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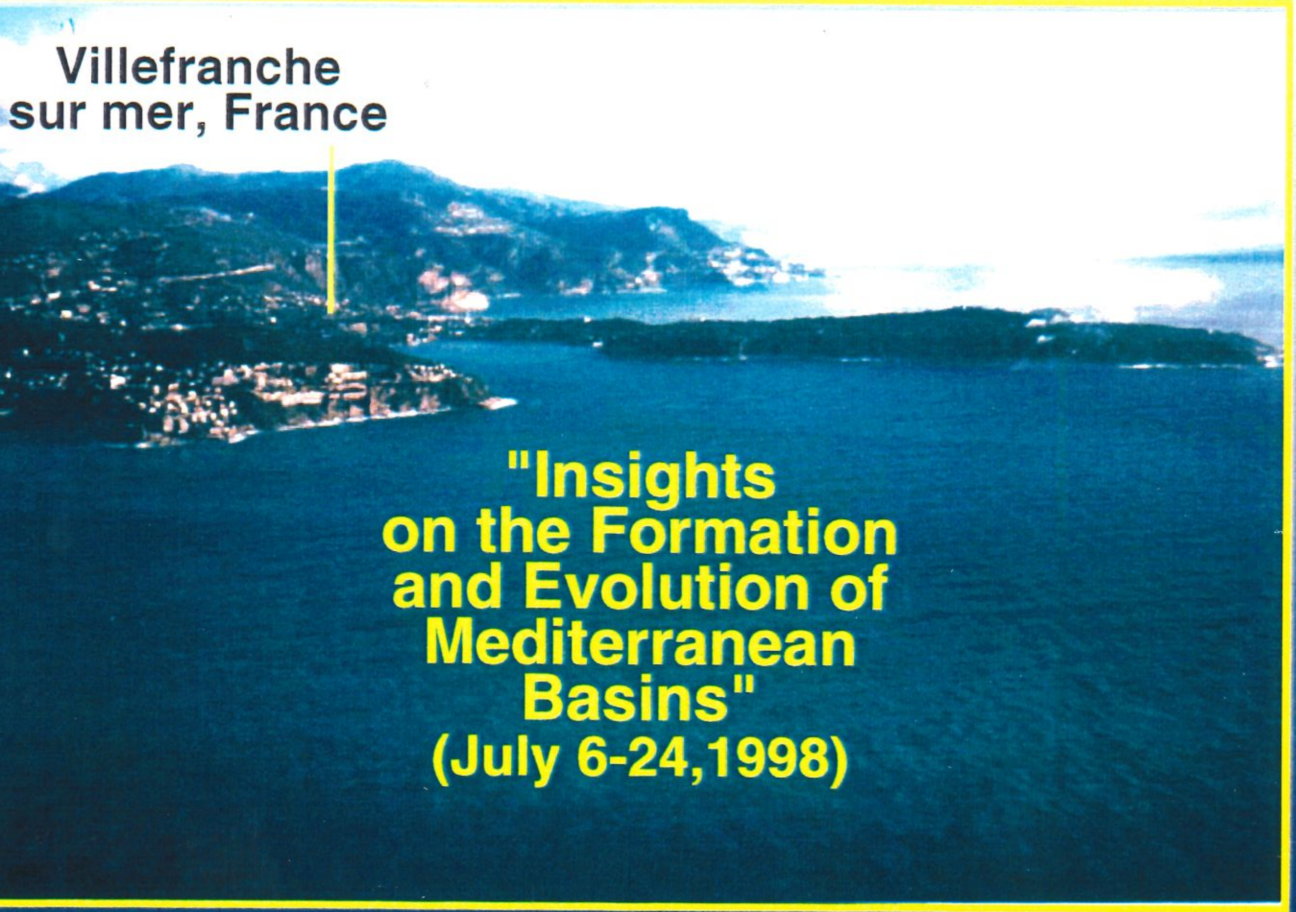
Géosciences Azur

MAST

Marine Science and Technology

ADVANCED STUDY COURSE 1998



"Insights on the Formation and Evolution of Mediterranean Basins"

(July 6-24,1998)

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PROGRAMME OF THE COURSE

BSTRACTS OF THE LECTURES

MAST Advanced Study Course

INSIGHTS ON THE FORMATION AND EVOLUTION OF MEDITERRANEAN BASINS

Villefranche-sur-Mer, France

July 6 - July 24, 1998

Programme

Organizing Committee :

Dr. Jacques Deverchère, Villefranche sur Mer, France
Prof. Laurent Jolivet, Univ. Paris 6, France
Dr. Françoise Sage, Villefranche sur Mer, France
Dr. François Michaud, Villefranche sur Mer, France
Prof. Gilbert Boillot, Villefranche sur Mer, France

Venue :
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MAST Advanced Study Course

INSIGHTS ON THE FORMATION AND EVOLUTION OF MEDITERRANEAN BASINS

Villefranche-sur-Mer, France

July 6 (evening) - July 24 (morning), 1998

■ **Participants: 24 students, 20 lecturers (15 invited). Organization : J. Deverchère**

■ **Lecturers:**

- Pr. G. Bertotti	U. Amsterdam, The Netherlands
- Pr. G. Boillot	Observatoire U. Paris 6, GéoAzur,Villefranche
- Pr. M. Canals	U. Barcelona, Spain
- Pr. A. Chemenda	GéoAzur, U. Nice, France
- Pr. G. Clauzon	U. Aix-Marseille, France
- Dr. J. Deverchère	Observatoire U. Paris 6, GéoAzur,Villefranche
- Pr. C. Eva	U. Genova, Italy
- Dr. C. Faccenna	Dip. Sc. Terra, Roma, Italy
- Pr. P. Gasparini	U. Napoli, Italy
- Pr. L. Jolivet	U. Paris 6, France
- Pr. E. Mantovani	U. Siena, Italy
- Dr. F. Michaud	Observatoire U. Paris 6, GéoAzur,Villefranche
- Dr. F. Sage	Observatoire U. Paris 6, GéoAzur,Villefranche
- Dr. B. Savoye	IFREMER, Brest, France
- Dr. G. Selvaggi	ING, Roma, Italy
- Dr. M. Sosson	CNRS, GéoAzur, Nice, France
- Dr. T. Toth	U. Budapest, Hungary
- Dr. A.B. Watts	U. Oxford, U. K.
- Dr. M. Wilson	U. Leeds, U.K.
- Pr. M.J.R. Wortel	U. Utrecht, The Netherlands

■ Brief description of the Course:

This Course aims at :

A. Transfering recent improvements on the understanding of the Tertiary-Quaternary evolution of Mediterranean back-arc basins, with a special emphasis on Ligurian and Tyrrhenian domains within the Alpine orogen;

B. Provide to students an opportunity to directly observe offshore and land evidences for Tertiary deformations depicting time-space relationships between basin, subduction, and orogen evolutions, thanks to a practical training in the Ligurian sea and in Corsica ;

C. Offering a combined methodological approach based on a full purchase, analysis and processing of marine seismic reflection data and on a tectonic field study.

PROGRAMME OF THE MAST COURSE

INSIGHTS ON THE FORMATION AND EVOLUTION OF MEDITERRANEAN BASINS

(Geolig)

Villefranche sur mer - 6-24 July 1998

July 6 : Arrival of Participants

First part : 7-8 July

The conceptual framework of formation and evolution of deep basins in the Mediterranean Sea

Tuesday, 7

10:00 - 12:00	Welcome to the participants. Presentation of the Course. *(J. Deverchère).* Registration. Practical informations.
12:00 - 14:00	*Break - Lunch*
14:00 - 15:45	*Lecture*: Continental break-up and initiation of seafloor spreading: the record of non-volcanic passive margins *(Pr. **G. Boillot**, Univ. Paris 6, Villefranche/Mer, France)*
15:45 - 16:15	Coffee Break
16:15 - 17:45	*Lecture*: Mechanics of subduction and the mechanisms controlling the stress regime in back-arc basins *(Pr. **A. Chemenda**, Univ. Nice-Sophia Antipolis, France)*

Wednesday, 8

09:00 - 10:30	*Lecture*: Plate boundary evolution in the Alpine-Mediterranean region : from structure to dynamics *(Dr. **M.J.R. Wortel**, Utrecht, The Netherlands)*
10:30 - 10:45	Coffee Break
10:45 - 12:15	*Lecture*: The nature, extent, and significance of recent volcanic activity in the Mediterranean region *(Dr. **M. Wilson**, Univ. Leeds, U.K.)*
12:15 - 14:00	*Break - Lunch*
14:00 - 15:30	*Lecture*: Mediterranean deformation pattern controlled by the minimum work condition *(Pr. **E. Mantovani**, Univ. Siena, Italy)*
15:30 - 15:45	Coffee Break
15:45 - 17:15	*Lecture* : Gravity anomalies, flexure and the deep structure of passive continental margins *(Pr. **A.B. Watts**, Oxford, U.K.)*
17:30 - 18:30	**Visit of the Observatory of Villefranche sur mer** *(Jean-Claude Braconnot)*
18:30 - 20:30	**Reception of lecturers and students in the garden of « *Géosciences Azur* » Laboratory - Appetizer - Refreshments**

<u>*Second part: 9-13 July*</u>

Cenozoic key events in the Mediterranean sea and surroundings

Thursday, 9 : The Tyrrhenian and Apennines domains

09:00 - 10:30	*Lecture*: Seismotectonics of the Apennines and Tyrrhenian Sea: New insights from the Mw=6.0 Umbria 1997 normal faulting earthquake *(Dr. **G. Selvaggi**, ING Roma, Italy)*
10:30 - 10:45	Coffee Break
10:45 - 12:15	*Lecture*: Recent volcanic activity in Italy *(Pr. **P. Gasparini**, Univ. Napoli, Italy).*
12:00 - 14:00	*Break - Lunch*
14:00 - 15:30	*Lecture*: The Tyrrhenian sea and surrounding areas : From structural geology to lithosphere dynamics (and back) *(Pr.**G. Bertotti**, Amsterdam, The Netherlands)*
15:30 - 15:45	Coffee Break
15:45 - 17:15	*Lecture* : A model of the evolution of the Tyrrhenian sea from experimental modelling *(Pr. **C. Faccenna**, Univ. Roma, Italy)*

Friday, 10 : The Ligurian domain and its surroundings

09:00 - 10:30	*Lecture*: New constraints on the Ligurian sea formation and evolution ***(M. Sosson, N. Rollet, J. Deverchère**, Géosciences Azur, Valbonne & Villefranche/Mer, France)*
10:30 - 10:45	Coffee Break
10:45 - 12:15	*Lecture*: Insights from historical and instrumental seismicity in the Alps, Liguria, and northern Apennines *(Pr. **C. Eva**, Univ. Genova, Italy)*
12:00 - 14:00	*Break - Lunch*

Afternoon : Exceptionally, lectures will be held in the « Citadelle » of Villefranche-sur-Mer

14:00 - 15:30	*Lecture* : The Messinian salinity crisis: a view from land *(Pr. **G. Clauzon**, Univ. Aix-en-Provence, France)*
15:30 - 16:00	*Welcome from the Mayor of Villefranche-sur-Mer, G. Grosgogeat*
16:15 - 17:00	*Lecture* : Deep sedimentary processes in the Ligurian Sea *(Dr. **B. Savoye**, IFREMER, Brest, France)*

Saturday, 11 : Introduction to practical sessions

09:00 - 10:45	*Lecture* : Extensional tectonics and sense of shear in the Mediterranean region *(Pr. **L. Jolivet**, Univ. Paris 6)*
10:45 - 11:00	Coffee Break
11:00 - 12:00	*Practical* : An introduction to the field trip in Corsica *(Pr. **L. Jolivet**, Univ. Paris 6)*
12:00 - 14:00	*Break - Lunch*
14:00 - 15:00	*Practical* : An introduction to the sea excursions offshore Liguria and Corsica : Objectives and methodological approach *(**J. Deverchère**, Univ. Paris 6, Villefranche/Mer)*

Sunday, 12 : Free

Monday morning, 13 :

09:00 - 10:30	*Lecture* : Evolution of the Valencia trough and the Gulf of Lions during the upper Neogene *(Pr. **M. Canals**, Univ. Barcelona, Spain)*
10:30 - 10:45	Coffee Break
10:45 - 12:15	*Lecture* : The Pannonian basin and its geodynamical significance in the Mediterranean evolution *(Dr. **T. Toth**, Budapest, Hungary)*
12:00 - 14:00	Lunch

Third part : 13 (afternoon) -20 July
Field trip in Corsica and Sea seismic profiling offshore Corsica

- First Group of students (**A**):
  - ***July 13, afternoon :*** Departure to Corsica by Ferry-Boat. Night at Saint-Florent.
  - ***From July 14 to July 16 :*** Field trip on land (Alpine Corsica), *led by L. Jolivet and M. Sosson.*
  - ***From July 17 to July 18 :*** Monochannel seismic profiling offshore Cap Corse and Calvi into the deep basin (R/V *Téthys II*, CNRS-INSU), *led by J. Deverchère and L. Royer.*
  - ***July 19 :*** Day off for 5 students, and return to Nice onboard TETHYS vessel for 5 others.

- Second Group of students (**B**):
  - ***July 13 and 14 :*** Days off in Villefranche/Mer.
  - ***July 15 :*** Departure to Corsica by Ferry-Boat and onboard TETHYS Vessel. Night at Saint-Florent.
  - ***July 16 :*** Monochannel seismic profiling offshore Cap Corse and Calvi into the deep basin (R/V *Téthys II*, CNRS-INSU), *led by J. Deverchère and L. Royer.*
  - ***From July 17 to July 19 :*** Field trip on land (Alpine Corsica), *led by L. Jolivet and M. Sosson.*

Accomodation is at Saint-Florent and on the ship.
All students come back by ferry-boat on July 20.

Fourth part : 21 July -23 July

Data Analysis, interpretations and conclusions

Tuesday, 21

09:00 - 10:30 (G. 1)	Practical : Preparation of analogical seismic profiles : scales, vertical exaggeration, correlations between profiles *(J. Deverchère, F. Michaud)*
10:30 - 10:45	Coffee Break
10:45 - 12:00 (G. 1)	Practical : Analysis of artifacts : multiples, bubble, hyperbolas, pull-up and pull-down effects *(J. Deverchère, F. Michaud)*
09:00 - 12:00 (G.2)	Practical : Data processing (1): flowchart ; presentation of CLARITAS software ; static shift ; gain ; filtering ; plots *(F. Sage, G. Lamarche)*
12:00 - 14:00	*Break - Lunch*
14:00 - 17:00 (G.1)	Practical : Data processing (1): flowchart ; presentation of CLARITAS software ; static shift ; gain ; filtering ; plots *(F. Sage, G. Lamarche)*
14:00 - 15:30 (G. 2)	Practical : Preparation of analogical seismic profiles : scales, vertical exaggeration, correlations between profiles *(J. Deverchère, F. Michaud)*
15:30 - 15:45	Coffee Break
15:45 - 17:00 (G. 2)	Practical : Analysis of artifacts : multiples, bubble, hyperbolas, pull-up and pull-down effects *(J. Deverchère, F. Michaud)*

Wednesday, 22

09:00 - 12:00	Practical: G. 1 : Data interpretation (1) : Messinian erosional surface, Messinian detritic fan, upper evaporites, infra-evaporitic Miocene sediments *(J. Deverchère)* G. 2 : Data processing (2): Stack ; Migration ; AGC ; Plots *(F. Sage, G. Lamarche)*
12:00 - 14:00	*Break - Lunch*
14:00 - 17:00	Practical: G. 1 : Data processing (2): Stack ; Migration ; AGC ; Plots *(F. Sage, G. Lamarche)* G. 2 : Data interpretation (1) : Messinian erosional surface, Messinian detritic fan, upper evaporites, infra-evaporitic Miocene sediments *(J. Deverchère)*

Thursday, 23

09:00 - 12:00	*Practical*: Data interpretation (2) : Geometry of the basement, correlations with multichannel profiles (MALIS cruise, 1995) and ECORS-Gulf of Lions profile; isobath and structural maps *(J. Deverchère)*
12:00 - 14:00	*Break - Lunch*
14:00 - 15:30	A synthesis of geophysical observations in the Ligurian sea - Links with tectonics of Corsica, Alps and Apennines *(J. Deverchère, L. Jolivet, M. Sosson)*
15:30 - 16:00	Coffee break
16:00 - 17:00	Conclusions of the Course *(Organizing Committee)*

MAST Advanced Study Course

INSIGHTS ON THE FORMATION AND EVOLUTION OF MEDITERRANEAN BASINS

Villefranche-sur-Mer, France

Abstracts of the MAST Advanced Study Course

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Continental break-up and initiation of seafloor spreading : the record of non-volcanic passive margins

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I - Introduction : origin and classification of passive margins

- Volcanic and non-volcanic passive margins (the control by temperature and duration of rifting mantle partial melting).
- Transform and stretched (rifted) margins (the control by plate tectonics and structural inheritance).

II - Extensional tectonics of the upper, brittle continental crust

- Tilted crustal blocks and set of normal faults between them (size of structures and scale of observation ; kinematics of the block tilting and normal faulting).
- Detachements at the bottom and within the brittle crust (seismic reflectors within the thinned continental crust ; tectonic contact of the upper, brittle crust on the lower, ductile crust and/or serpentinized uppermost mantle).

III - Extensional tectonics of the lower, ductile continental crust and lithospheric mantle

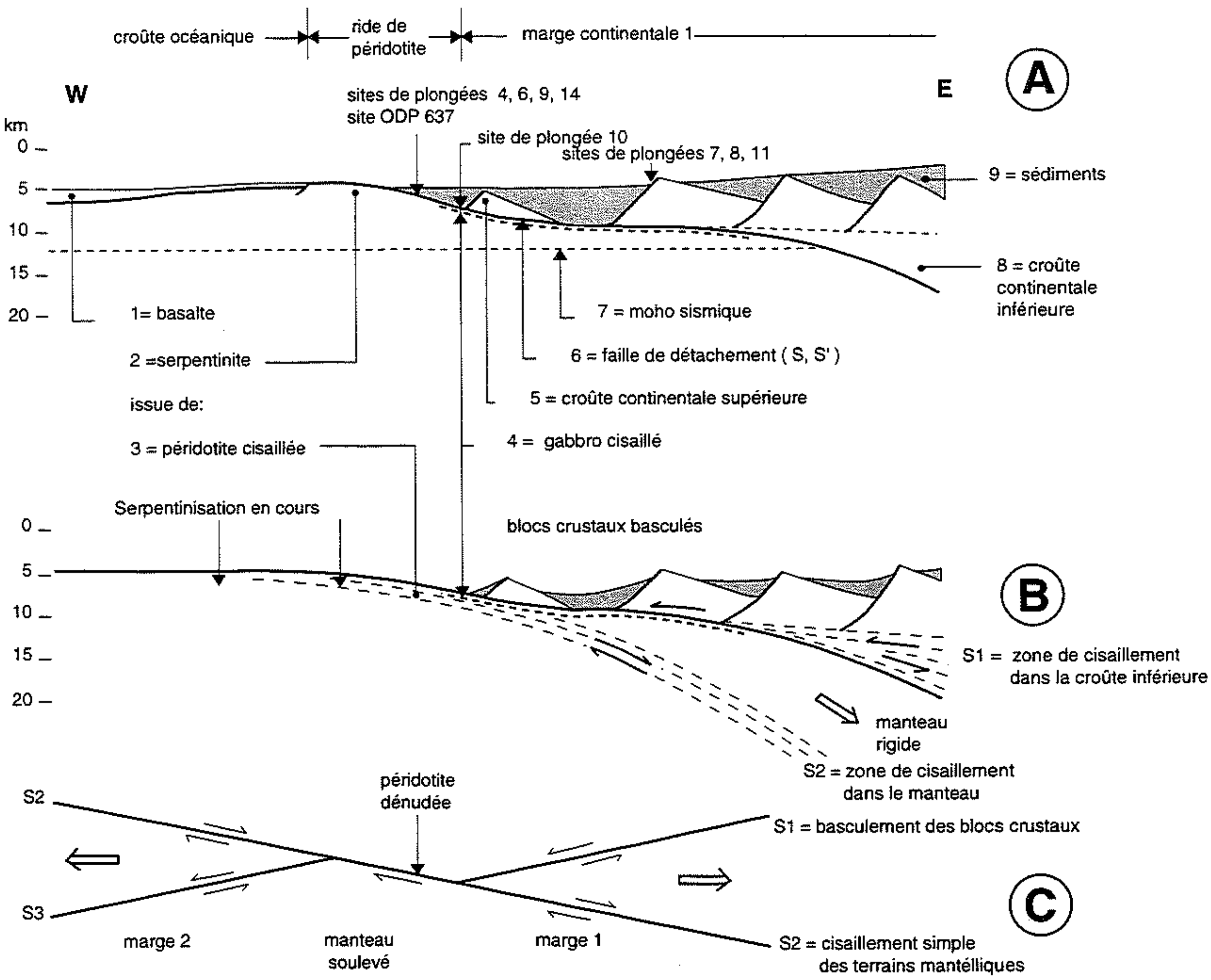
- Crustal structure at the Ocean-Continent Boundary (the peridotite ridge of the Galicia margin and the ultramafic seafloor in the global ocean ; the P-T path of the ultramafic terranes from depth to the seafloor).
- Final continental break-up and initiation of seafloor spreading (tectonic processes versus magmatic processes).

IV - Models and perspectives (simple shear versus pure shear ; unique shear zone versus conjugate shear zones accomodating lithospheric thinning).

References :

Banda, E., Torné, M. and Talwani, M. (eds.) - Rifted Ocean-Continent Boundaries. NATO ASI series C, vol. 463, Kluwer Academic Publishers, Dordrecht, 387 p., 1995.

Boillot, G. et Coulon, C. - La déchirure continentale et l'ouverture océanique : géologie des marges passives (*continental rifting and initiation of seafloor spreading : geology of passive margins*). Gordon and Breach Science Publishers, London, Paris, 224 p., 1998.



Figures :

(A) Cartoon of the crustal structure of the West Galicia (Spain) Ocean-Continent Boundary. Numbers relate to the § of the original paper (in *Banda* et al., 1995).

(B) Kinematic model accounting for the crustal structure depicted in A.

(C) Diagram of the lithosphere thinning accomodated by conjugate simple shear zones S_1, S_2 and S_3 depicted in B.

Mechanics of subduction and the mechanisms controlling the stress regime in back-arc basins

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Géosciences Azur,
Université de Nice - Sophia Antipolis, Valbonne, France
(E-mail: chem@faille.unice.fr)

The results from both physical (experimental) and numerical modelling of oceanic subduction as well as the analysis of natural situations will be presented. The conclusions can be summarised as follows :

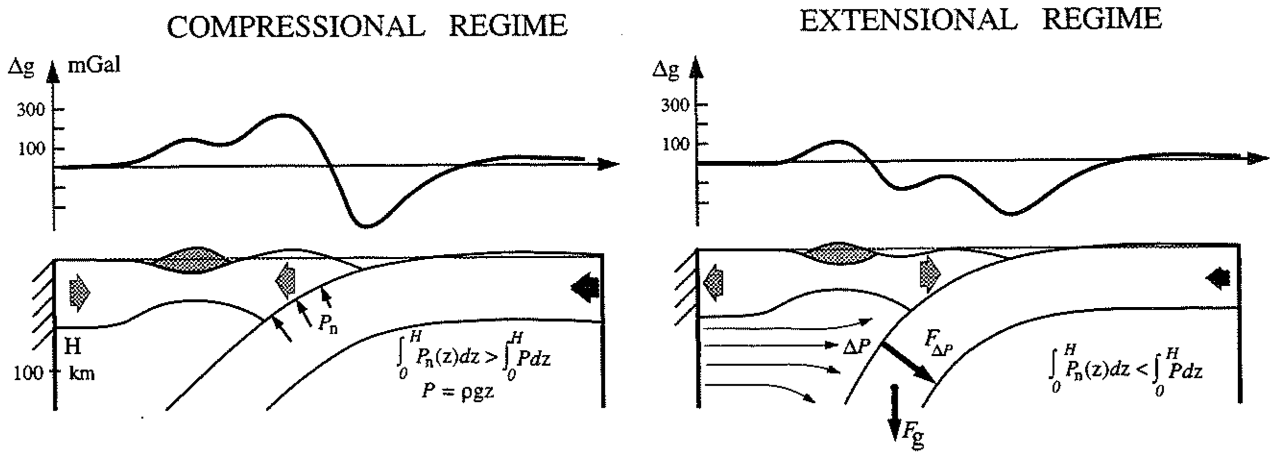
1. Tension of the overriding lithosphere arises in situations where some forces tend to separate the plates in the subduction zone. Such conditions can occur when:
a) there is subduction of an old (dense) plate;
b) a horizontal asthenospheric (mantle) flow acts on the frontal surface of the subducted plate (Benioff zone);
c) there is a motion component of the overriding plate away from the subduction zone in the mantle reference frame;
d) the relative rate of the plate motion in the subduction zone is negative in sign, that is, when the subducted plate is being pulled towards the ocean basin.

2. Separation of the plates in these cases does not occur due to hydrostatic suction between them. The suction is caused by intensive hydrostatic pressing of the plates against each other in the subduction zone. To separate the plates, it is necessary to overcome this hydrostatic pressure, although this usually proves impossible due to the relatively low lithosphere strength (yield limit), the σ_s. In other words, large tectonic stresses needed for plate separation cannot be created in the lithosphere as they cannot exceed σ_s. Therefore, failure of the lithosphere would occur under existing tectonic tension in some weakened place before the subducting and overriding plates could be separated.

3. Tectonic tensile stresses σ_h which can be generated in the overriding plate are several times lower than the effective yield limit of the lithosphere σ_s. For example, the extensional force $F_h = \sigma_h H$ (H is the plate thickness) can reach only $\approx 2 \times 10^{12}$ N/m for the mechanism of gravitational sinking of the lithosphere. Further growth of σ_h proves impossible in this case, because after the subducted plate reaches a certain length it is broken down under its own excess weight (slab brake off). Such a comparatively low tension caused by hydrostatic suction can be easily suppressed by the friction between the plates. Since back-arc tension exists in nature, the friction is probably low in « extensional » subduction zones.

4. The location where the overriding plate breaks (is rifted) under tension is determined first of all by weakened zones in the lithosphere. Failure occurs in the weakest zone. There are several mechanisms that weaken the plate. Depending on their effectiveness, failure in the lithosphere can occur either along an active volcanic arc or on either side of it.

5. The stress-state of the overriding plate is governed by change of the contact pressure P_n in the interplate zone. If the P_n value becomes less, on average than the hydrostatic pressure, then back-arc tension arises and vice versa. On the other hand, P_n affects also the vertical level of the overlapping plate surface and its departure from isostatic equilibrium. In other words, P_n should determine the anomalous gravitational field Δg in the island arc relating it to the back-arc regime. A large positive free air gravity anomaly maximum Δg_m of 200-300 mgal occurring at the frontal arc is inferred to be evidence of compression in the overriding plate (Kuril zone). A shift of Δg_m towards the volcanic arc where the gravity anomaly does not normally exceed 150 mgal is a sign of back-arc tension (Ryukyu, Mariana). The larger the tension, the greater the decrease in Δg_m that must take place. σ_h reaches a maximum during the earlier stages of rifting. Then tensile stresses decrease after the breakage of the lithosphere and initiation spreading.



6. A young age for the subducting plate, a high rate of subduction, the subduction of different asperities and collision with plateaux, microcontinents and continents result in compression of the lithosphere in the subduction zone. If this compression is intensive enough it results in deformation localisation (shortening) in either the volcanic arc or the back-arc basin (depending on where the lithosphere is weakest). Localisation culminates in failure of the lithosphere along inclined faults and in a jump of the subduction zone to this place which results in subduction reversal.

7. A consideration of the geodynamics of the Scotia Sea and Aegean regions shows that an important (perhaps even principal) part in back-arc dynamics is played by the dynamics of the asthenosphere. Both the viscosity and flow rate of the asthenosphere have proved in nature to be sufficient to essentially affect the lithospheric dynamics not only on a global scale, but on the regional level too. The differential pressure due to asthenospheric flow on opposite sides of thick continental blocks seems to be sufficient (under certain conditions) to force these blocks to override a thinner oceanic lithosphere and to form an active back arc basin behind. On the other hand, the continental blocks driven by some external forces can change (increase, in particular) the pressure in the asthenospheric lenses confined between these blocks. This can in turn, cause extension of the overlying lithosphere perpendicular to compression of the asthenospheric lenses. Phenomena of this kind seem to contribute to the nearly north-south extension of the lithosphere in the Aegean Sea and some other regions.

Plate boundary evolution in the Alpine-Mediterranean region: from structure to dynamics

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Results of seismic tomography studies on the 3D mantle structure of the Alpine-Mediterranean region (Spakman, 1988, 1991; Spakman, Van der Lee, and Van der Hilst, 1993; Bijwaard et al., 1998) are our basis for a quantitative approach of the lithospheric dynamics - in particular the plate convergence or subduction processes - in the region. These results allow for new ways of exploring the kinematics and dynamics of the geodynamical evolution of the region.

First, the 3D structure enables us to investigate the merits of various (published) regional paleogeographic/tectonic reconstructions.To this purpose we investigate the quantitative agreement between such reconstructions and the structure of the upper mantle, as obtained by seismic tomography.This is done by forward numerical modelling - on the basis of kinematic reconstructions - of the temperature distribution in the upper mantle, converting the calculated temperature distribution into seismic velocity structure and comparing these model results with the tomographic results(de Jonge, Wortel and Spakman, 1993,1994).

Secondly, from the seismic velocity structure we have inferred that - in the depth range of about 100 to 200 km - deeper parts of subducted slabs have become detached from the lithosphere near the surface and we hypothesize that this detachment process has migrated laterally along the strike of the subduction zones. This process is referred to as: lateral migration of slab detachment (Wortel and Spakman, 1992; see also Yoshioka and Wortel, 1995; Wong a Ton and Wortel, 1997). The process of lateral migration of slab detachment is envisaged to have geodynamical implications on a variety of scales. In particular, the formation and evolution of island arcs and their back-arc regions are adequately accounted for.

With slab detachment as a key element we presented a hypothesis for the Cenozoic evolution of the Alpine-Mediterranean region, with emphasis on the dynamical basis for observed kinematic patterns (Wortel and Spakman, 1992). On the basis of this hypothesis quantitative predictions can be derived for several areas in the Alpine-Mediterranean realm which can be - and are - tested against geological and geophysical data (see Meijer and Wortel, 1996; Van der Meulen et al, 1998; Carminati et al., 1998a,b).

Of special interest in this respect are the spatial and temporal variations -implicit in the model of lateral migration of slab detachment - in state of stress, in vertical motions and in volcanic activity along the strike of convergent plate margins. Analysis of pertinent observables

(Miocene to recent) supports our hypothesis of slab detachment (including lateral migration) in the Hellenic and the Apenninic-Calabrian arcs and also in the Carpathian arc, and leads us to conclude that these three arcs are in different stages of evolution (Wortel and Spakman, 1993). The advancement of the slab detachment process and the associated processes increases in the given order: the Hellenic arc being the youngest and the Carpathian arc being the oldest (evolved) version.

In summary, the test results provide increasing support for the hypothesis of lateral migration of slab detachment, and for the significance of the process in the geodynamical evolution of the region.

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Bijwaard, H., W. Spakman andE.R. Engdahl, Closing the gap between regional and global travel time tomography, *submitted to J. Geophys. res.* , 1998.

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The nature, extent and significance of recent volcanic activity in the Mediterranean region

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Tertiary-Quaternary magmatism within the Mediterranean and surrounding regions, including the European foreland of the Alps, the East Iberian and North African margins and the Eastern Mediterranean, occurs in three distinct associations:

- **extension-related intra-plate magmatism:** typically alkali basalts, basanites and their differentiates but locally including subalkaline (tholeiitic) basalts and rare potassic magma types (leucitites and leucite nephelinites).
- **subduction/post-collisional magmatism related to plate convergence:** characterised by a spectrum of calcalkaline, High-K calcalkaline and potassic magma series (shoshonites and lamproites), including relatively primitive mafic magmas and their differentiates.
- **localised oceanic spreading centres:** erupting subalkaline basalts with affinities to mid-ocean ridge basalts (MORB).

Magmatism is closely associated with the Late Cretaceous-Cenozoic convergence of Africa-Arabia with Eurasia, involving the deformation of intervening microplates (e.g. the Italo-Dinarides block), the gradual closure of oceanic basins in the Mediterranean domain and ultimately the collision of the evolving Alpine orogen with the southern passive continental margin of Europe. The stress field affecting the Alpine-Mediterranean region changed repeatedly during this period, related to changes in the convergence direction. There was a gradual shift of compressional tectonic activity away from the foreland of the Carpathians and Eastern Alps to the foreland of the Central and Western Alps, related partly to dextral translation during the late Eocene-Pliocene.

There appears to have been an intermittent build-up of horizontal compressive stresses in the European foreland, transmitted from the Alpine and Pyrenean collision fronts. Stresses related to the collision of Iberia with Europe, the latest phases of which occurred in the Oligocene-earliest Miocene, probably interfered with stresses transmitted from the Alpine collision zone, at least during the main phases of the Pyrenean orogeny. Phases of compressional deformation occurred during the late Paleocene, late Eocene-early Oligocene, late Oligocene-early Miocene and Pliocene. The Eocene and younger compressional deformation of the northwestern Alpine foreland is broadly synchronous with the evolution of the Cenozoic rift system of eastern and central Europe, which initiated in Middle Eocene-Early Oligocene times.

The geodynamic setting of the western Mediterranean during the Miocene is complex because of the mutual interference of the Alpine-Betic (Cretaceous-Miocene) and Apennine-Maghrebides (Late Oligocene-Pleistocene) collision systems. Continental collision between

Africa and Europe, related to the Alpine-Betic system, occurred in the Early Miocene and since the Tortonian (8-9 Ma) dextral oblique shortening has been occurring between North Africa and Iberia.

The major basins, the Alboran Sea, Valencia Trough and Liguro-Provençal Basin, probably developed as a coherent system of back-arc basins related to eastward roll-back of a westward directed Apennines-Maghrebides subduction zone. These Late Oligocene-Middle Miocene basins developed both within the Betic Cordillera (Alboran Sea) and in its foreland (Valencia and Provençal troughs), cross-cutting the Betic orogenic front. The Alboran Sea opened mainly during the Early Miocene (22-10 Ma), with the zone of extension migrating progressively eastwards. Extension in the Liguro-Provençal Basin probably started in the Late Eocene-Oligocene with the main syn-rift phase from Oligocene-Aquitanian (32-23 Ma). From the Late Aquitanian, sea-floor spreading resulted in a 25-30_ counterclockwise rotation of the Sardinia-Corsica block at a rate of 4-5 cm/yr. During the Lower-Mid Miocene the zone of extension migrated eastwards from the Liguro-Provençal Basin to the Tyrrhenian Sea.

The Western Mediterranean is characterised by large variations in crustal and lithospheric thickness. The lithosphere has been thinned to less than 60 km beneath the major basins (e.g. Valencia Trough - 50-60 km; East Alboran Sea - 40 km; Tyrrhenian Sea - 20-25 km) while it remains 65-80 km thick below the Corsica-Sardina block and the Balearic Promontary, which may be regarded as continental boudins separating zones of intensely stretched lithosphere.

The Tertiary-Quaternary evolution of the Eastern Mediterranean has been controlled by the collision of the African and Arabian plates with the Eurasian plate along the Hellenic arc and, further to the east, along the Bitlis-Zagros suture zone. Northward subduction of a remnant of the Tethys ocean has generated a broad zone of extension and associated magmatism in the Aegean which may be related to slab roll-back to the south.

In order to understand the petrogenesis of the magmas within this wider geodynamic context it is necessary to establish the ages and geochemical characteristics of the main magmatic episodes and their relationship to the local tectonic setting. Magmatism spatially and temporally associated with plate convergence is referred to as being of *orogenic* affinity, whilst that associated with extensional tectonics is termed *anorogenic*. The igneous rocks of each association can be distinguished on the basis of their major and trace element and Sr-Nd-Pb isotope geochemistry; this will be discussed in the context of the Central Mediterranean domain. Emphasis will be placed on the geochemistry of the most primitive mafic igneous rocks as this provides the best indicator of the geodynamic setting of the magmatism. In general, the geochemical and isotopic characteristics of more differentiated (i.e. more silica-rich) magmatic rocks are strongly influenced by high-level crustal contamination of their primitive, mantle-derived, mafic parent magmas.

Mediterranean deformation controlled by the minimum work condition

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It is argued that the complex space-time distribution of deformations in the central-eastern Mediterranean since the Middle Miocene may be plausibly and coherently explained as a consequence of the convergence between Africa, Arabia and Eurasia, without the need of invoking other driving forces, as those connected with active rifting or slab-pull mechanisms. A significant or even dominant role of these last forces has been mainly hypothetized in literature to explain the formation of arc-trench-back arc systems, as the Tyrrhenian and Aegean ones. However, qualitative and quantitative considerations suggest that the major features of arc-trench-back arc systems and of the Tyrrhenian and Aegean cases, in particular, may be more easily explained as effects of the lateral extrusion of crustal wedges. The occurrence of this kind of process might be controlled by the need of minimizing the total work of horizontal forces, induced by plate convergence, against the forces resisting shortening. This may occur, for instance, when the consumption of continental like lithosphere along a collision boundary starts encountering a very high resistance due to the large accumulation of crustal material in the vicinity of the trench zone. In this situation, it may become more convenient, from the energetic point of view, to interrupt lithosphere consumption at that boundary and activate lateral escapes of buoyant crustal wedges, away from highly constricted zones and towards more easily consumable lithospheric domains. The probability of occurrence of this phenomenon increases with the attenuation of the coupling of the buoyant wedges with the underlying structure, due to the presence of ductile layers at depth, and with the adjacent crustal structures, through the formation of major decoupling shear zones. The most clear widely recognized example of this behavior was the lateral extrusion of eastern Anatolia, away from the Arabia-Eurasia collision zone and towards the dense oceanic lithosphere of the Ionian and Levantine areas, but other important examples of extrusion tectonics may be identified in the Neogenic-Quaternary evolutionary history of the central-eastern Mediterranean region. In particular, the concept of extrusion tectonics controlled by the minimum work principle may coherently account for the large scale tectonic/kinematic reorganizations that occurred in the zone considered around the middle Miocene, late Miocene and late Pliocene. The lecture describes the proposed geodynamic interpretation, by illustrating the main observational constraints considered, the major underlying concepts and the evolutionary reconstruction, through a series of paleogeographic maps. A discussion is then reported about the compatibility of the major implications of the various interpretations so far proposed in literature with the space-time distribution of deformations observed.

Gravity anomalies, flexure and the deep structure of passive continental margins

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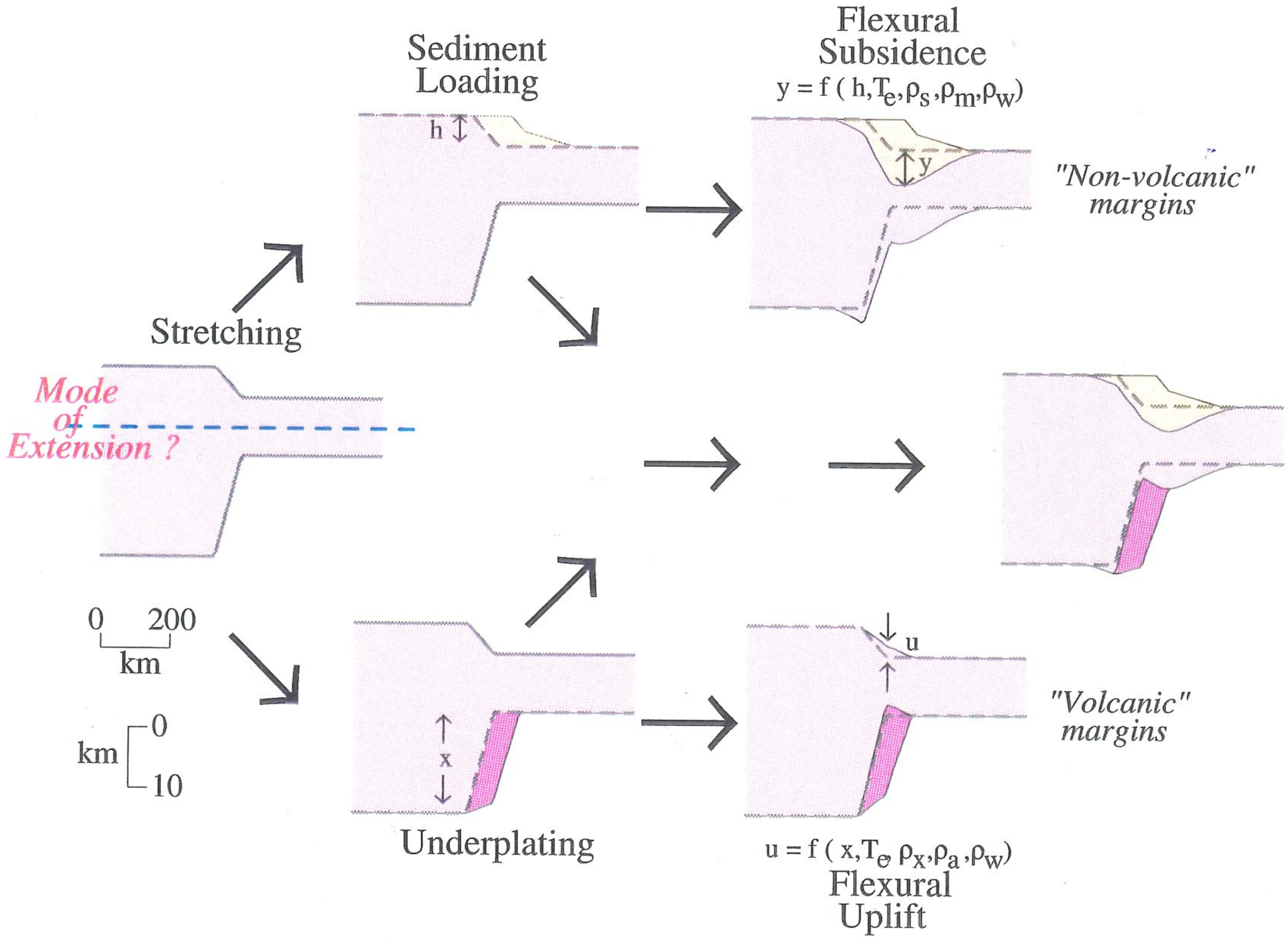
Passive margins form in response to continental rifting and the formation of new ocean basins. Some margins (e.g. Hatton Bank) are associated with relatively thin sediments and large amounts of magmatic material in the form of seaward dipping reflectors and high velocity (P wave velocity > 7.3 km/s) underplated bodies. Others (e.g. East Coast, USA) correlate with large thicknesses of sediment and an absence of significant magmatic activity. While differences in the amounts of magmatism and sediments explain the tectonic diversity of present-day margins, they obscure our understanding of the mechanics, styles and geometry of initial rifting (see for example the enclosed figure).

In order to address this problem, we have been developing backstripping and gravity modelling techniques to quantify the contribution of rifting, sediment loading and magmatic underplating to the crustal and upper mantle structure that is observed at passive margins. Studies at the East Coast, USA margin suggest that sediments there have loaded rifted crust which has a low flexural strength. The predicted depth of the Moho is in reasonable agreement with the depth that is measured seismically. Studies elsewhere, however, suggest that the predicted depth of the Moho is not always in agreement with the depth measured seismically. At the SW Approaches margin, the predicted Moho is shallower than is observed seismically suggesting that material there has been added to the base of the crust during or following rifting. At the western Mediterranean margin, in contrast, the predicted Moho appears to be shallower than is observed suggesting that material has been removed. Each of these studies assume, however, that the gravity anomaly due to rifting can be computed from the backstripped tectonic subsidence and uplift using an Airy-type model. The UK margin generally has less sediment than the East Coast, SW Approaches or Western Meditteranean margins, and so the gravity anomalies there should closely reflect the anomaly associated with rifting. The UK margin has been modified along much of its length, however, by magmatic underplating. At Hatton Bank, seismic refraction data constrain the amount of magmatic underplating, so its contribution to the gravity anomaly can be computed and removed and the rifting anomaly isolated. Again, the rifting anomaly resembles that predicted by an Airy-type model suggesting that, like the East Coast, USA, the SW Approaches, and western Meditteranean margins, this model adequately describes inital rifting at the UK margin.

While the assumption of Airy isostasy may be justified by high lithospheric temperatures, widespread normal faults, and high heat flow, several workers have argued that extended continental lithosphere may possess significant strength during rifting. We have therefore developed techniques that allow the gravity anomaly due to rifting to be calculated from the backstripped tectonic subsidence and uplift which take into account the possibility of strength during rifting. We examine here some recent results of the application of these techniques for a) the segmentation of passive margins, b) the development of foreland basins which may "inherit" the thermal and mechanical properties of ancient passive margins and, c) the modes of extension that develop during continental break-up.

Thermal-Mechanical Properties of Extended Lithosphere ?



Seismotectonics of the Apennines and Tyrrhenian Sea: new insight from the Mw=6.0 Umbria-marche earthquake

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I will treat the present day kinematics of the Apennines and Tyrrhenian sea system, taking the recent Mw=6.0 Umbria-Marche earthquake as pretext. Although such jump seems a little too ambitious, I will show that earthquake seismology can tell a lot in those regions where geodetic data are still too patchy to provide a complete description of motion.

Continental tectonics is far from being as well describe by plate tectonics as oceanic basins. The reason why this is so lies in the growing evidence that continents are characterised by diffuse deformation rather than being restricted to narrow plate boundaries. This led to look for a new framework to describe continental kinematics. Much efforts have been done on this problem and it has been proposed that the kinematics of continents is dominated by the behaviour of the creeping lower lithosphere and is best described by a continuous velocity field, mathematically expressed by the velocity gradient tensor. However, earthquakes are a discontinuous process resulting from strain accumulation in the upper crust. A main problem is thus to understand how earthquakes accommodate this continuous velocity field.

Examples from other continental regions like Greece and Asia testify that seismic deformation is spread over great distances. Recently, it has been shown that earthquakes can provide the complete velocity gradient tensor, that is composed by sum of two tensors: the symmetric strain rate tensor and an antisymmetric tensor corresponding to rigid body rotation. Both quantities are retrieved from seismological observations that are moment tensor of earthquakes. After having recall these basic concepts, I will show at what extent seismic deformation of the Apennines is able to contribute to understand the present day kinematics of Italian peninsula.

The available data show that seismic deformation is achieved differently along the belt both in time and space. The jointly interpretation of historical and recent instrumental crustal seismicity clearly shows that the release is concentrated in a ~ 30 km wide belt running along the highest elevations of the Apennines and that it is possible to divide the Apennines into three sectors. The first corresponding to the northern Apennines, where largest events barely exceed 6 in magnitude involving 10-12 km long faults. The second sector coincides with the southern Apennines where large crustal earthquakes (M ~ 7) occur and where the background seismicity is mainly clustered around major fault segments (that can be even longer than 40 km). The third sector is the Calabrian arc. Here, although seismic data suffer for larger uncertainties, earthquakes with magnitude greater than 7 do occur along the Tyrrhenian coasts. The mode of crustal deformation of the Apennines is mainly by normal faulting indicating NE-SW extension in northern and southern Apennines and NNW-SSE in Calabrian arc. The velocity field is derived from the moment tensors associated to recent and historical earthquakes occurred in these three sectors of the Apennines and shows that velocity up to 2.5 mm/yr are observed.

Once the kinematics is set, dynamics can be discussed. Forces in the lithosphere arise mainly from subduction processes, collision and crustal thickness contrasts.

While subduction generally involves the occurrence of intermediate depth and deep earthquakes, collision and crustal thickness contrasts do not.

Deep and intermediate-depth earthquakes occur beneath two distinct areas: the southern Tyrrhenian Sea and the northern Apennines while they are absent in the southern Apennines.

The distribution of this seismicity of the southern Tyrrhenian allows to delineate the geometry of the subducting slab. Events between 40 and 100 km depth are located beneath the Ionian Sea, and the Calabrian Arc, delineating a sub-horizontal seismic zone that represent the subducting Ionian Plate. The deep seismicity is mainly concentrated in a north-westward dipping "tongue" offshore Calabrian arc, 200 km laterally extended and 50 km thick. A continuous 70° dipping plane is well delineated by seismicity distribution down to 450 km depth occurring within a large portion of the descending slab.

The intermediate-depth earthquakes located beneath the Northern Apennines occur in a south-westward thickening wedge dipping about 40° from the Adriatic towards the Tyrrhenian Sea, until 90 km depth. The intermediate depth earthquakes recorded in this region may indicate that the Adriatic lithosphere plate is still subducting beneath the Northern Apennines, though at a slow rate. Comparison with tomographic images halp to sustain subduction beneath the southern Tyrrhenian Sea and the northern Apennines. In southern Apennines both the absence of deep earthquakes and the lack of clear evidences of velocity anomalies leads to invoke other driving mechanisms for active deformation. Finally, the stress resulting from crustal thickness contrasts will be introduced as speculative hypothesis valid for the Apennines.

Recent volcanic activity in Italy

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Plio-Pleistocene volcanic activity developed along the Tyrrhenian margin of Italian peninsula, in the Tyrrhenian basin in Eastern Sicily and the Sicily channel. The age distribution follows trends which are generally consistent with the gradual opening of the Tyrrhenian basin. Chemical composition of primitive magmas feeding volcanic activity ranges from highly potassic to potassic to calc-alkaline to sodic to typical MORB basalts, indicating different sources which are generated in a mantle which is chemically heterogeneous even at a less than a hundred km scale. Isotopic compositions of elements containing radiogenic isotopes (Sr, Nd, Pb) are reliable indicators of differences in magma sources. The heterogeneity of magma sources is reflected in the regional variations of isotopic composition of Sr, Nd and Pb. It is noteworthy that these strong chemical and isotopic variations occur in a comparatively restricted area. However, isotopic compositions change within the same volcanic district and even in the same volcano. They should be related to depth variations of magma sources and, hence, to variations in the crustal and upper mantle thermal regime. Variations within a same volcano may be related to magma mixing or/and contamination. These processes are temperature dependent. It is therefore very useful to estimate the variation of temperature with depth in the different volcanic areas. Crustal and upper mantle geotherms can be constructed using the available seismic CROP and other refraction\reflection data and heat flow determinations. The major uncertainties of thermal models are bound to the bad knowledge of crustal thermal conductivity. Uncertainties of thermal models compatible with available data are assessed. As diffusion coefficients of chemical elements have a strong dependence on temperature, the thermal state of the crust will affect the possibility of contamination of long residing magmas by diffusion. Residence times of magmas in crustal reservoirs can be evaluated using radioactive disequilibria among the longest lived Th and Ra isotopes of the ^{238}U series. Computed depths for 700°C and 1000°C isotherms are compared with isotope data. They show high crustal temperature in the Tuscanian- Latium volcanic areas. Inferred crustal temperature are lower in Campania and further lower in the Eastern Sicilian area. Consequently depth of magma generation is increasing and possibility of crustal contamination is decreasing from north to south. The relationship between isotopic composition and geotherms is used to infer the characteristics of the source zone of the different magma types and their relationships with the evolution of the central Mediterranean geodynamics.

The Tyrrhenian Seà and surrounding areas: from structural geology to lithosphere dynamics (and back)

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There is no doubt that the Tyrrhenian Sea is a complex system. Its birth and evolution are controlled by a combination of complex boundary conditions and complex internal mechanical changes. Outside the system, the anticlockwise rotation of Adria and the roll-back of the Ionian subducting plate with associated retreat of the subduction zone play a primary role. Inside the system, important players are thermal changes affecting the rheology of the system, asthenosphere dynamics, flexure of elastic plates and several others.

Complex systems such as the Tyrrhenian are very difficult to understand quantitatively when considered as a whole and are practically impossible to model. In general, the modelling of complex systems produces little new understanding and provides few predictive tools. In this presentation, I take a different approach, looking at the constitutive processes, where causal relations are clearer, leaving to a more qualitative procedure (of the reader?) their assemblage.

In general, vertical movements can be explained by changes in the weight of the lithospheric column and consequent isostasy-controlled vertical movements. Since the lithosphere typically retains substantial strength even during extension, compensation will be regional and the vertical movements will also effect areas away from the domain where load changes take place. Depending on the depth of necking, vertical movements of different signs are expected. Modelling techniques have provided a coherent description of the relations between progressive thinning and vertical movements. In a first stage of extension, between 9 and 7 Ma, crustal thinning was concentrated off-shore Sardinia and led to the formation of the Cornaglia basin. Areas on the sides of the basin were either stable or experience uplift, as, for instance, continental Sardinia. Between 7 and 5 Ma, the site of stretching shifted to the SE and thinning caused substantial subsidence in the central parts of the future margin. Eventually, some 3 Ma, extension caused thinning of the most distal parts of the margin and finally led to crustal separation and the formation of oceanic crust. During the post-rift stage subsidence was in the order of hundreds of metres.

Other features cannot be explained without abandoning a «continuum mechanics» approach and adopting n elastic plate approximation. Ideally, plates which are faulted show down-ward flexure of the hanging wall and upward flexure of the foot-wall. As a consequence vertical movements are determined and new stresses are generated in the flexure zones. The most significant conclusion is that a fault cannot accommodated an unlimited amount of extension. The fault will then be abandoned and, with persisting extension, migration will take place either towards the hanging-wall or towards the foot-wall.

Extension in the external parts of the Tyrrhenian system, in the Apennines, typically occurs with this mode of deformation. Foot-wall blocks are uplifted creating morphology and thereby influencing the local and more distant sedimentation pattern. The Bologna fault is a very representative example of such systems. Fault migration in this case occurred towards the foot-wall.

A similar approach, applied to the mantle underlying the southern Tyrrhenian provides phenomenological explanation for the observed and neglected shift of the extension site towards the SE.

A model of the evolution of the Tyrrhenian sea from experimental modelling

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In this paper we present geological constrains and laboratory experiments to highlight the style, the kinematics and the dynamic of the extensional process in the Tyrrhenian Sea. Geological constrains derive from of field-structural analysis, metamorphic petrology and paleomagnetic investigations, mainly performed by our group during the ten years in the northern and southern Tyrrhenian area, and by a compilation of structural-stratigraphic data available for the whole Central Mediterranean regions.

In the Central Mediterranean two back-arc basins, the Liguro-Provençal and the Tyrrhenian basin, opened progressively and consecutively from early Oligocene to present to the back of the subduction Adria-Ionian plate. We compile rift/drift diagrams in space-time coordinates along three transects across these basins. Three different modes of extension are envisaged; in the Liguro-Provençal basin, extension is narrow and localized in the centre of the basin; in the Northern Tyrrhenian basin extension is distributed, and the loci of extension progressively migrated toward the east without any drifting of the Italian margin; in the Southern Tyrrhenian basin extension is distributed but drifting of the Calabrian margin occurred. We interpret the different extensional modes as due to the initial rheological properties of the overriding plate: extension of the Tyrrhenian basin affected a weak and warm post-orogenic Alpine crust, whereas the Liguro-Provençal is settled on a cold Hercynian crust. In the post-orogenic crust, the extensional style depends also upon strain rate, which in the Tyrrhenian basin increases (three time on average) southwards where oceanic lithosphere sinks faster than the continental lithosphere in the north. The nature and distribution of volcanism and heat flow anomalies suggest that the change in the style of deformation are progressive along the Italian peninsula. We propose that, as in the continental extensional process, different pre-rift geotherms and strain rates can explain the different styles of extension in back-arc environments.

Using these boundary conditions, we have performed lithospheric laboratory experiments at the Laboratory of Rennes and at Laboratory of Rome. The aim of these experiment is the semi-quantitative definition of the relative contribution of different mechanisms that could explain the extensional process of the Tyrrhenian area. Three driving mechanisms have been proposed to explain the dynamic evolution of the Tyrrhenian-Apennine system: i) the northward indentation of the African plate, ii) the retreating subduction of the Adria-Ionian lithosphere and iii) the gravitational collapse of the Alpine wedge. To reproduce these mechanism, we have performed 2D and 3D laboratory experiments, where we simulated a retreating subduction process in a compressional regime oriented perpendicularly to the direction of subduction; in this framework we also tested the influence of the gravitational collapse of the overriding plate.

The main conclusion of our experiments is that large scale continental extension, similar to that observed in the Tyrrhenian area, could be reproduced perpendicular to the shortening direction induced by the indentation of the African plate; in this framework, extensional processes are indeed possible if the trench retreat velocity is higher than the rate of shortening induced by the advancing African plate. Our experimental results indicate that this high trench retreat velocity could be explained by the coexistence of the gravitational collapse of the post-Alpine wedge with a slab-pull process, linked to the retreating subduction of the Adria-Ionian plate. While the first mechanism is predominant in the Northern Tyrrhenian area, the second one seems to be important in the latest stage of extension and oceanic accretion of the Southern Tyrrhenian area.

New constraints on the Ligurian Sea formation and evolution

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The NW Mediterranean has been partly formed by the counterclockwise rotation of the Corsica-Sardinia block away from Europe in the Late Oligocene-Early Miocene. A narrow oceanic basin formed, the Ligurian sea, at least partly inside the Alpine belt. The mechanisms and forces responsible for the formation of this domain remain unclear, mainly because the initial rheology, the nature and extent of the stretched crust, the type of oceanic crust formed, the amount of finite extension, and the detailed kinematics of the Corsica drift are poorly constrained by data, or at least questionable.

The objective of this lecture is to provide an overview of the numerous existing geophysical data in this area, a new structural mapping of the margins and the deep basin, and a report on age and nature of several outcrops recently sampled in the deep basins. Indeed, many cruises and experiments have been realised in the last years : multichannel and wide-angle seismics (MALIS 1995), monochannel seismics (MALIGU 1993, SIBONI 1994), dredging (MARCO 1995), diving (CYLICE 1997), together with reprocessing of other geophysical data.

First, steep and narrow margins of the Ligurian sea display strong differences compared to the Gulf of Lions and Western Sardinian margins where a wide continent-ocean transition domain exists. Although they appear relatively linear at a regional scale, investigation and mapping of the Ligurian margins at different structural levels have revealed a close segmentation at a scale of a few tenths of kilometers. Whether this geometry is a consequence of a possible obliquity of rifting (rather than related to rheology or strain rate) remains unclear. Although the overall structure of the conjugate margins results from the Ligurian sea opening, large post-rift volcanism, vertical movements, Messinian erosion and very coarse sedimentation have played a significant role in shaping the Ligurian margins and basin.

Second, the Ligurian basin differs from Atlantic-type oceans by a quick and short Oligo-Miocene opening, giving birth to narrow and segmented conjugate margins with contrasted geometry and structure. The Provençal-Ligurian margin (PLM) is generally composed of two ~15 km wide tilted-fault blocks, whereas the Corsican margin depicts shorter ones below volcanic rocks. Over 50 km along the eastern PLM, we observe highly reflective, parallel, landward dipping reflectors at the base of the crust between 8 and 11 km depth. We improve the basement and Moho geometry thanks to a forward modeling of WAS data. A new map of the basement is presented and discussed. The top of the basement deepens down to 9 km depth in the basin and the Moho rises abruptly from 21-26 km depth under the upper slope to 13-15 km in the basin. On the Corsican margin, the rough geometry of the Moho proposed and the dipping reflectors observed allow us to qualitatively precise the opening style of the Ligurian sea: a detachment-style opening with a simple shear at depth is a possible explanation for the structures observed, although no modelling has been attempted yet.

Third, we rêport new and re-analyses of rocks sampled in several points in the whole Ligurian domain. It appears that the Miocene magmatism is important within two areas : (1) NW Corsica and Genoa Gulf ; and (2) SW Corsica, in the prolongation of the Sardinian rift. These two zones coincide with areas of « wide » margins, separated by a narrow, avolcanic and steep margin between Porto and Calvi. According to K/Ar datings, two groups of ages appear: an old volcanism between 18,5 My and 15 My, and a recent one between 12 My and 7 My. Part of this volcanism widely spread out on the Corsican margin up to the Continent-Ocean Boundary and is active at the end of (or just after) the Corsica-Sardinia drift. It is partly similar in age and nature to the Miocene volcanic outcrops of Sardinia. The conjugate PLM margin seems much less volcanic, and displays ages either older (30-20 My) or youger (6 My).

Most of this rocks display mineralogies close to basic lavas, basalts, andesites and ryodacites. SiO_2 contents are anomalously low, and multi-element spectra reveal typical calco-alkaline magmas (Nb and Ti anomalis) from potassic to shoshonitic.

Finally, we evidence a huge lowstand system tract (slope fan) connected to the salt layer at the foot of the margins, witness of the Messinian salinity crisis. Deformation at the base of these erosional deposits and other current tectonic clues in the PLM and the basin confirm the recent compressive reactivation of the easternmost foot of the PLM linked to the on-going convergence between Europe and Africa.

Insights from historical ad instrumental seismicity in the Alps, Liguria and northern Apennines

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The seismicity of the Western Alps and neighbouring areas has been studied by many authors fron the beginning of this century. In the1940, Roth, on the basis of macroseismic informations, suggested that seismicty distributs in the Western Alps following two active bands named the Piedmontese and the Brianconnais arcs. The more recent instrmental data confirm that the seismicity seems to follow these two arcs even if with some important difference. Indeed, one of the arcs is related with the limit of the Western Alps and the Po Plain and the second follows the Pennidic domain and seems to limit the eastern border of the external massifs. It is usually assumed that earthquakes in intraplate regions occur in the upper crust, and North-Western Italy is generally assigned to this kind of normal seismicity. The depth distribution of the events localized in this area by the IGG seismic network in the period 1991-1997 has been recently analyzed in detail (Cattaneo et al., 1998). In particular, the location capability of the network has been tested adopting as reference terms some quarry blasts (for the epicentral position) and the locations obtained from a dense temporary network (for the depth estimate). Within the so-obtained error limits, the depth distribution of events show a characteristic pattern: while for most of the area covered by the network the well-located seismicity lies within the first 20 km of depth, in a band following the inner arc of the Western Alps many events show anomalously high depth estimates, down to 114 km. These values cannot be attributed to instabilities of the location procedure: completely different choices of the propagation models used for the hypocentral determination led to very similar depth values, always well outside the standard values for the surrounding areas. A strong correlation has been found between the 3-dimensional distribution of these foci and the *P*-wave propagation anomalies obtained from tomographic studies, suggesting a direct link between elastic and rheological properties of lower crust-upper mantle in this area.

The seismotectonic main feature of the Ligurian Sea has been well illustrated in different papers. The continental slope of the Western side of the Ligurian Sea is characterized by a step fault structure, due to the distensive processes affecting the wole area in the pre-Pliocene periods that produced the migration of the Corsica and Sardinia block towards southeast. The old structure appears intersected by a more recent fault system perpendicular to the coast. These faults, as nearly vertical walls, limit the borders of submarine canyons that characterize all the continental margin. This probably indicates an interference of a subsequent distensive phase, trending E-W, that gives rise to some extensional structures (mini-grabens) involving prevailingly the shallower crustal layers. As indicated by the seismic reflection profiles performed in the area, the most important and impressive fault system appears to be related with the foot of the continental margin. where faults displace of some thousand meters the plio-quaternary marine sediments. This is particularly evident at the canyons foot where very thick sedimentary deposits are in direct contact with the basement of the margin and the evaporitic level appears displaced of about 3000 m from the continental slope to the bathyal plain. Seismicity recorded in the last fifteen years (1985-1998) by the seismic network of the DISTER, has been revised and relocated using specific propagation models (Eva et al., 1998) evaluated for the area. Even if, in this time interval, some events of moderate magnitude (M=4.8:Ventimiglia earthquake of the 15 April 1995: Courboulex et al., 1998) occurred along the shore line, major seismic events have been located offshore along the fault systems bordering the foot of the continental margin. The minor activity (M<3.5) sometime seems to indicate a trend perpendicular to the coast. It is enphasizing that the most important events seems to cluster at the interference knots of the two fault systems: respectevely perpendicular and parallel to the coastal line. An other seismic band is present in the center of the Ligurian Sea. Only in very recent times, on the basis of an interpretation of a high resolution reflection seismic profile, perfomed in the frame of italian CROP-mare project, this band has been correlated with the presence a drastic change of the tectonic regime between the Ligurian oceanic floor and the Corsicastructure. Indeed southwards of this line the continental crust of the Corsica is characterized by a system of distensive ensialic faults.

These two bands of seismic activity converging in the north-western side of the Ligurian Sea limit the oceanic crust indicating that both margins are still active. The distribution of forces acting in the Western Alps ad Ligurian Sea is still somewhat uncertain. Up to now many efforts have been made to map the distribution of *P* and *T* axes of focal mechanisms that, as well known, can be largerly different from the principal stress direction. A detailed analysis of focal mechanisms of events with magnitude spanning from 2.5 to 5.3 has been performed on the whole area in order to define the stress orientation axes. The results confirm the impossibility to define, within the available data, a regional stress field. In fact different local behaviour have been pointed out in four subregions. For the first, namely the northern part of the Western Alps, the inversion of 28 focal mechanisms, resulting in a misfit of 5.9°, revealed a distensive regime NS oriented. For the second area, the outer part of the western Alps, the inversion of 16 earthquakes lead to a misfit of 5.3° for a distensive EW oriented regime. Conversely, the inner part of the chain an opposite result was obtained by the inversion of 14 earthquakes. The region of the Ligurian Sea revealed an almost horizontal NW-SE oriented $\sigma 1$ axis, and $\sigma 3$ is NE-SW oriented with a dip of around 30° to 40°. These results confirm that most part of the Western Alps is sujected to a distensive field probably due to a compression produced by the Po Plain that is probably pushed toward West by the rotation of the Italian peninsula around a pole located aproximately North of Genoa.

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The Messinian salinity crisis: a view from land

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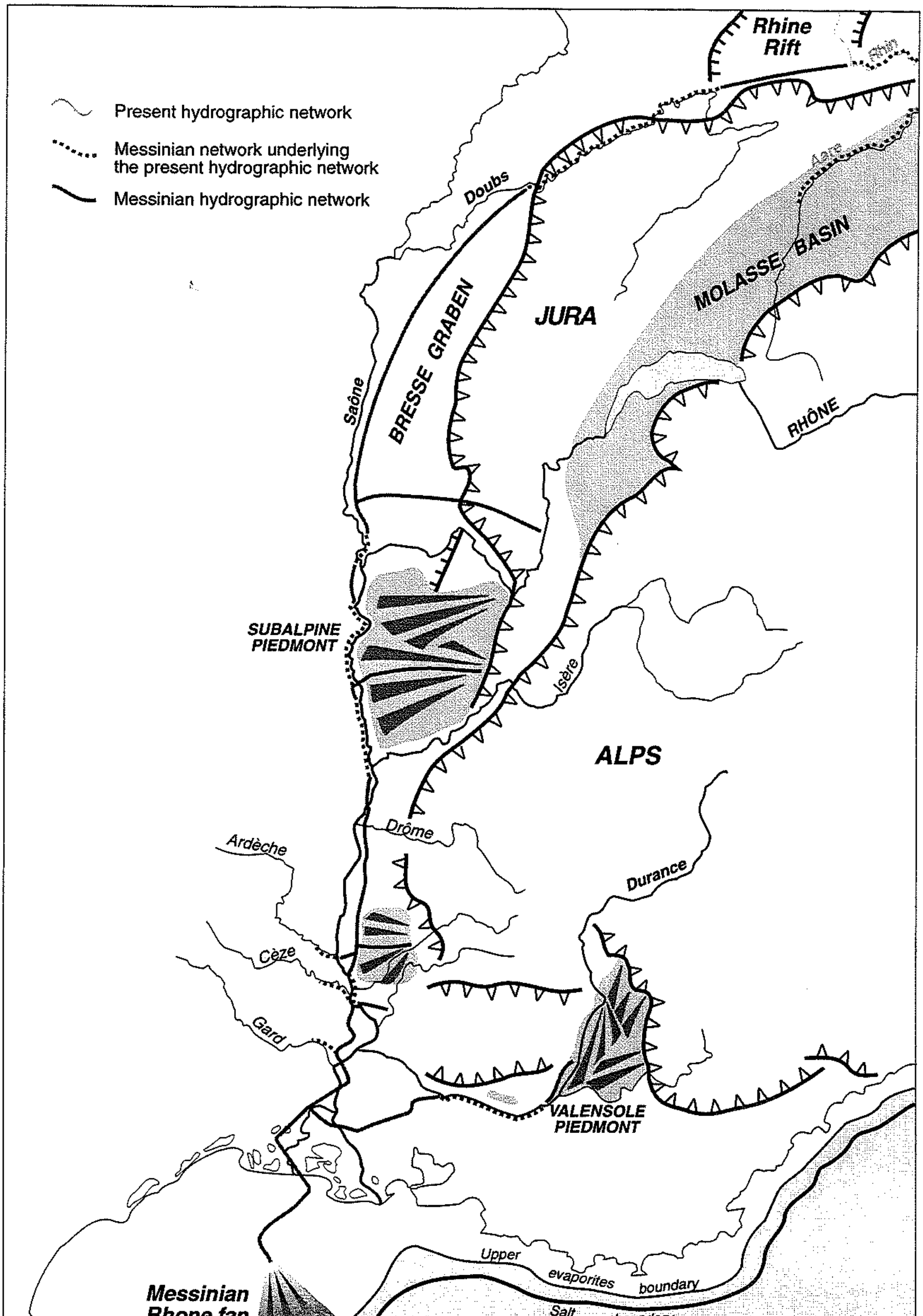
Plates presented :

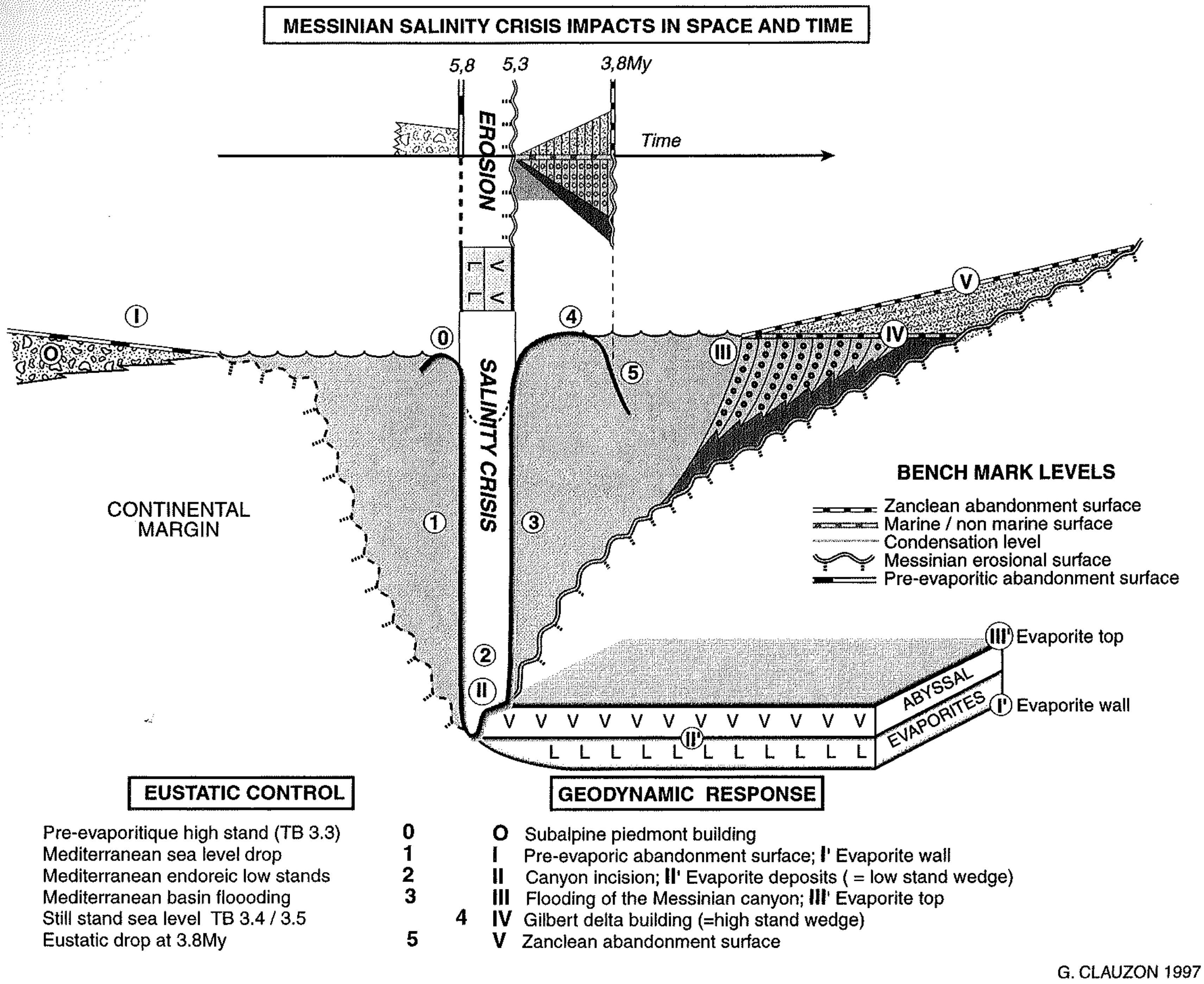
- **Plate 1 :** Messinian an present-day hydrographic networks around the Alps, and position of the evaporitic basin of the Western Mediterranean sea.

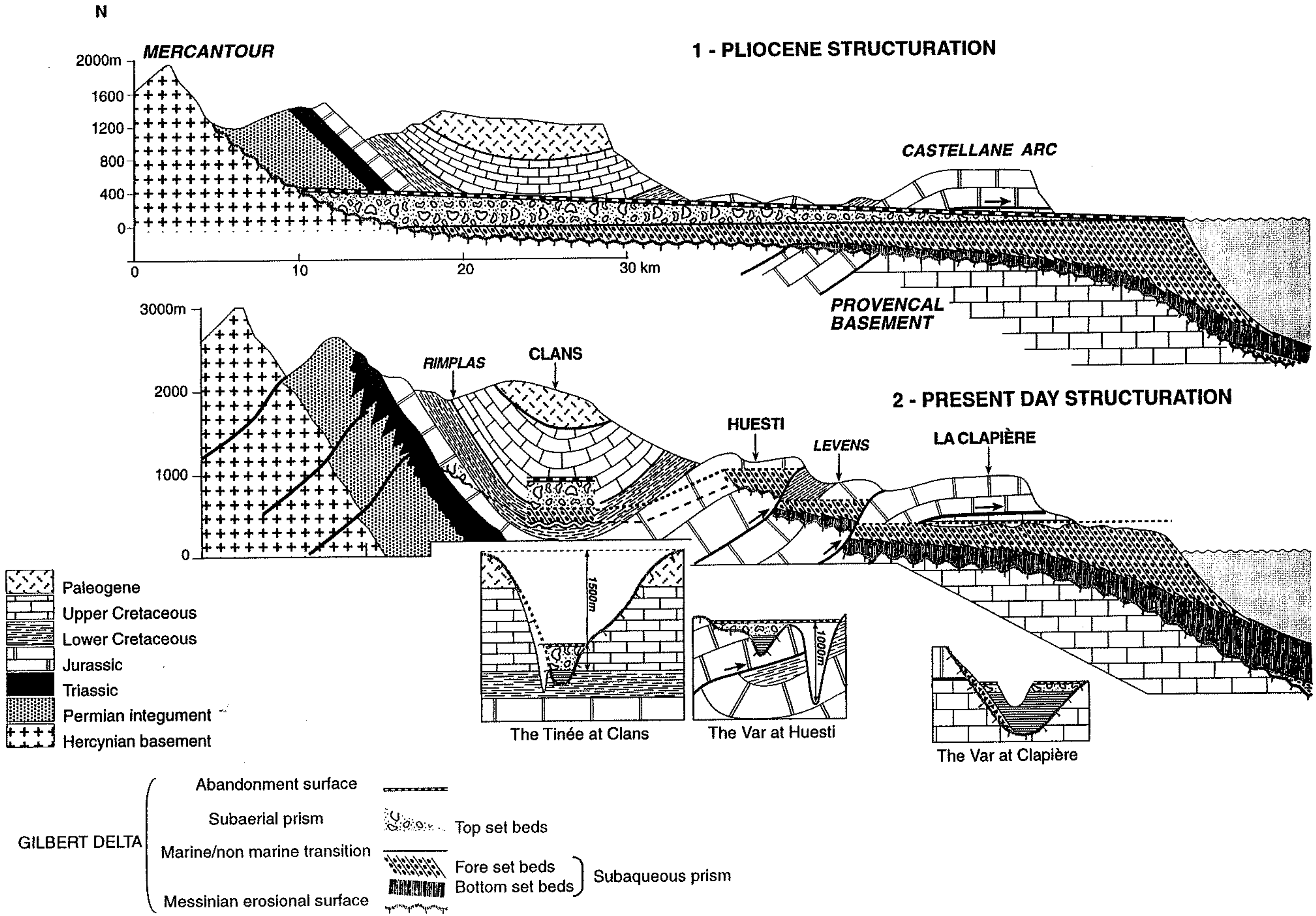
- **Plate 2 :** Messinian salinity crisis impacts in space and time.

- **Plate 3 :** Cross section from Mercantour (Argentera) Massif to the Mediterranean Sea : (1) Pliocene structuration ; (2) Present-day structuration.

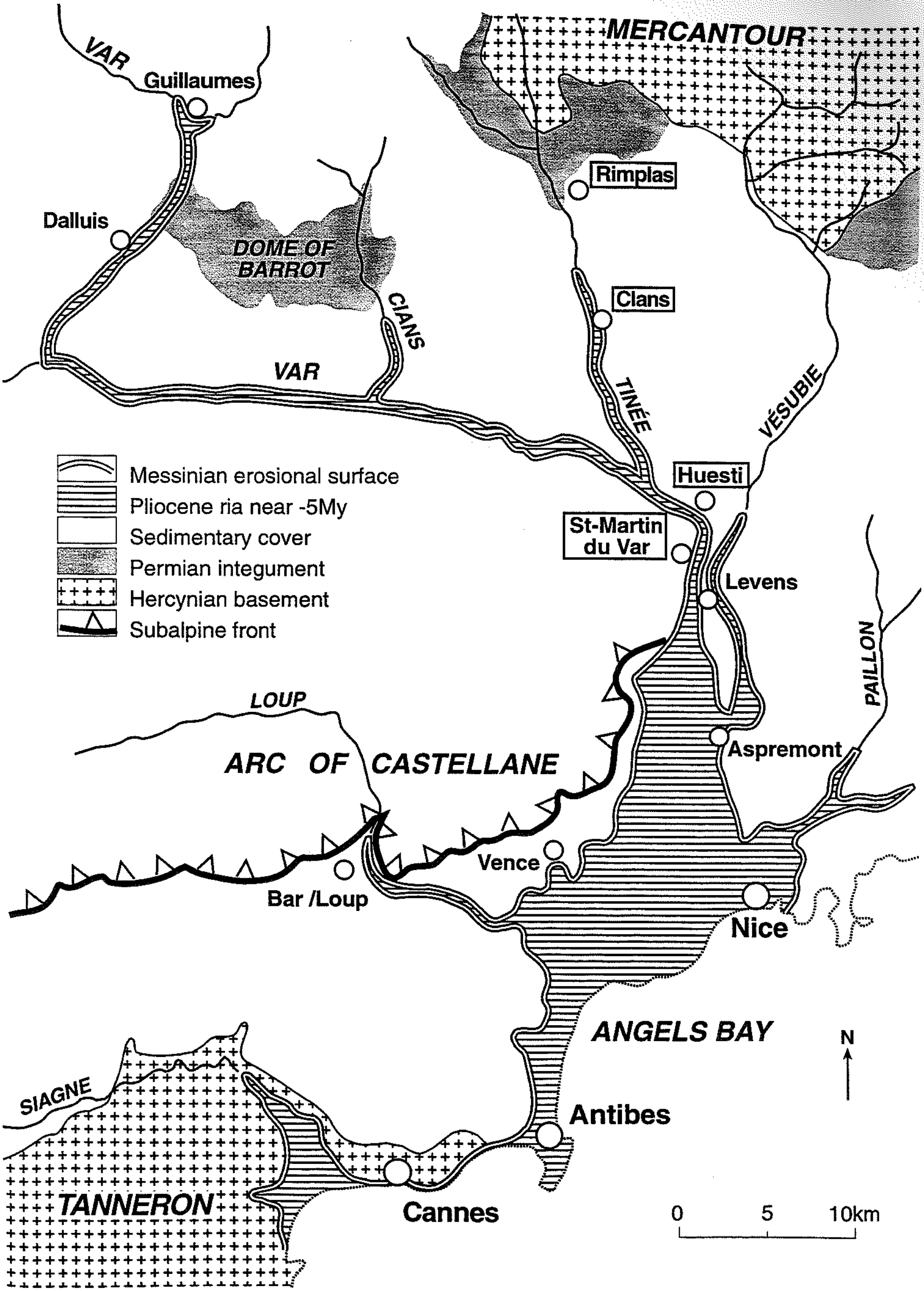
- **Plate 4 :** Distribution of Messinian erosional surface and Pliocene rias in the back-land of Nice, and structural framework.


Present hydrographic network
Messinian network underlying the present hydrographic network
Messinian hydrographic network
Rhine Rift
Rhin
Aare
Doubs
MOLASSE BASIN
JURA
BRESSE GRABEN
Saône
RHÔNE
SUBALPINE PIEDMONT
Isère
ALPS
Drôme
Ardèche
Durance
Cèze
Gard
VALENSOLE PIEDMONT
Upper evaporites boundary
Salt boundary
Messinian Rhone fan
EVAPORITIC BASIN
0 25 50 75km


MESSINIAN SALINITY CRISIS IMPACTS IN SPACE AND TIME
5,8
5,3
3,8My
Time
EROSION
SALINITY CRISIS
CONTINENTAL MARGIN
ABYSSAL
EVAPORITES
BENCH MARK LEVELS
Zanclean abandonment surface
Marine / non marine surface
Condensation level
Messinian erosional surface
Pre-evaporitic abandonment surface
III' Evaporite top
I' Evaporite wall
EUSTATIC CONTROL
Pre-evaporitique high stand (TB 3.3) 0
Mediterranean sea level drop 1
Mediterranean endoreic low stands 2
Mediterranean basin floooding 3
Still stand sea level TB 3.4 / 3.5 4
Eustatic drop at 3.8My 5
GEODYNAMIC RESPONSE
O Subalpine piedmont building
I Pre-evaporic abandonment surface; I' Evaporite wall
II Canyon incision; II' Evaporite deposits (= low stand wedge)
III Flooding of the Messinian canyon; III' Evaporite top
IV Gilbert delta building (=high stand wedge)
V Zanclean abandonment surface
G. CLAUZON 1997



N
MERCANTOUR
1 - PLIOCENE STRUCTURATION
2000m
1600
1200
800
400
0
0
10
20
30 km
CASTELLANE ARC
PROVENCAL
BASEMENT
3000m
2000
1000
0
RIMPLAS
CLANS
2 - PRESENT DAY STRUCTURATION
HUESTI
LEVENS
LA CLAPIÈRE
1500m
1000m
Paleogene
Upper Cretaceous
Lower Cretaceous
Jurassic
Triassic
Permian integument
Hercynian basement
The Tinée at Clans
The Var at Huesti
The Var at Clapière
GILBERT DELTA
Abandonment surface
Subaerial prism
Top set beds
Marine/non marine transition
Fore set beds
Bottom set beds
Subaqueous prism
Messinian erosional surface


MERCANTOUR
VAR
Guillaumes
Rimplas
Dalluis
DOME OF
BARROT
Clans
CIANS
VAR
TINÉE
VÉSUBIE
Messinian erosional surface
Pliocene ria near -5My
Sedimentary cover
Permian integument
Hercynian basement
Subalpine front
Huesti
St-Martin
du Var
Levens
PAILLON
LOUP
ARC OF CASTELLANE
Aspremont
Vence
Bar /Loup
Nice
ANGELS BAY
N
SIAGNE
Antibes
TANNERON
Cannes
0
5
10km

Deep sedimentary processes in the Ligurian Sea

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The basement of the Ligurian basin is covered by 6-7 km of sediment, consisting of 1-4 km of Oligocene-Miocene detrital sediments, 1.5 km of Messinian salt overlain by bedded evaporites, and 1 to 1.5 km of Pliocene-Quaternary turbidites (Mauffret et al., 1973; Mauffret, 1982). There is widespread evidence for extensive erosion on continental margins and deposition of salt and evaporites in basins throughout the Mediterranean during the Late Miocene. Recent analysis of seismic reflection profiles, augmented by submersible observations, allowed the pre-Pliocene morphology of the continental margin to be defined in detail (Savoye and Piper, 1991). The continuation of the Messinian Var paleovalley has been mapped offshore. The return of open-marine conditions in the early Pliocene resulted in the invasion by the sea of the subaerial Messinian Var valley, which thus became a ria. The Var ria was filled by Gilbert-type fan deltas (Clauzon et al., 1990), as were all the other main Messinian valleys southern France. A 600-1000 m thick sequence of marls and conglomerates on the continental slope largely masks the pre-existing morphology.

The Pliocene - Quaternary sedimentary succession, consisting of marls and conglomerates (Gennesseaux and Glaçon, 1972; Irr, 1984), was deposited on the continental slope seaward the Var delta and the Var deep-sea fan began to accumulate in the basin. Subsequently, the present canyons appear to have eroded deep into the cover of Pliocene-Quaternary sediments on the continental slope (Pautot, 1981; Gennesseaux and Le Calvez, 1960; Le Cann, 1987). The Var River system, which heads in the Alps, has been the dominant contributor to the fan and the Ligurian basin throughout the Pliocene and the Quaternary, although some sediment has been provided La Roya and Furria di Tagia canyons.

The present surface morphology and sedimentary structure of the ligurian sea south of Nice are therefore the result of complex interaction between the Messinian paleo-morphology and Pliocene - Quaternary tectonic and sedimentary processes.

The Var fan has a single fan valley that displays abrupt bends separated by long straight reaches, and an extremely asymmetric levee system. It thus does not closely resemble passive margin, delta-fed submarine fans such as the Mississippi (Bouma et al., 1985, 1989), Indus (Kolla and Coumes, 1984), Amazon (Damuth et al., 1988) or Rhône (Droz and Bellaiche, 1985), which are characterized by distributary systems of numerous fan valleys. In some respects, Var fan, with single fan valley and asymmetric levee, is much more similar to smaller fan such as the Monterey (Normark et al., 1984) or Cap-Ferret (Nely et al., 1985) fans.

In the talk, we will use seismic data to define in detail the Pliocene-Quaternary seismic stratigraphy and the depositional geometry of the Var sedimentary system to better understand its evolution in space and time. The fan evolution is related to the known history of the Var River on land.

Accurate observations (side-scan sonar, Huntec boomer, submersible, ...) were carried out during several detailed oceanographic surveys conducted from the source area to the distal part of the Var fan lobe. The fan has a morphology suggesting important deposition from both sandy and muddy turbidity currents. Deposition has continued during the Holocene, partly by hyperpycnal flows. Many Holocene turbidites have been observed in cores on the levees. During landfilling operations to extend Nice airport in 1979, a submarine slide affected the muddy prodelta slope, resulting in a tsunami and the cables breaks near and across the lower Var fan valley.

Deep-water SAR and SeaMARC sidescan sonar studies showed fresh gravel waves within the upper valley. Fresh erosion marks on the sea-floor were observed 6 months after the 1979 Nice failure during submersible dives in the lower Var canyon and upper Var fan valley. Backscattering changes of the sonar images along the middle fan valley point out the limit of the sand deposition. Features like sand ridges and erosional scars are observed downslope the fan valley, suggesting that turbidity currents are powerful enough to rework the sea-floor. Recent EM12D and SAR side-scan data show that the distal lobe of the Var fan is located near the northwest Corsican margin covering an area of up to 1900 km^2 at a distance of about 200 km from the head of the canyon. The lobe has a single channel with smaller distributaries, displaying a goose foot like pattern.

High-resolution seismic boomer profiles, with a vertical resolution of less than 1 m, together with piston cores and previous sidescan sonar data have been used to define the late Quaternary sedimentation on the Var deep-sea fan. Chronologic control is provided by foram biostratigraphy and radiocarbon dating in cores and extended over the fan by seismic correlation. Major erosional events are recognised corresponding to the isotopic stage 2 and 6 glacial maxima.

Cores and seismic data define a widespread surface sand layer that is correlated with prodelta failure in 1979 and subsequent submarine cable breaks. Numerical modelling places some constraints on the character of the 1979 turbidity current. It originated from a relatively small slide on the upper prodelta that put sufficient material in suspension to form an accelerating turbidity current which eroded sand from the Var canyon. The turbidity current was only 30 m thick on the Upper Valley, but experienced significant flow expansion in the Middle Valley to thicknesses of more than 120 m, where it spilled over the eastern Var Sedimentary Ridge with a velocity of about 2.5 ms-1. Other Holocene turbidity currents (with a 103 yr recurrence interval) were somewhat muddier and thicker, but also deposited sand on the levees of the Middle Valley, and are inferred to have had a similar slide-related origin.

Late Pleistocene turbidity currents deposited thick mud beds on the levee. The presence of sediment waves and the mean cross-flow slope inferred from levee asymmetry indicates that some of these flows were many hundreds of metres thick and flowed at velocities of about 0.35 ms-1. This contrast with Holocene turbidites suggests that a slide origin is unlikely. Estimated times for deposition of thick mud beds on the levees are many days to weeks. The Late Pleistocene flows may therefore result from hyperpycnal flow of glacial outwash in the Var river. The variation in the Late Pleistocene - Holocene turbidite sedimentation is controlled more by variations in sediment supply than by sea level change.

Changes through time in abundance and character of turbidity currents suggest that variations in the Quaternary turbidite sedimentation are controlled more by climatic variations than by sea-level changes.

Extensional tectonics and sense of shear in the Mediterranean region

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Post- and syn-orogenic extension has been active since the last 25-30 Ma in the Tyrrhenian and Aegean Seas. In both regions a continuum of extensional strain and exhumation of metamorphic rocks is recorded during this period with little kinematic variations. Ductile extension observed in metamorphic core complexes has been achieved in the same overall strain field as brittle extension, active and fossil. Of prime importance are shallow-dipping extensional shear zones which were mostly active within the brittle-ductile transition zone. Those shear zones exhibit consistent shear sense indicators over large regions, of the order of 200 km.

The Aegean Sea offers a large number of core complexes in the Cyclades and Crete. In the central and southern Aegean, from Crete to Mykonos and Tinos, all core complexes were exhumed below shallow north- or northeast-dipping extensional shear zones which were active during the Early and Middle Miocene. Extension is associated to a HP-LT environment in the south and a HT-LP one in the north. Present-day extension also involves shallow north-dipping extensional shear zones in the brittle-ductile transition as recently shown by microseismicity studies. During the Early Miocene top-to-the-SW shear sense indicators are recorded along similar extensional shear zones north of the North Aegean Trough.

The northern Tyrrhenian Sea also shows several metamorphic core complexes along a transect running from Alpine Corsica to Tuscany in the inner zones of the Apennines. Extension is now active within the Apennines after an eastward migration which started the Early Miocene in Alpine Corsica. A continuum of extension is recorded from the Early Miocene in Corsica, to the Late Miocene in Elba and Monte Cristo, the Pliocene in Giglio and Monte Argentario and Quaternary in the Apennines. As in the Aegean Sea a cool geothermal gradient is recorded during the Miocene in the east (Giglio, Argentario, Apuan Alps) as attested by the presence of HP-LT metamorphic parageneses, while a warmer gradient is associated with post-orogenic extension in Elba. Extension is achieved through shallow east-dipping extensional shear zones, with consistent top-to-the-east kinematic indicators from Corsica to Giglio.

The two regions are characterized by a migration toward the external zones of a compressional domain followed in the backarc region by an extensional domain with consistent shear senses over large regions. Symetric shear sense is observed on either sides of the volcanic arc. The sense of shear along the brittle-ductile transition is always toward the volcanic arc. This situation is similar to some scale models published earlier where a velocity discontinuity at the base of the ductile crust controls the distribution of shear sense along the brittle-ductile transition.

We propose that the volcanic arc introduces a velocity discontinuity in the upper mantle and lower crust: the high thermal gradient induces a softening of crustal and mantellic material below the arc. The retreat of the trench and arc (1.5 cm/yr for the northern Tyrrhenian Sea - Apennines system, 3 cm/yr for the Aegean-Hellenic system measured form the migration of the volcanic arc) induces a traction of the subcontinental mantle below the continental crust between the trench and the arc. The upper continental crust resists to this traction and an "arc-ward" shear zone forms along the brittle-ductile transition. This traction will not be transmitted through the weak upper mantle and lower crust in the vicinity of the volcanic arc. Extensional stresses will only be transmitted through the upper brittle crust to the opposite side of the arc. The upper crust will then be dragged toward the volcanic arc and a shear zone will form along the brittle-ductile transition with a reversed shear sense.

The Pannonian basin and its geodynamical significance in the Mediterranean evolution

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Geological setting: The Pannonian basin is one of the Mediterranean back-arc basins developed during the last phase of the continent/continent collision of the African and European plates. The basin is a zone of areal expansion and subsidence in the compressional orogenic belt, now completely surrounded by a mountain ring of the Eastern Alps, Western-, Eastern- and Southern Carpathians and the Dinarides. The non-uniform Neogene-Quaternary subsidence of this surrounded area resulted in the development of several sub-basins. The largest of these is the Pannonian basin which is separated by the Little Carpathians from the Vienna basin and the Apuseni Mountains from the Transylvanian basin. The Pannonian basin can be further subdivided. The basinal area to the NW from the Transdanubian Range is called the Little Hungarian Plain on the Hungarian side and Danube Lowland on the Slovakian part. The southeastern part is the Great Hungarian Plain, its northeastern corner is called the East Slovakian basin or Transcarpathian depression. Two elongated sub-basins, the Drava and the Sava troughs North to the Dinarides can be considered as part of the Pannonian basin as well.

Tectonic evolution: As discussed by Horváth and Tari (1998), four major periods of the tectonic evolution can be distinguished since Late Permian times :

- *Late Permian through Early Cretaceous.* Two distinct episodes of continental breakup occurred during this period in the future Alpine-Mediterranean domain of Pangea. While the Triassic rifting aborted in most of the area, the Jurassic extension led to the formation of the Tethys ocean, flanked by two rifted continental margins: the African-Adriatic (on the South) and the European (on the North). After the rifting, the continental margins and the intervening ocean were controlled by thermal subsidence until the end of Early Cretaceous.
- *Late Cretaceous through Paleocene.* It was a period of first major compressions in the Alpine system, when many of the oceanic troughs and passive margins disappeared, due to convergence of the continental margins and subduction of the Tethys ocean. During this period, three subperiods of compressional events can be recognized: the Austrian phase (Aptian-Albian), the Pre-Gosau phase (Cenomanian-Turonian) and the Laramian phase (Maastrichtian-Danian). These events played a decisive role in shaping the structure of the pre-Tertiary strata in the intra-Carpathian area. In addition to that, it was an important period of basin formation, which took place in the Senonian, after the second and before the third compressional event. Accordingly, the Senonian basin fill always represent a seal on the thrusts and folds developed during the Austrian and pre-Gosau phases.
- *Eocene through Early Miocene.* This period represents the second major interval of collision and compression in the Alps, which affected mostly the more external parts. In the internal

part a set of basins developed. The two most remarkable basins are the Paleogene "epicontinental" basin and the Szolnok-Maramures "flysch" basin. At the end of this period (latest Oligocene-Early Miocene) large-scale lateral displacement (continental extrusion) and/or rotation of internal blocks occurred, which disintegrated the former Alpine thrust-fold belt, and strongly dismembered also the Paleogene basins. Disintegration includes juxtaposition in the intra-Carpathian area of two Alpine terranes of different early Mesozoic paleographic position: the North Pannonian terrane (African-Adriatic continental margin) and the South Pannonian terrane (European continental margin). The boundary of the two juxtaposed terranes is actually a wide zone of intensive early Miocene deformation, called the mid-Hungarian shear zone.

- *Middle Miocene to Recent.* Continuing convergence between Europe and Africa has formed further thrust-fold belts in the most external domains. In the rearranged internal domain the Middle Miocene was the period when widespread continental rifting initiated the formation of the intra-Carpathian basins. It was followed by the postrift thermal subsidence, however, compressional events causing local basin inversion and fault reactivation also occurred.

As a result of this evolution the present day Pannonian basin can be characterised by the following geophysical/geological features:

- Thin (25-30 km) crust below the Pannonian basin and thick (40-65 km) crust below the Outer Carpathians and the Dinarides.
- The mantle lies in an elevated position (45-65 km) under the basin and the thin lithosphere is underlain by an updomed asthenosphere.
- Pronounced geothermal highs within the area of the basin and heat flow highs (80-130 mW/m^2) particularly in the area of the Great Hungarian Plain. The Vienna basin and the Transylvanian basin however can be characterised by heat flow values of about 50 mW/m^2.
- Gravity anomaly maps show that the Carpathian arc is characterized by negative Bouguer anomaly up to -120 mgal, the axes of which do not follow exactly the trend of the main tectonic zones. The Pannonian basin exhibits slightly positive and negative Bouguer anomaly values between -20 and +25 mgal.
- Several independent observations (e.g. geomorphology, magnetostratigraphic measurements on cored sediment samples, fission-track dating) indicate strong vertical differential movements in the basin. The Transdanubian Range and the North Hungarian Range are uplifting, while the Little Hungarian Plain, the Great Hungarian Plain and the Sava and Drava troughs are subsiding parts. Subsidence rate of about 170 m/m.y. has been estimated for the Quaternary-late Miocene times in the Great Hungarian Plain.
- The Vrancea zone at the junction of the Southern and Eastern Carpathians exhibit high seismic activity with large earthquakes occuring at intermediate depth (between 70 and 130 km), most probably reflecting a fragment of the subducted lithospheric slab. The Pannonian basin can be characterized by low seismic activity, however recent studies suggest, that some of the main faults of the basinal area still have to be considered active.

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MAST Advanced Study Course

INSIGHTS ON THE FORMATION AND EVOLUTION OF MEDITERRANEAN BASINS

Villefranche-sur-Mer, France

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