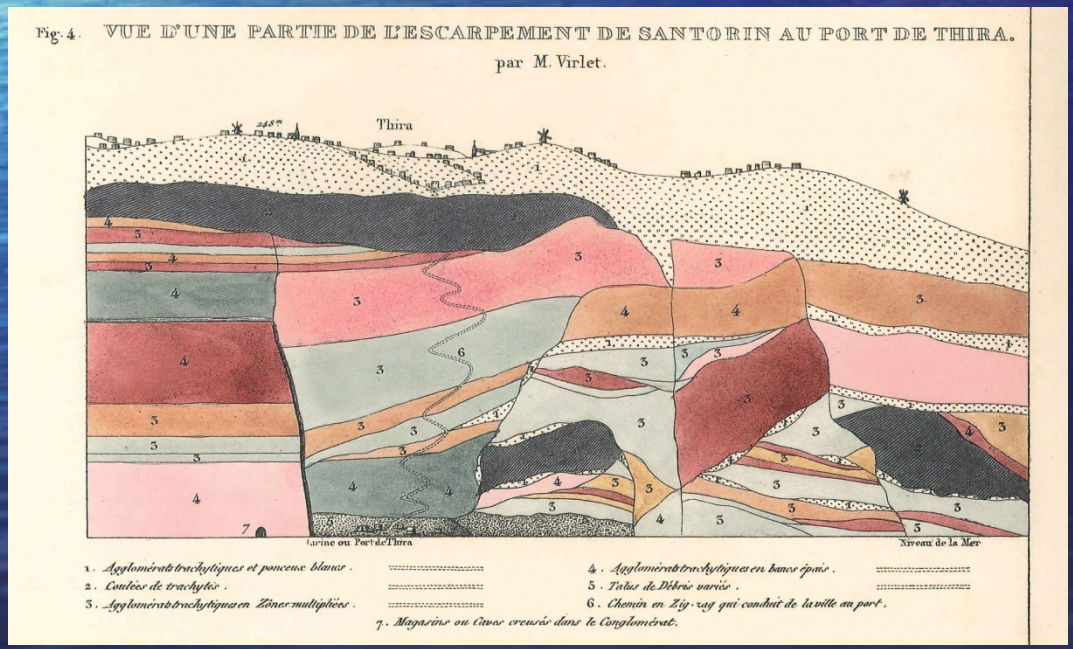


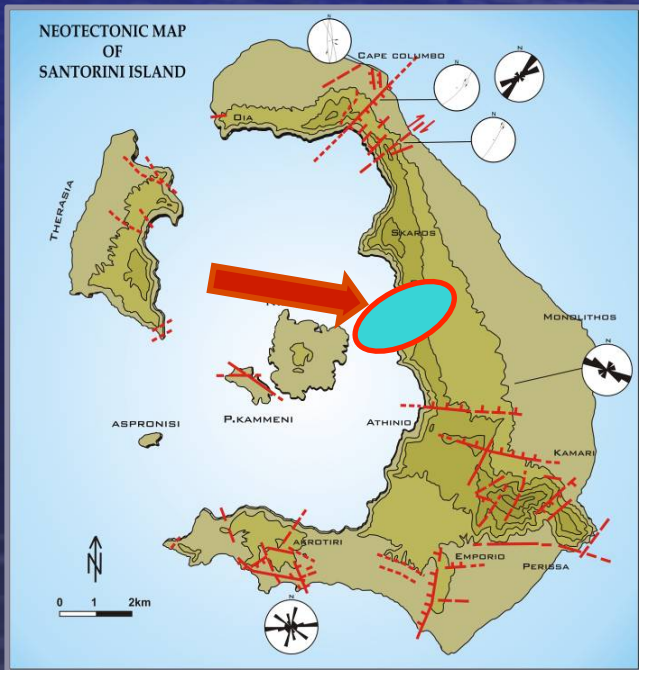

Fault
and
dyke

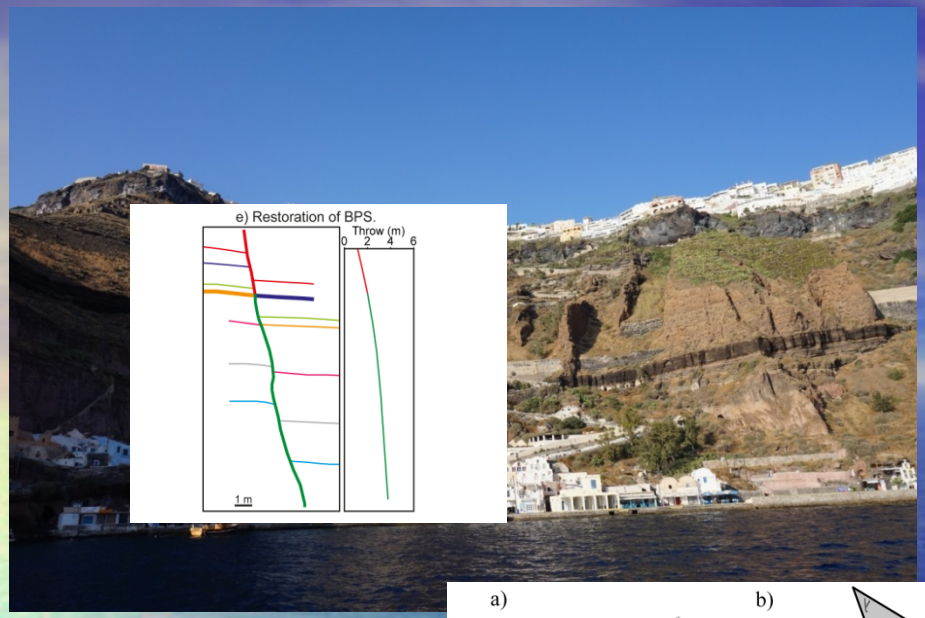

NE-SW trending FAULTS and DYKES
Fault and dyke
Fault

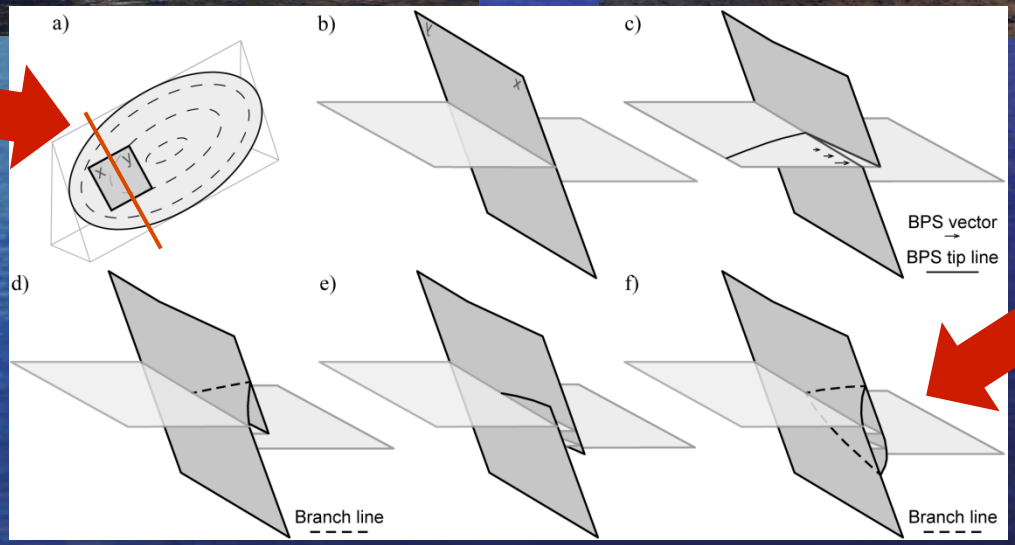
The Fira fault

hrough the France expedition de Moree (1829-38) to modern scientific approach.





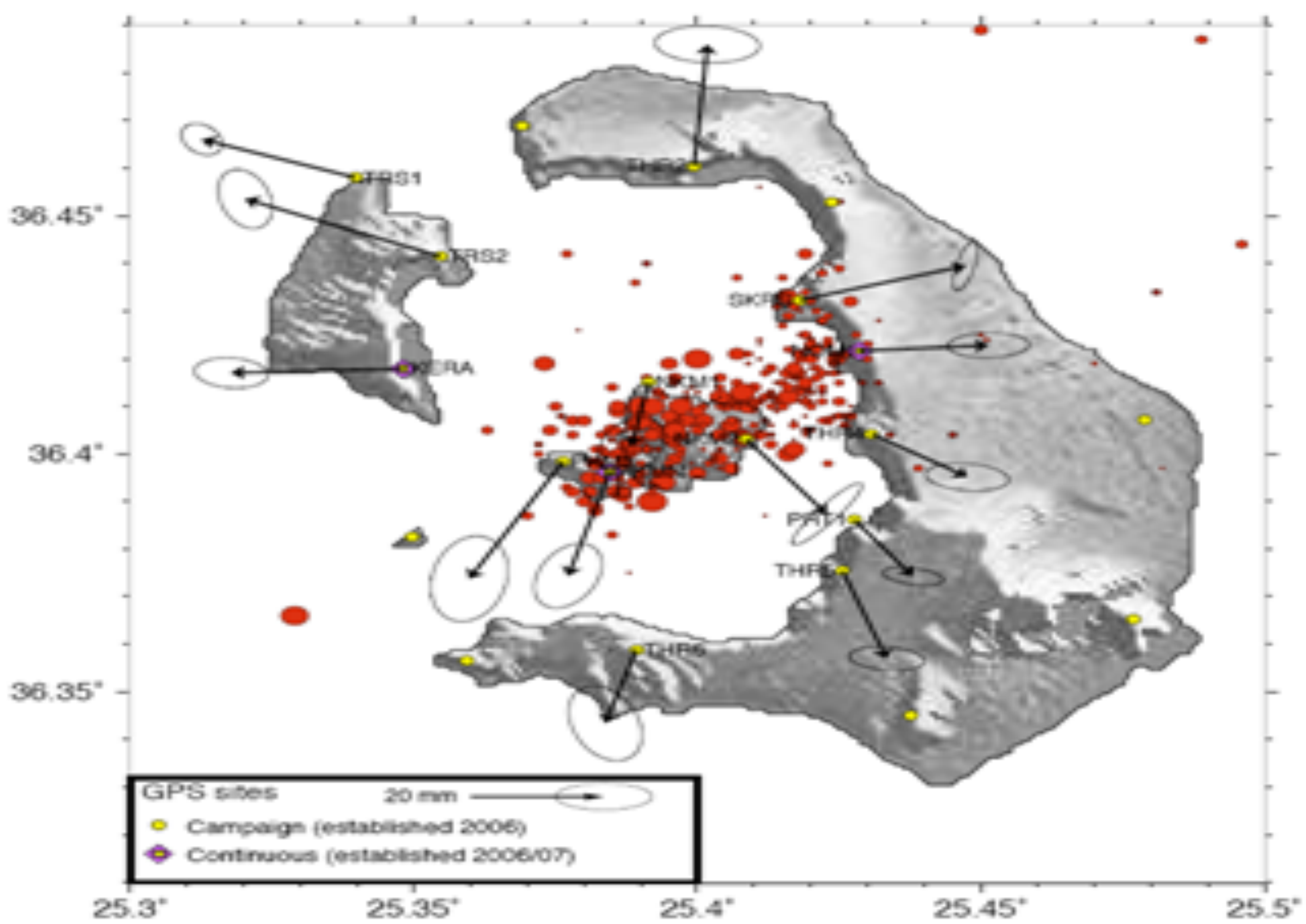




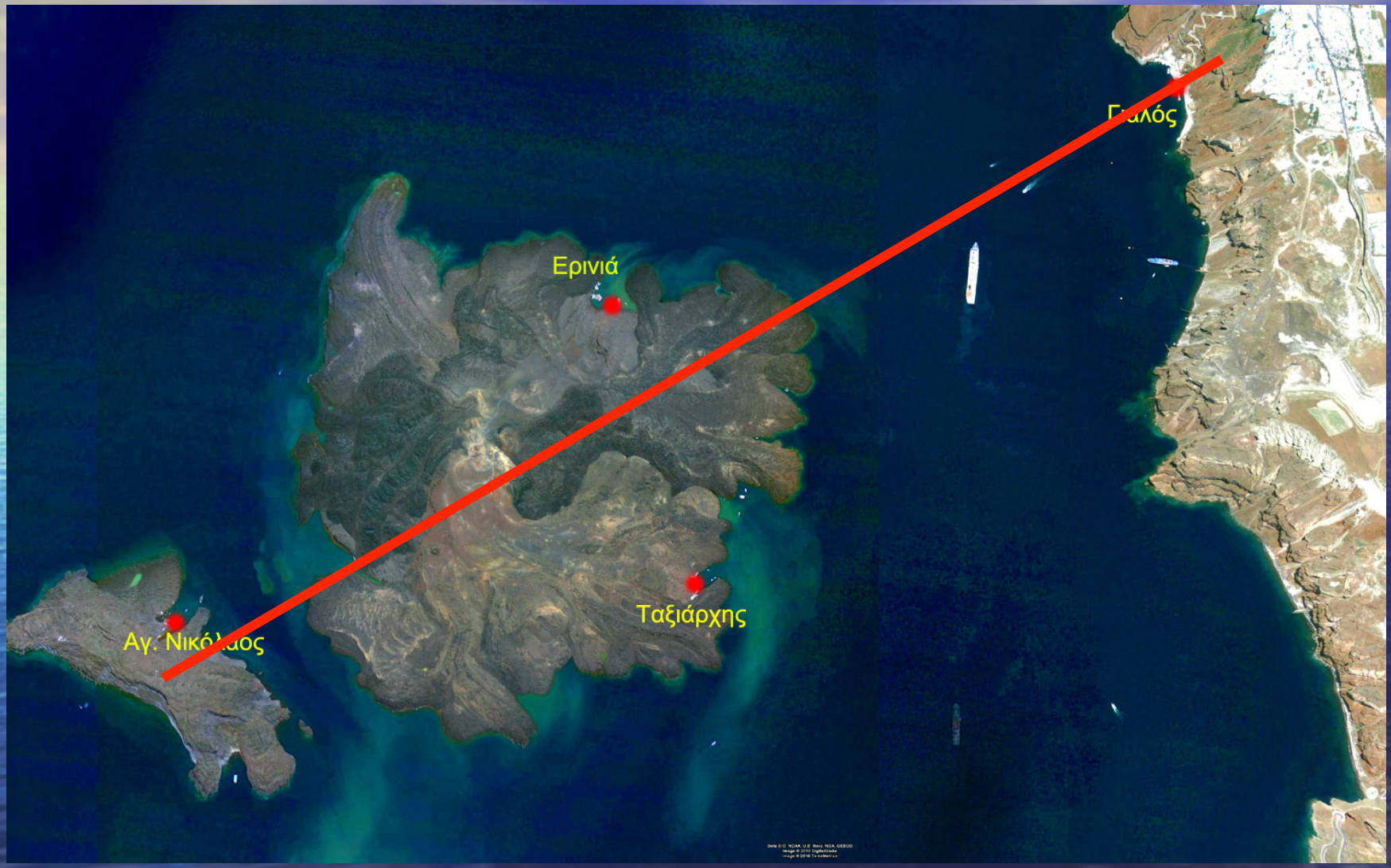
a) An ideal elliptical normal fault surface showing fault displacement contours (dashed lines) and tip-line (solid line), in propagation of both fault segment and the formation of a relay zone which with increased displacement the two fault segments form a fault bounded lens (f) encloses a repeated part of the sequence, within an otherwise continuous fault surface.

- The Fira (Phera) fault is a Normal Fault trending ENE-WSW.
- It is a “segment” of subparalle structures of a longer “fault zone”, including the known volcanic centers and the 1956 earthquake great Amorgos-Thera fault.
- It shows gradually smaller Displacement from the see level to top lava layer (*Nomikos Conference Center*). Syn-volcanic fault growth.
- It’s internal structure is complex (*under investigation*).
- It’s known fault length corresponds to weak or moderate earthquake.

Projected displacement field from 2010–2011 GPS campaigns



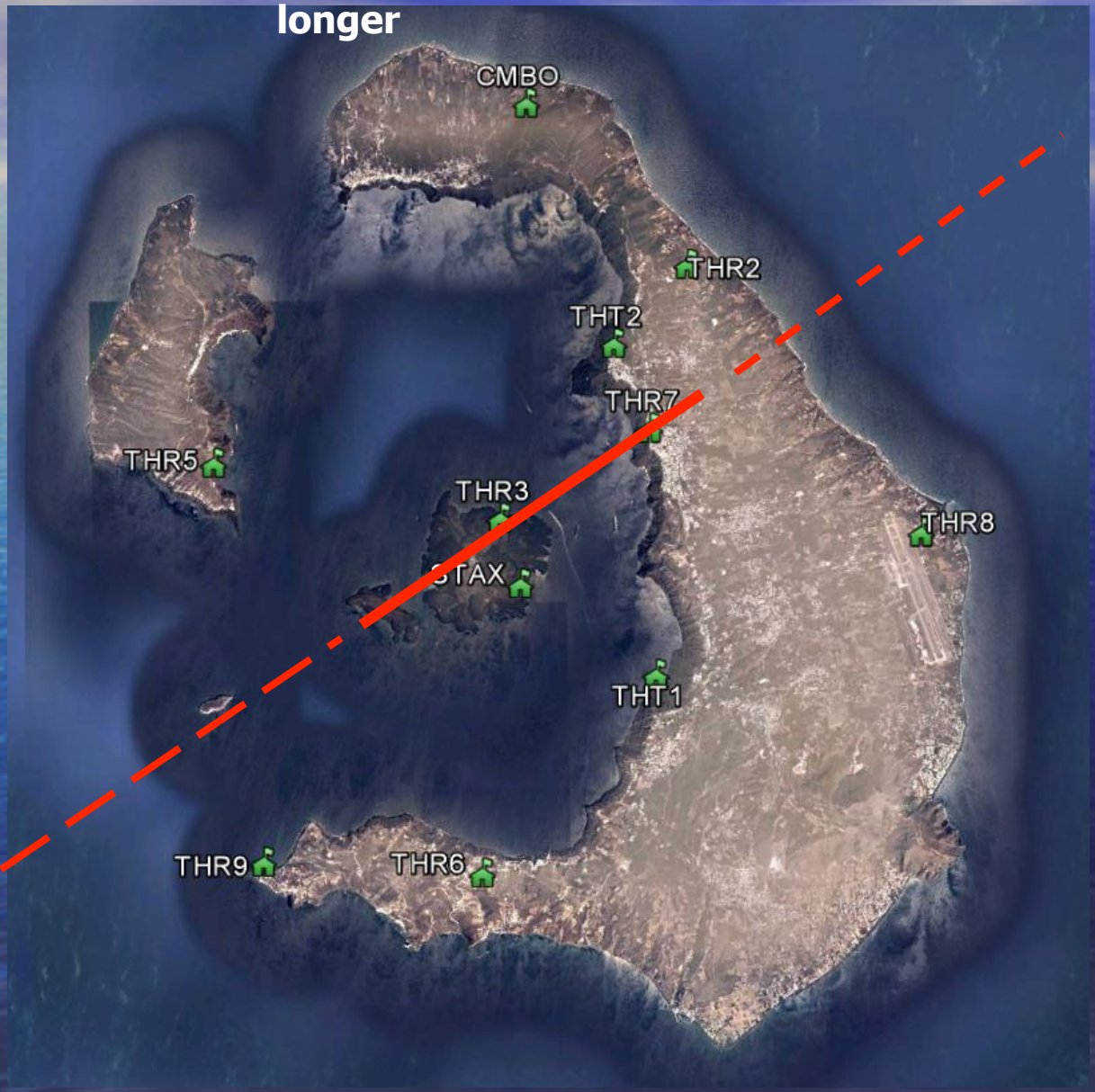
Known fault length (seismogenic segment) ~6 km



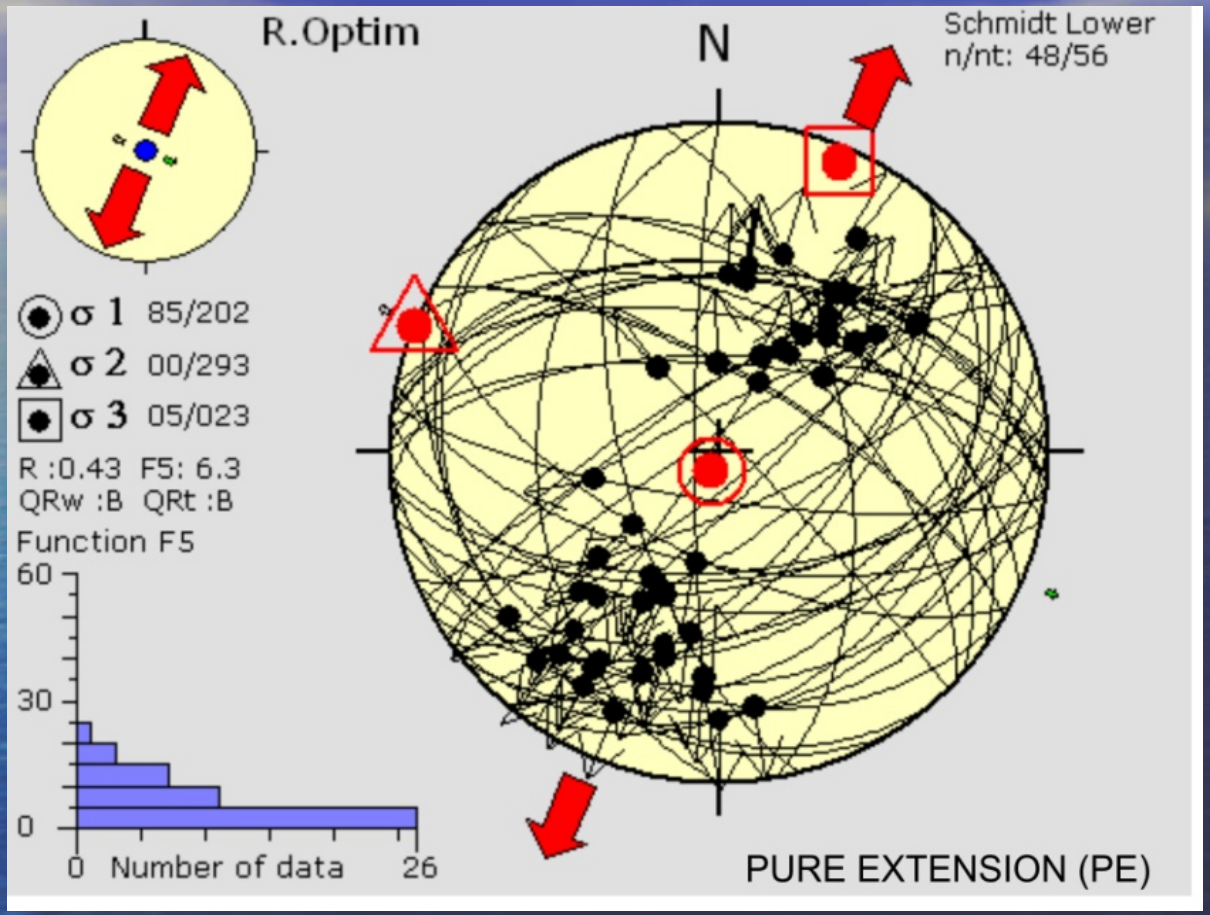
FAULT LENGTH

Known : **5 - 6 km**

Unknown : 6+5+5 = **16 km or longer**

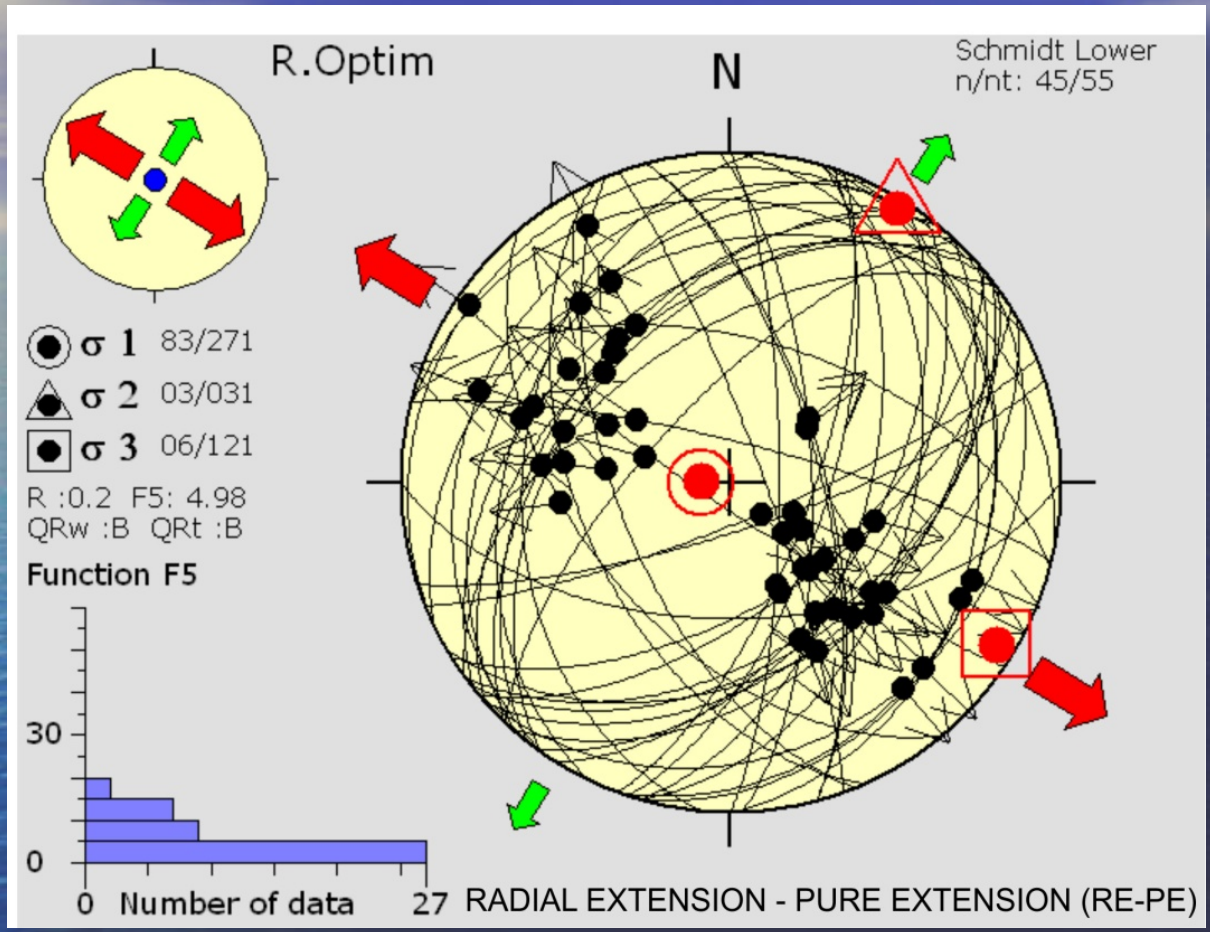


NE-SW Oblique-slip high angle extensional Faults and E-W dip-slip low angle normal fault

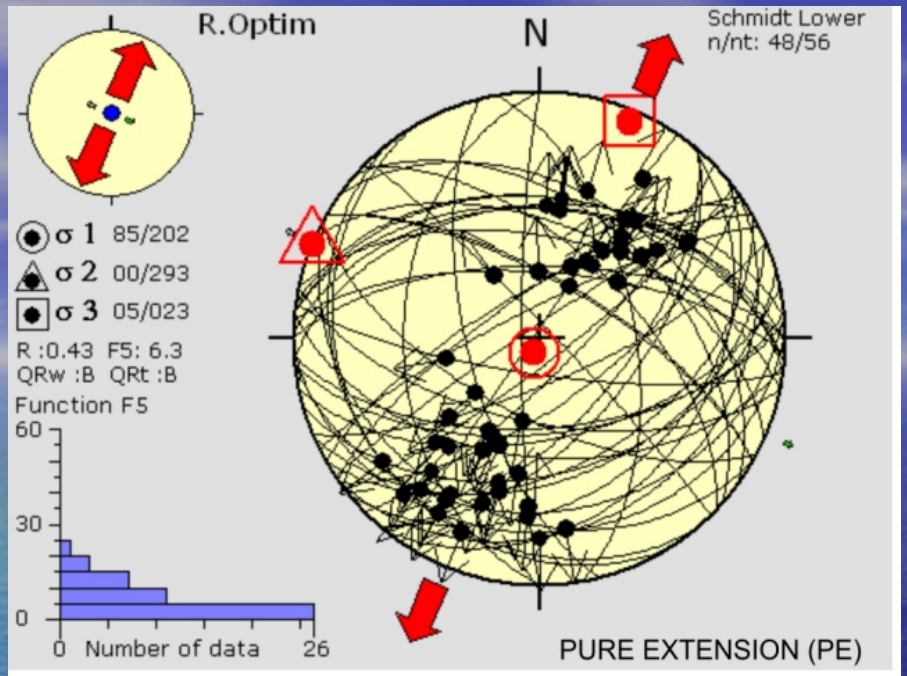


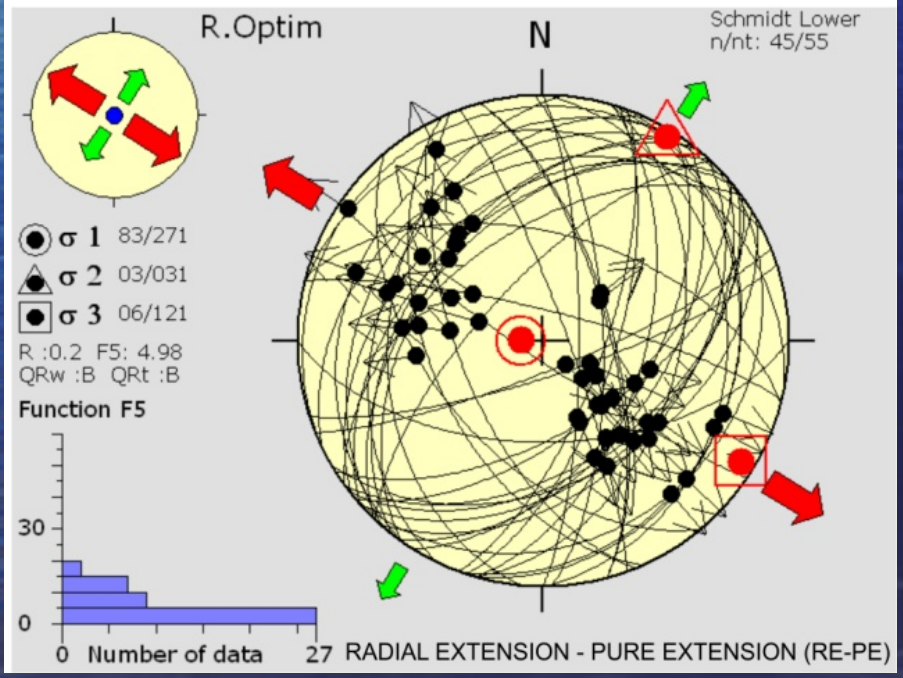
The stress inversion method applied on these fault-slip data and on doing this we use the software Win-Tensor 3.0 as provided by Delvaux, 2011).

NE-SW normal faults low angle mainly



The stress inversion method of fault-slip data and on doing this we use the software Win-Tensor 3.0 as provided by Delvaux, 2011).





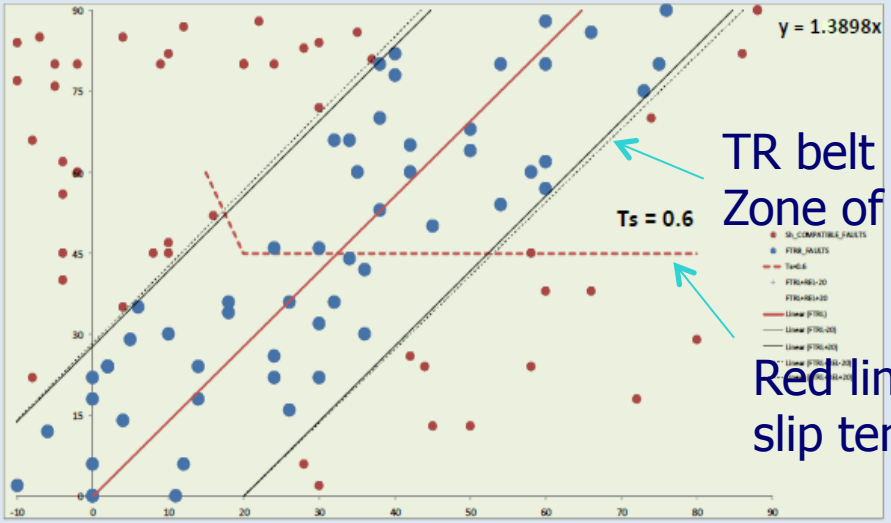
a) Extension with σ1: 202°-85°, σ2: 293°-00°, **σ3:023°-05°** and stress ratio R= 0.42

b) the second Extension σ1: 271°-83°, σ2: 031°-03°, **σ3:121°-06°** stress ratio R= 0.2.

TR FAULT FINDER version 1.0

M.D.TRANOS - 2012 - ARISTOTLE UNIVERSITY OF THESSALONIKI - HELLAS

(least principal horizontal stress axis) σ_h =	30
TRL = 1.4578	FTRL = 1.3898

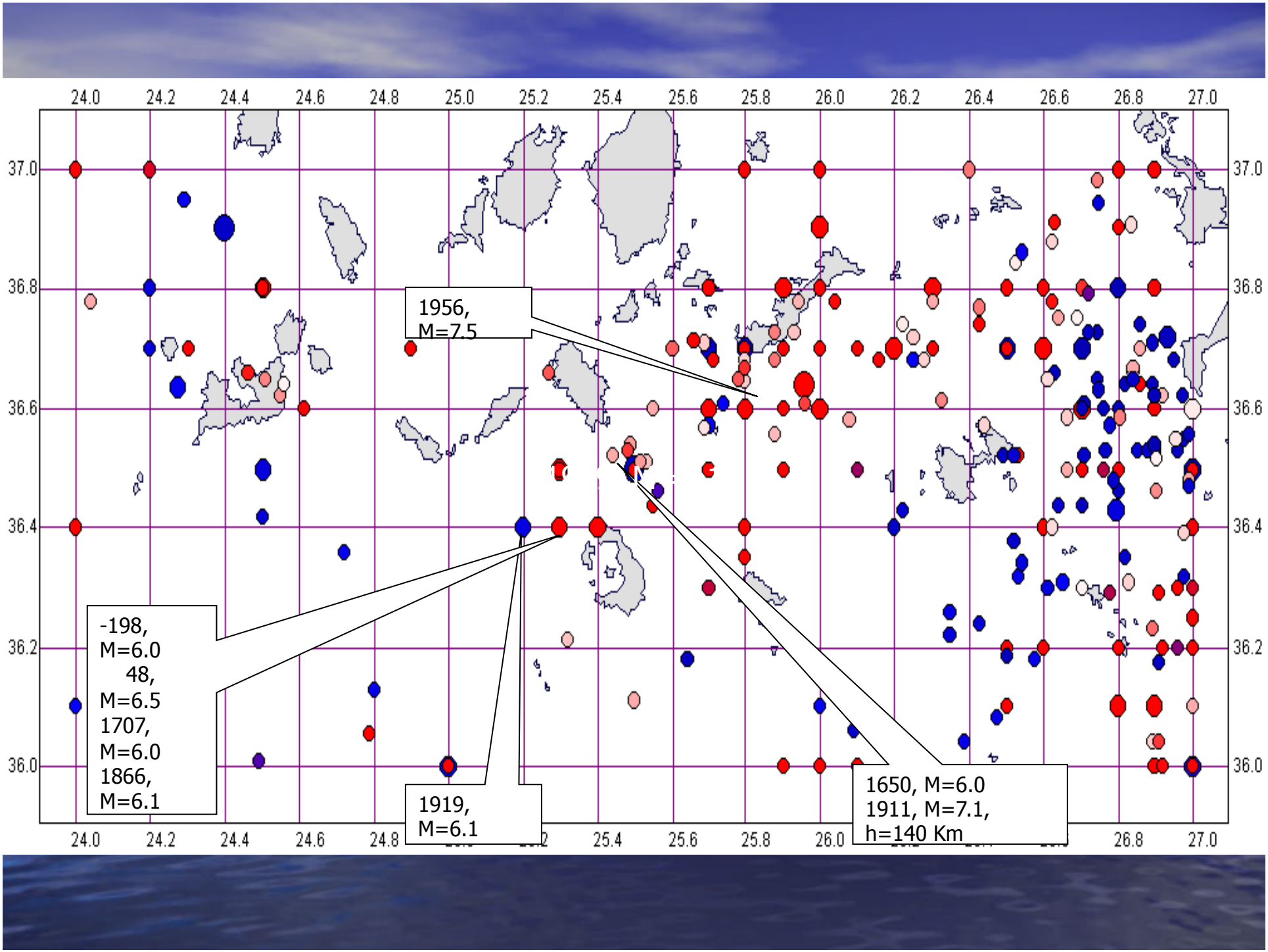


TR belt
Zone of compatibility

Red line = lower limit slip tendency

R^2 =	0.9001
NUMBER OF FAULT-SLIP DATA IN FTRB =	55
FAULTS WITH Ts < 0.6 =	26

A/A	LABEL	SD(PT90-A)	[(Sh-FTDIPD)]	Ts<0.6	FT_DIPD	FT_DIPA	L_TREND	L_PLUNGA	PITCH	SOS	COMMENTS
3	SAN_003	26	16		46	86	324	64		NS	
11	SAN_011	42	60	SAN_011	270	44	219	31		NS	
12	SAN_012	76	90	SAN_012	300	48	219	10		NS	
13	SAN_013	18	34		176	60	209	55		ND	
18	SAN_018	66	86	SAN_018	304	88	33	24		ND	DD
19	SAN_019	60	80	SAN_019	310	74	31	29		ND	DD
20	SAN_020	50	64	SAN_020	326	86	53	40		ND	
23	SAN_023	18	36		174	58	206	54		NS	
25	SAN_025	32	66	SAN_025	144	68	203	52		ND	
28	SAN_028	12	6		24	52	43	50		ND	NN
29	SAN_029	-10	2		208	64	230	62		ND	NN
31	SAN_031	24	22		8	42	39	38		ND	
40	SAN_040	60	88	SAN_040	298	36	233	17		NS	
44	SAN_044	40	82	SAN_044	128	30	172	23		ND	
45	SAN_045	54	80	SAN_045	130	58	199	30		ND	


24.0
24.2
24.4
24.6
24.8
25.0
25.2
25.4
25.6
25.8
26.0
26.2
26.4
26.6
26.8
27.0
37.0
36.8
36.6
36.4
36.2
36.0
1956,
M=7.5
-198,
M=6.0
48,
M=6.5
1707,
M=6.0
1866,
M=6.1
1919,
M=6.1
1650, M=6.0
1911, M=7.1,
h=140 Km

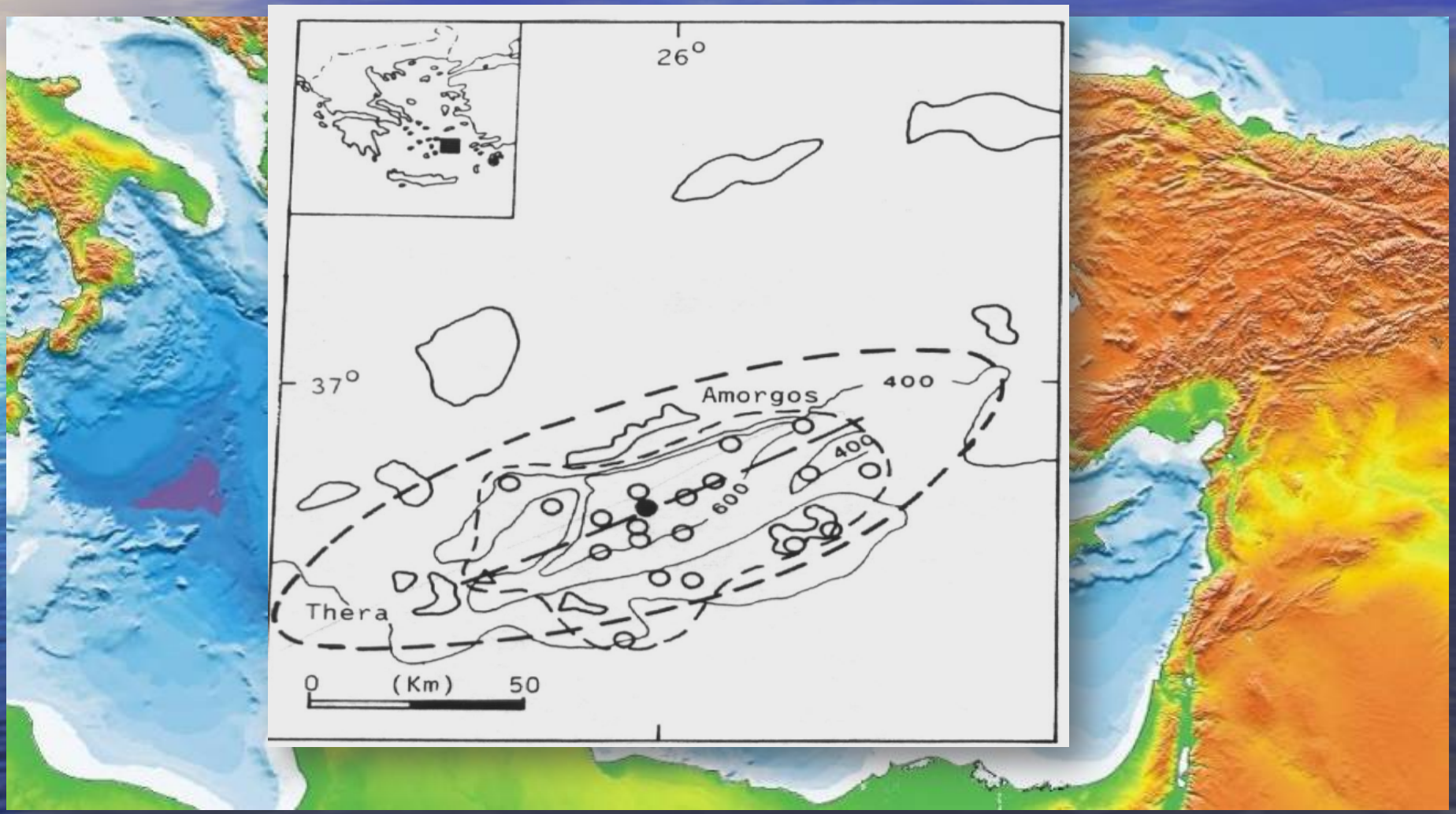
MEAN RETURN PERIOD OF STRONG EARTHQUAKES

Μέση Περίοδος Επανάληψης Σεισμών στην Ευρύτερη περιοχή της Σαντορίνης

TM

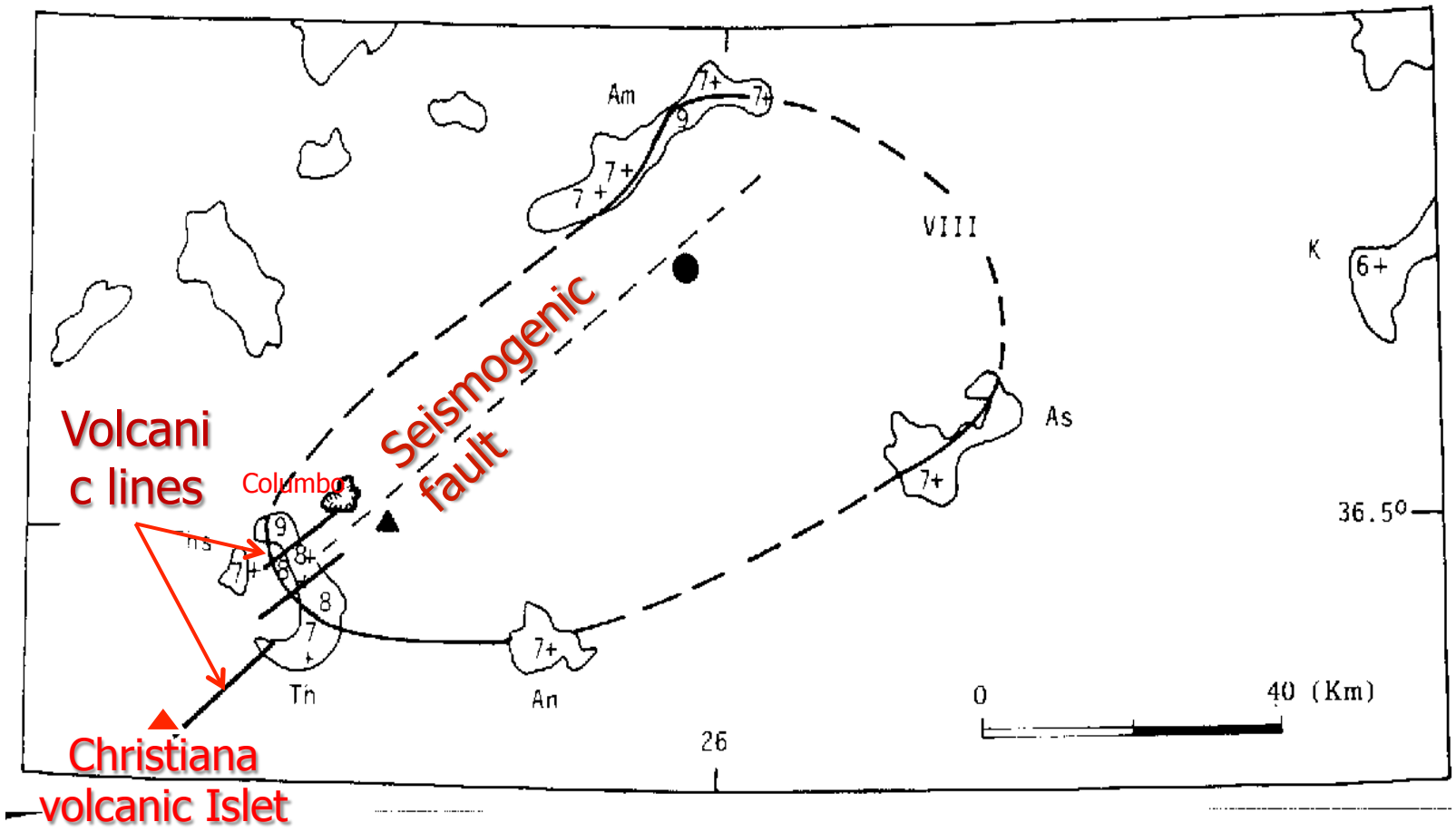
Magnitude	Tm
6.0	**15** (yrs)
7.0	**97** (yrs)
7.5	**250** (yrs)

SANTORINI AMORGOS NEOTECTONIC PATTERN AND THE 1956 Ms=7.5 EARTHQUAKE (Amorgos Trough - Santorini volcanic activity, South Aegean sea



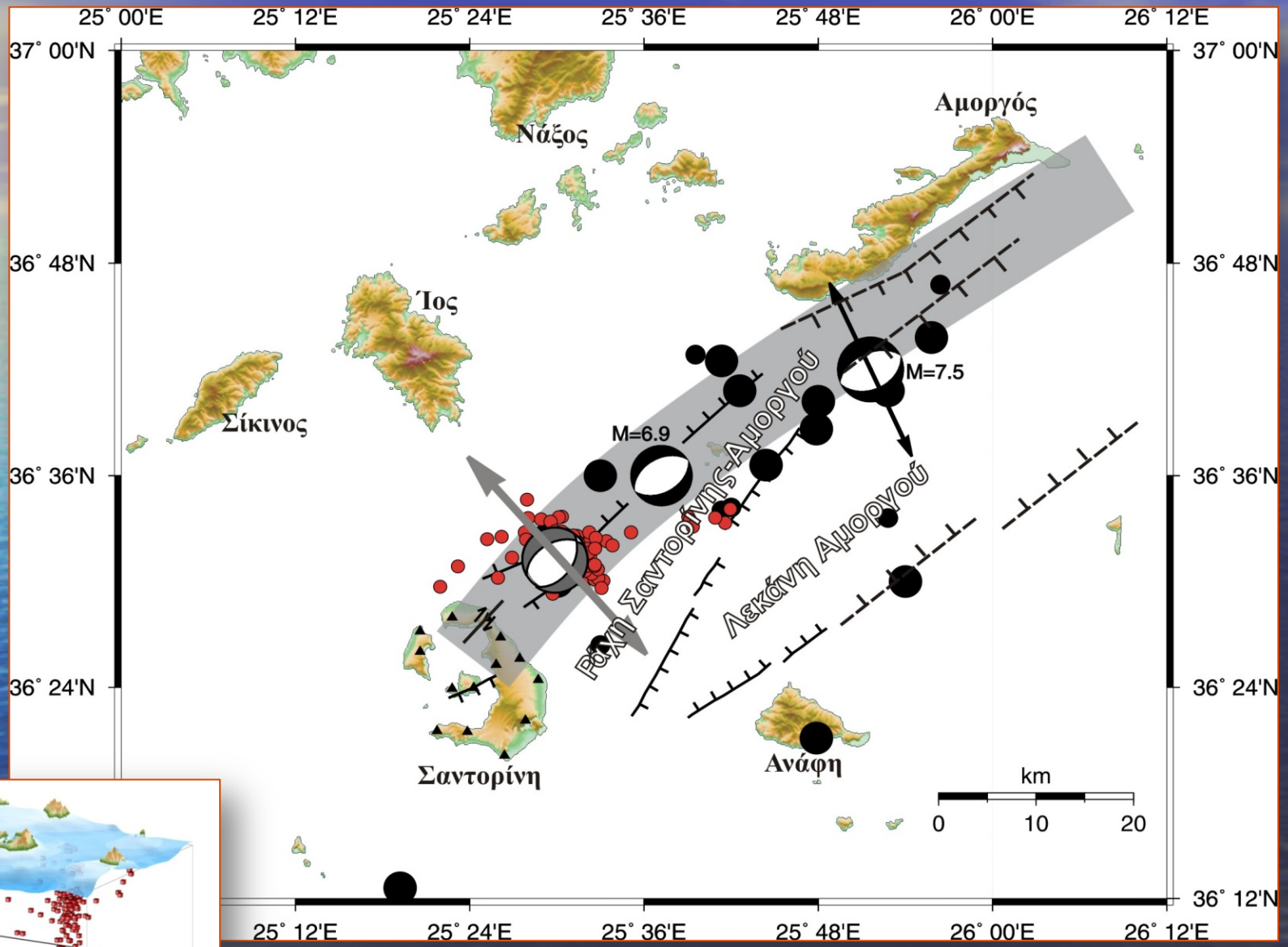
Papadopoulos & Pavlides 1991

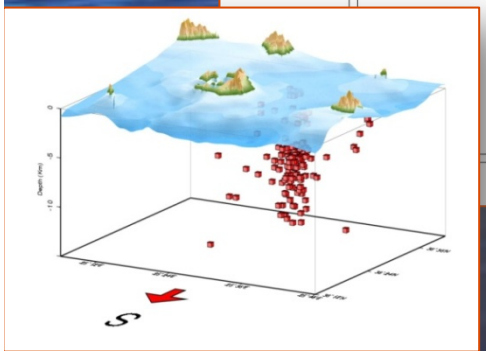
The 1956 earthquake intensities an the main tectonic lines



Papadopoulos & Pavlides, 1992

SEISMOTECTONICS OF SANTORINI-AMORGOS

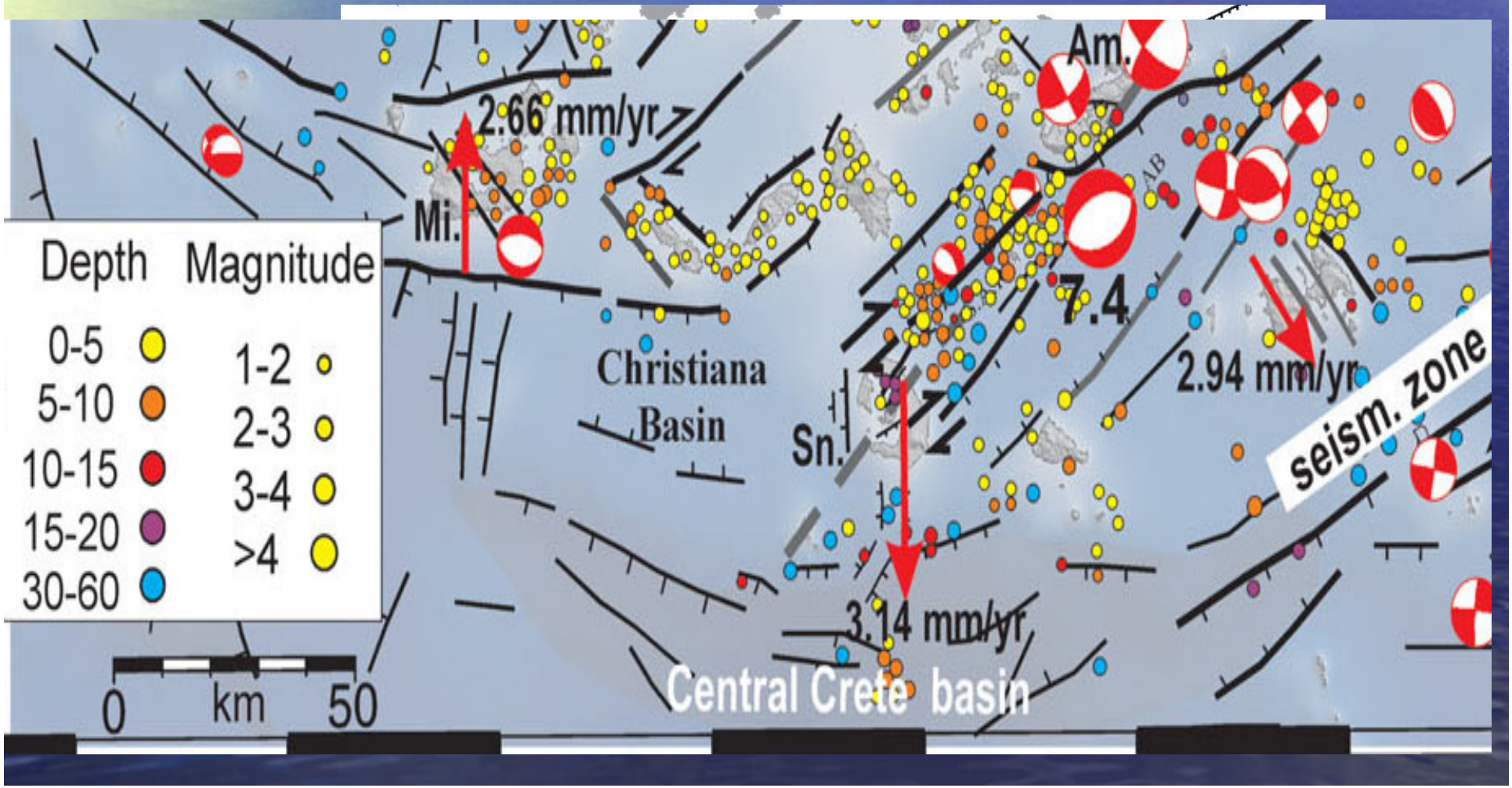




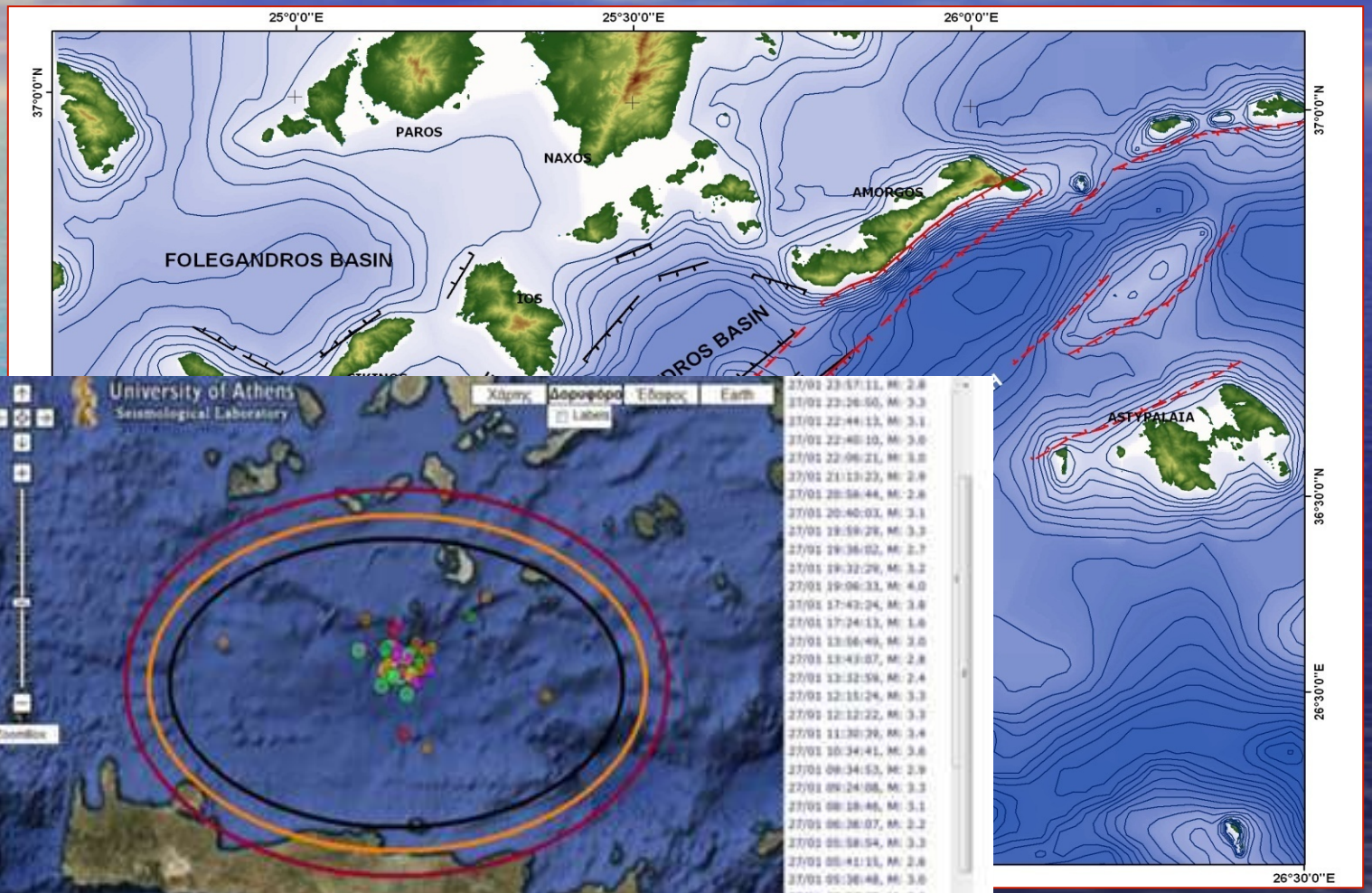
Δημητριάδης Ιορδάνης (Dimitriadis),
PhD 2008

NE- SW striking faults primarily and WNW - ESE striking faults secondarily host most of seismic activity in the south-central Aegean.

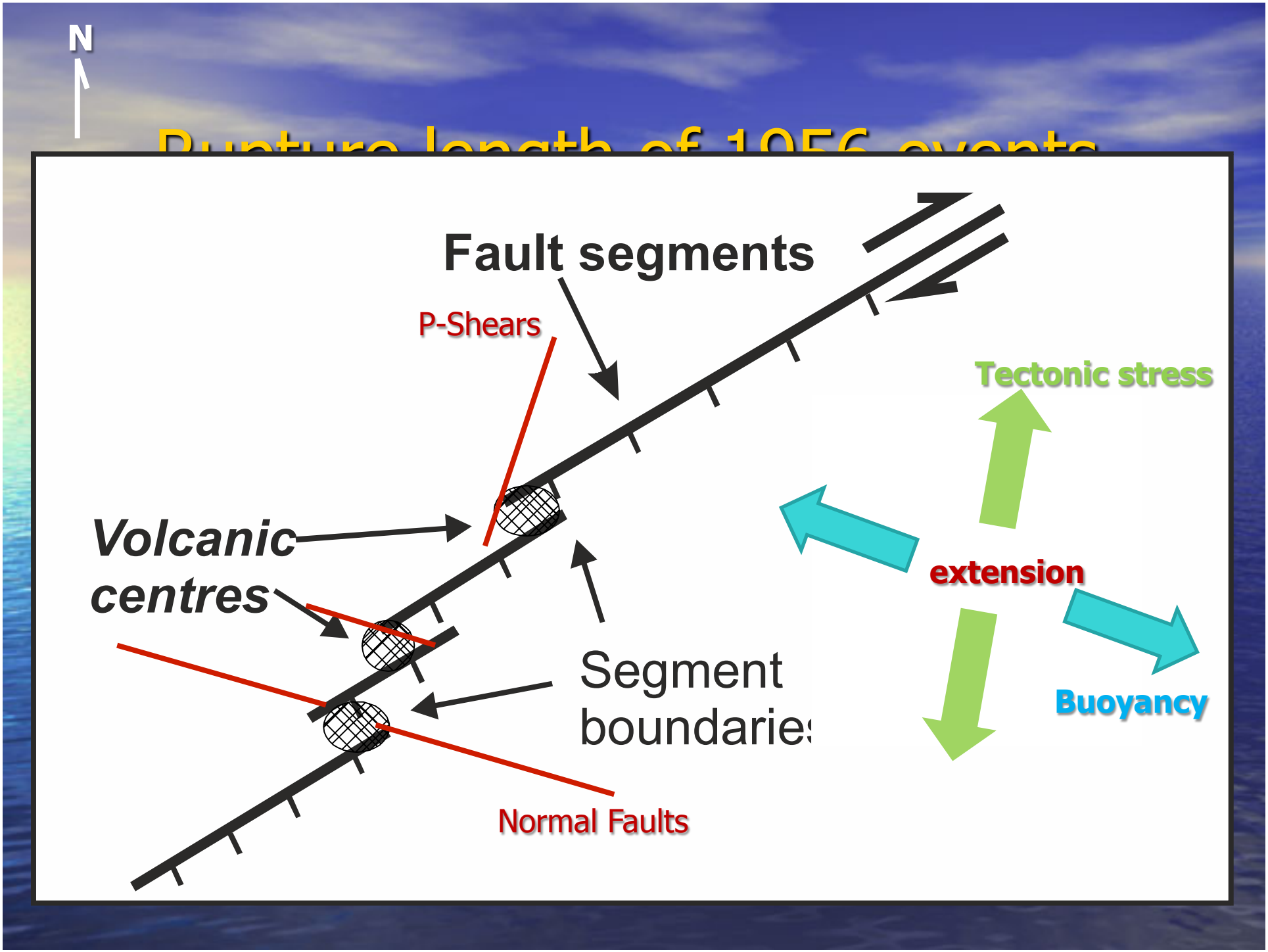
Detailed observations of surface fault kinematics and earthquake focal mechanisms can help to determine more accurately the underlying brittle tectonics and the associated stresses below



The first is a pure extension (**PE**) activating E-W to ESE-WSW trending faults as normal, NE-SW to ENE-WSW trending faults as right-lateral oblique extensional faults to right-lateral oblique-normal faults and NNE-SSE to NE-SW trending faults as right-lateral oblique extensional to strike-slip faults.



the NN area are important in localizi agma.


N
Rupture length of 1956 events
Fault segments
P-Shears
Tectonic stress
Volcanic centres
extension
Segment boundaries
Buoyancy
Normal Faults

CONCLUSIONS

This work is a quantitative study of the fault geometry and kinematics of Santorini Island and surrounding area

The refined stress regimes that have been resolved through the Win-Tensor software (Delvaux, 2011) are both extensional with the first having σ1: 202°-85°, σ2: 293°-00°, σ3:023°-05° and stress ratio R= 0.42 and the second σ1: 271°-83°, σ2: 031°-03°, σ3:121°-06°and stress ratio R= 0.2.

The first is a pure extension (PE) activating E-W to ESE-WSW trending faults as normal, NE-SW to ENE-WSW trending faults as right-lateral oblique extensional faults to right-lateral oblique-normal faults and NNE-SSE to NE-SW trending faults as right-lateral oblique extensional to strike-slip faults. The second stress regime is a Radial-Pure Extension (RE-PE) that mainly activates N-S to NE-SW trending faults as normal ones

The volcanic centers and dykes, i.e., the magmatic feeders trend along the NNE-SSW to NE-SW tectonic lines and not along the large E-W trending normal faults

The almost vertical right-lateral oblique-extensional to strike-slip faults that act as bridges among the E-W normal faults facilitate the pull-apart geometry and basin formation, and thus the extrusion of the volcanic rocks.

conclusion

- **The fact that these stress regimes are contemporary in the area implies that the first is attributed to the tectonic stresses related with the well-established Aegean motion towards SSW, whereas the second, which gives rise to recent microseismicity of the area, is a local stress regime attributed to buoyancy forces relating the magmatic processes of the area.**

- **Therefore, the combination of these two stress regimes reflects the competition between the tectonic (lithospheric) and magmatic-(local volcanotectonic) forces, in a fault-dynamic regime that could be characterized as extensional-transtentional field.**

Thanks

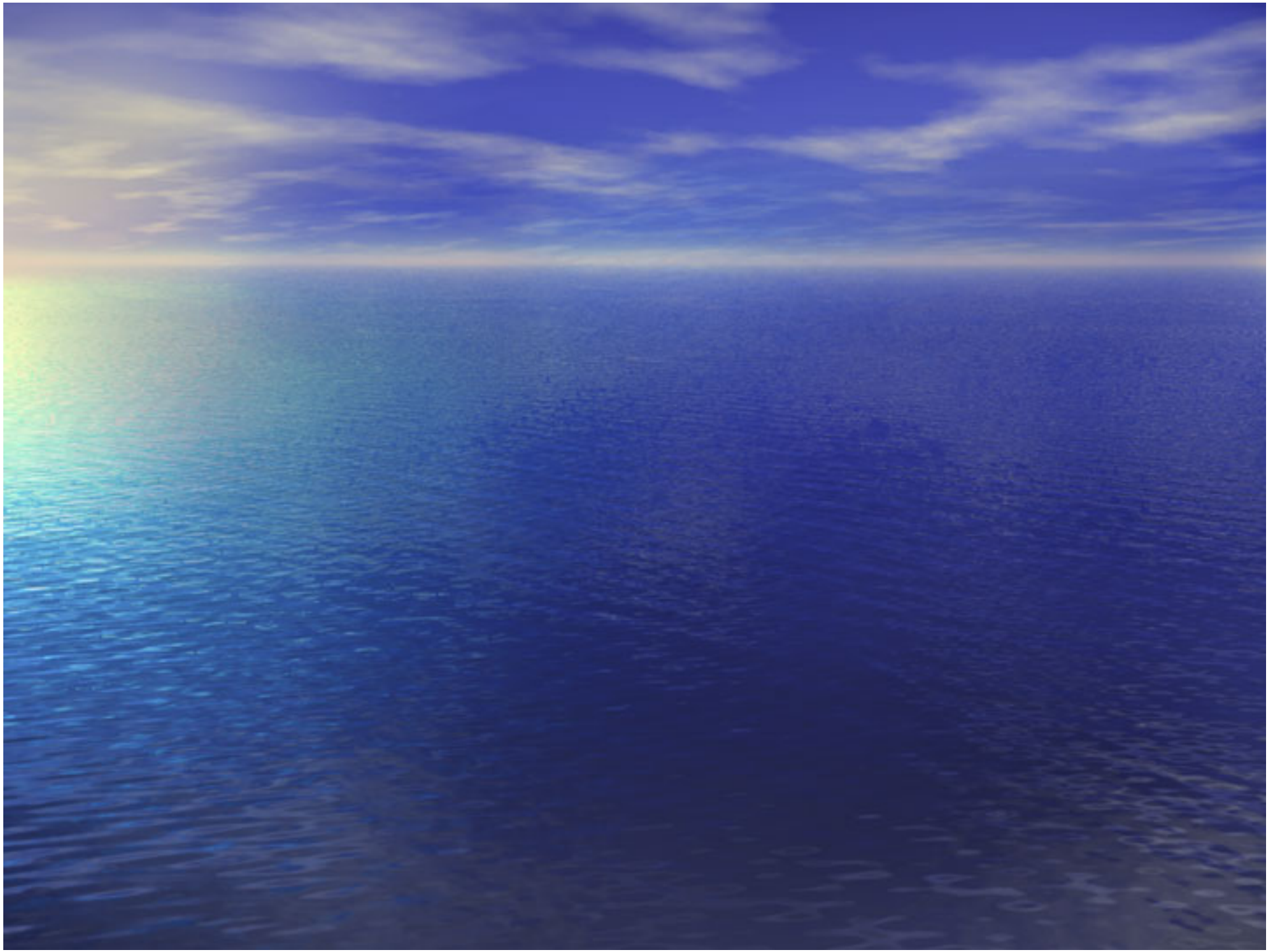
for your attention

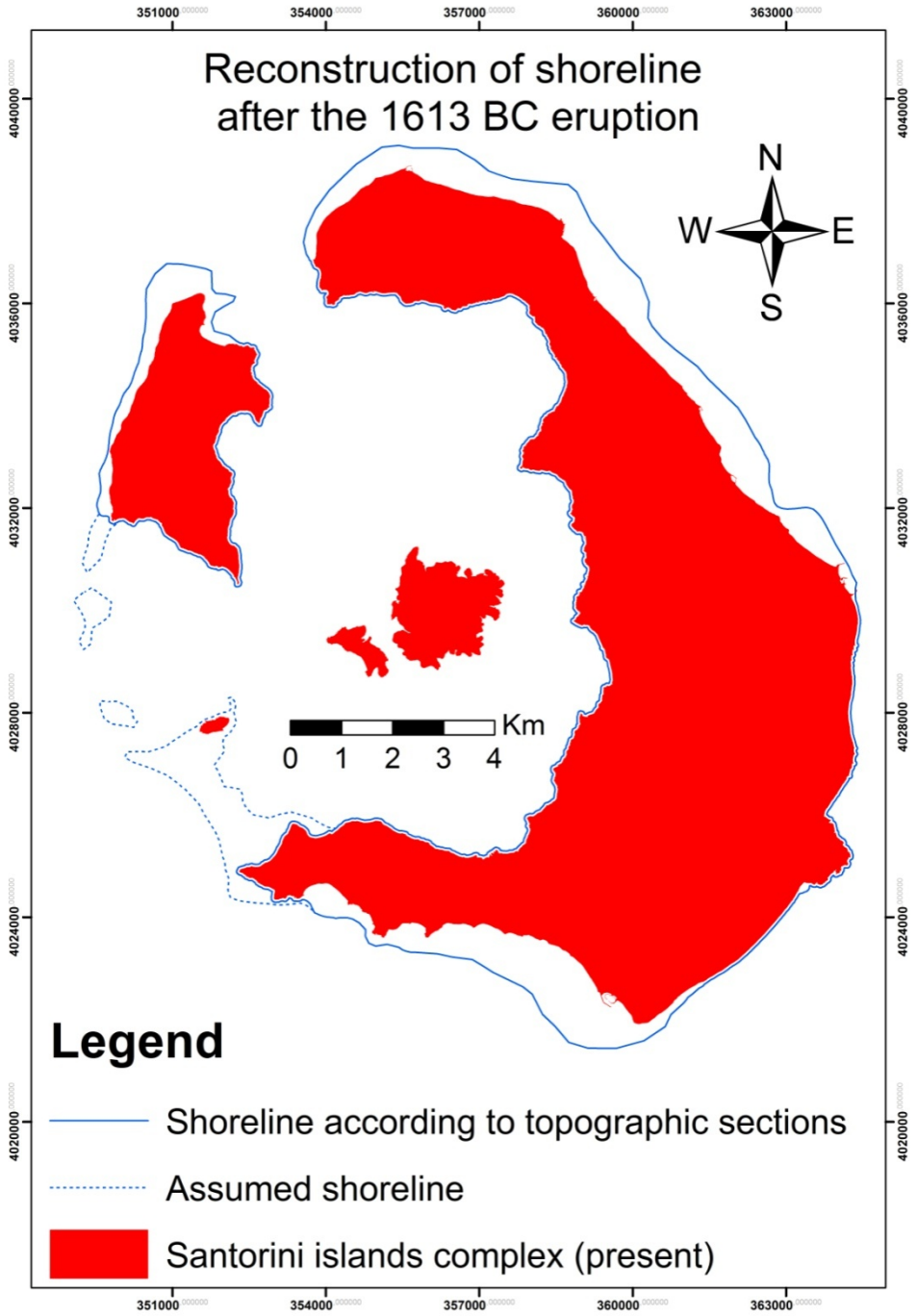
Ευχαριστώ

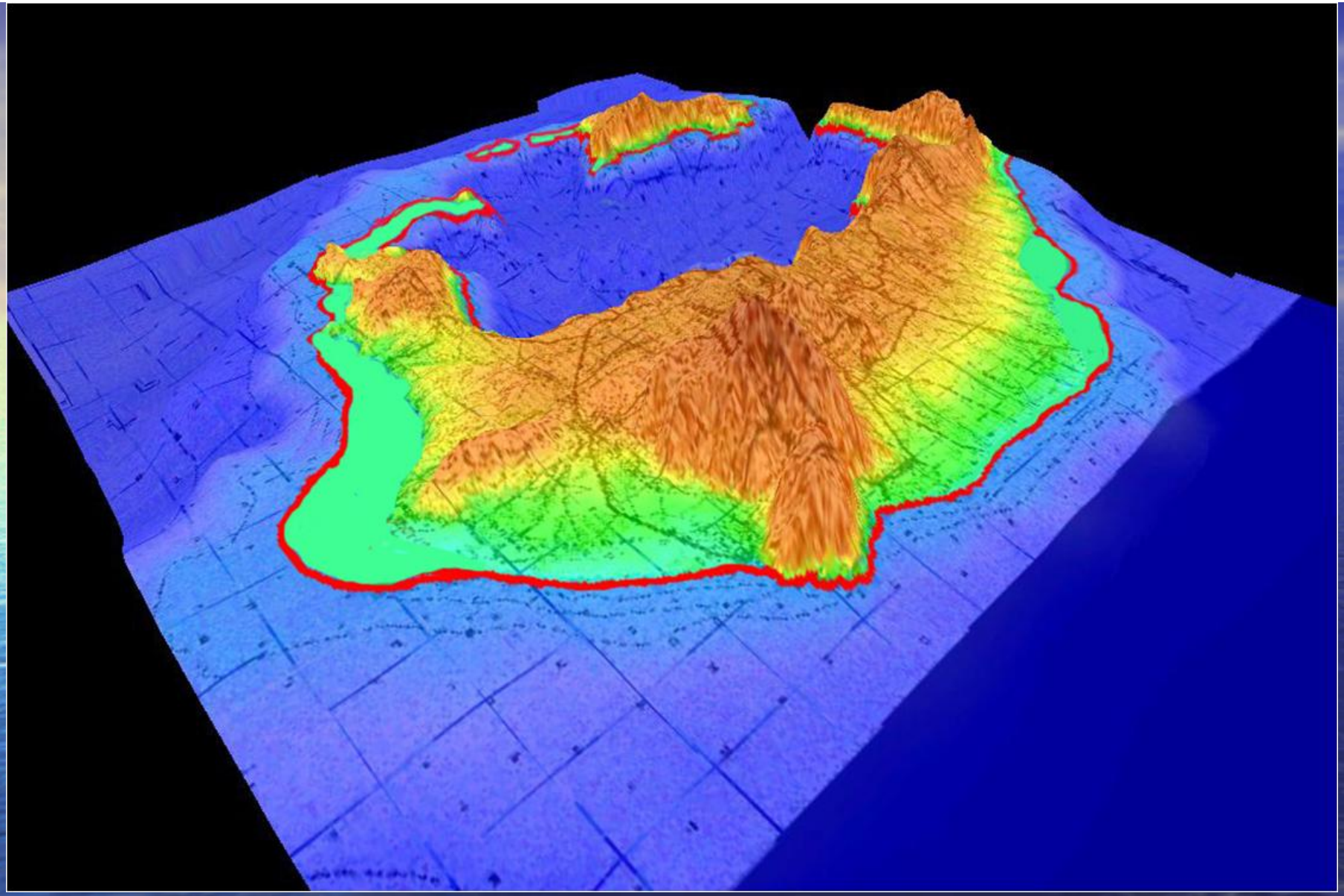
για την προσοχή σας

Thanks

Ευχαριστώ
για την προσοχή σας




Reconstruction of shoreline
after the 1613 BC eruption
N
W
E
S
Km
0 1 2 3 4
351000
354000
357000
360000
363000
4040000
4036000
4032000
4028000
4024000
4020000
Legend
Shoreline according to topographic sections
Assumed shoreline
Santorini islands complex (present)



A three dimensional view of Santorini Island, just after Minoan eruption from southeast to northwest direction

References

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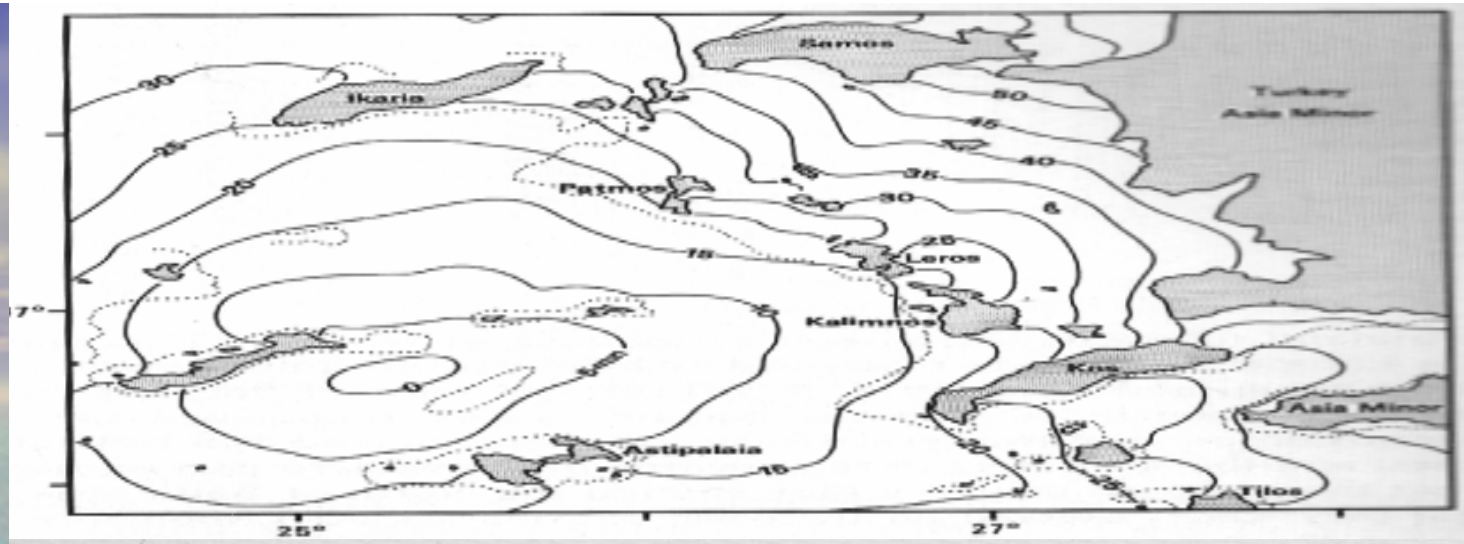
- http://users.skynet.be/damien.delvaux/tensor/tensor-index.html.
- Tranos, M.D. 2012. Slip preference on pre-existing faults: a guide tool for the separation of heterogeneous fault-slip data in extensional stress regimes. Tectonophysics, 544-545, 60–74, doi: 10.1016/j.tecto.2012.03.032.



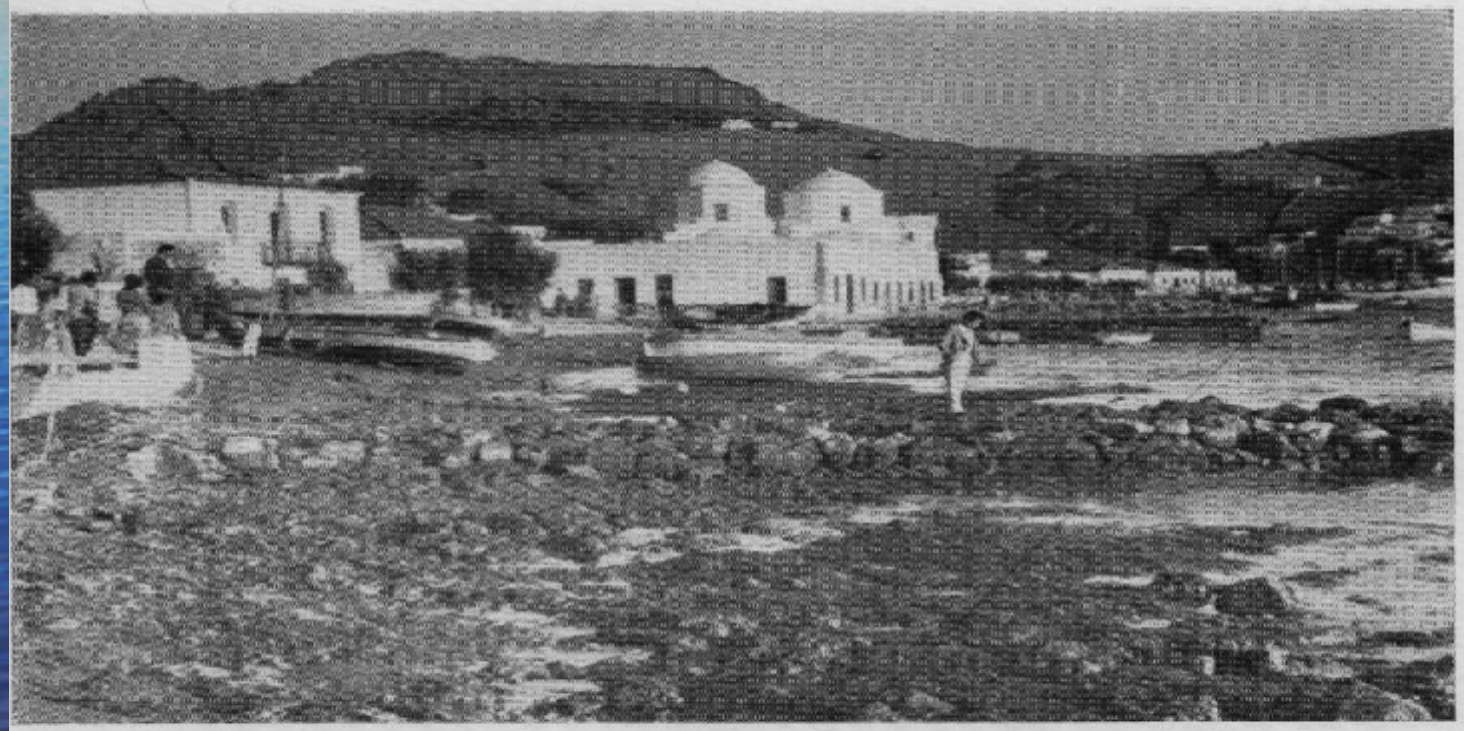


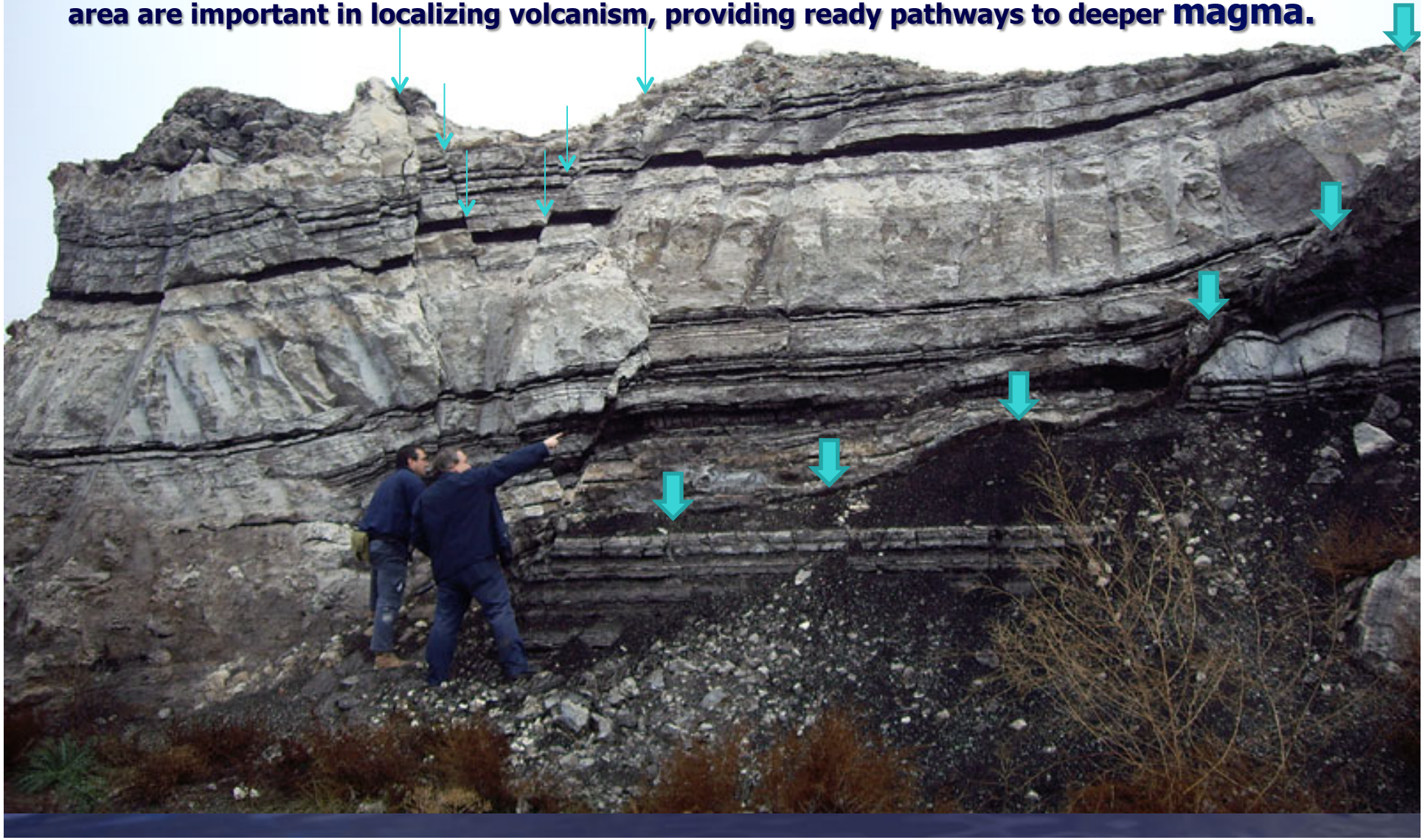
Fig. 39—Above, normal sealevel, and below, withdrawal of the waters at Skala, Patmos.


1939

The large E-W trending normal faults

The volcanic activity and more precisely the buoyancy forces could not overcome the gravity forces due to the overburden material of the hanging wall and the listric geometry of these E-W normal faults.

On the other hand the NNE- and NE-trending strike-slip faults in the Santorini area are important in localizing volcanism, providing ready pathways to deeper magma.



TR FAULT FINDER version 1.0

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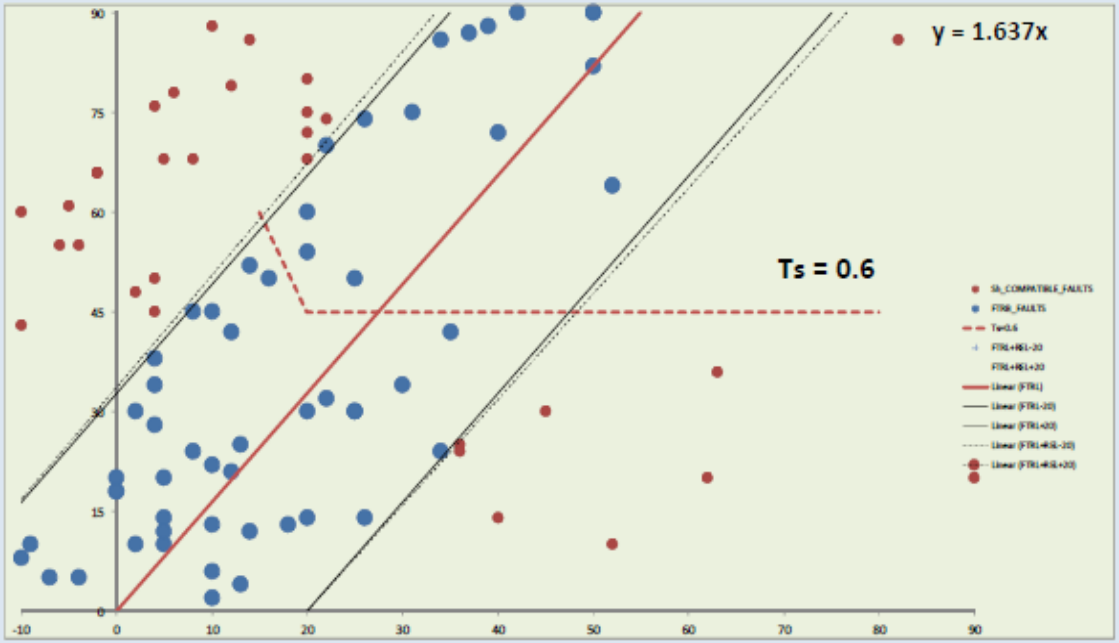
(least principal horizontal stress axis) σ_h =	120

TRL =	1.5358	FTRL =	1.6370



R^2 =	0.8046

NUMBER OF FAULT-SLIP DATA IN FTRB =	55
FAULTS WITH Ts < 0.6 =	15