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Integrated Peri-Tethyan Basins studies (Peri-Tethys Programme)

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Abstract

This issue brings together 12 papers presenting results of geodynamic/subsidence studies performed in the frame of the Peri-Tethys Programme (PTP). The areas in question are for the northern Peri-Tethyan Platform: the Dniepr-Donets, Precaspian, Polish Basin, southern Carpathians, North Fore-Caucasus, South Caspian and Black Sea basins. For the southern Peri-Tethyan Platform, the basins studied include basins of Morocco, North Algerian Atlas' basins, Tunisia and Arabia basins. Some features of these basins' evolution are given for each area. The tectonic evolution and driving mechanism of these basins' subsidence are placed in the general context of the break-up of Pangea, opening of the Tethys ocean, followed by its closure before the general collisional regime.

Keywords: Tethys; Peri-Tethyan platforms; Rifting; Compression; Subsidence modelling; Flexure

1. Introduction

This special issue is dedicated to the studies of a number of Peri-Tethyan Basins performed in the frame and with funds of the Peri-Tethys Programme (PTP).

The aim of PTP which lasted from 1993 to 2000, was the analysis of north and south Peri-Tethyan Platforms from Carboniferous to Present. It was the successor to an Atlas on the Tethyan area (Dercourt et al., 1993), the final product of a previous program: "Tethys". PTP was sponsored by 13 companies or institutions which were (before some merging): Agip, Arco, BRGM, Chevron, CNRS-INSU, Conoco, Elf, Exxon, IFP, Shell, Sonatrach, Total and Pierre & Marie Curie University.

The area covered by PTP is located between the Atlantic Ocean and Ural Mountains in the north and from Morocco to Arabia in the south. The main focus was the examination of the behaviour of Peri-Tethyan sedimentary basins in the context of the end of the Variscan structural heritage, the opening of the Tethys and its subsequent closure between Eurasia and the Arab-African plates.

In the course of PTP, contributors have published hundreds of scientific papers presenting scientific results funded by the program. Some were published

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in specific series of Peri-Tethys Memoirs (Roure, 1994; Ziegler and Horváth, 1996; Crasquin-Soleau and Barrier, 1998a,b, 2000; Ziegler et al., 2001a) and three special issues of Geodiversitas (Crasquin-Soleau and De Wever, 1997, 1998, 1999).

The final products of PTP comprise an Atlas of 24 palaeogeographical maps (Dercourt et al., 2000) and three volumes published as special issues of international journals. These volumes are, respectively, devoted to the palaeostresses and tectonics (Barrier et al., in press), the palaeogeography of the Peri-Tethyan areas (Gaetani, submitted for publication) and the present volume to the basin studies.

2. Peri-Tethyan Basins studies in the Peri-Tethys Programme

2.1. General setting

Geodynamic analysis of the sedimentary basins situated on the north and south Peri-Tethyan Platforms was performed by the «Basins Geodynamics» Group of PTP and also for complementary areas and works by the IGCP 369 Group «Peri-Tethyan Rift/Wrench Basins and Passive Margins», led by W. Cavazza, P. Ziegler and A. Robertson. Creation of the IGCP 369 was initiated by PTP leaders in 1994. The results of this group are published in the PTP Memoir 6 (Ziegler et al., 2001a).

The «Basins Geodynamics» Group (PTP) focused on formation and evolution of sedimentary basins of 11 regions distributed in three zones of the Peri-Tethyan domain which were studied by three series of teams (see Fig. 1). On the northern platform, research was concentrated on eastern Europe, at first on the old basins of Dniepr-Donets (Stovba et al., 2003) and Precaspian (Brunet et al., 1999; Volozh et al., 2003). Subsequent research focused along the major lithospheric feature, the Trans European Suture Zone (TESZ). That is to say on the Polish Basin (Stephenson et al., 2003), and also on the flexural basins of southern Carpathians (Matenco et al., 2003) that cover this trend in part. The Group has also worked on the basins associated to the Great Caucasus (Ershov et al., 1999, 2003), the South of the Caspian Sea (Korotaev, 1998; Brunet et al., 2003) and the Black Sea (Cloetingh et al., 2003; Nikishin et al., 2003), i.e. the complex area where the margins of oceans, or marginal basins, were successively superimposed during a very long lapse of time. For the southern Platform, a number of basins in Morocco (Ellouz et al., 2003) and North Algerian Atlas-related basins (Bracene et al., 2003) were studied, as well as basins in Tunisia (Patriat et al., 2003) and Arabia (Le Nindre et al., 2003).

2.2. Objectives

For each basin, the teams in charge aimed to compile the available data on basin fill. Sedimentary data recorded the basin evolution through time. The geophysical data provides constraints on the present basin configuration (sedimentary and crustal thicknesses and densities), resulting from the general evolution of the basin. This combination of all available data allowed hypotheses to be tested on the origin of the basin, the subsidence driving mechanisms, the behaviour of the basin and its evolution through time. The timing of the different tectonic events is registered in the sediments and in the movements of faults with subsidence or uplift (also documented by fission tracks study).

Stratigraphy (outcrops, wells, seismic reflection profiles) are used to infer ages, thicknesses according to the period of time, and lithology to calibrate the decompaction parameters and the environment of deposits. Reflection–refraction data, gravimetry, and heat flow give information on the crust (thickness, velocity/density) and lithosphere structure permitting the derivation strength profiles of both the crust and the lithospheric mantle when more elaborate modelling was undertaken.

The main purpose was to employ a methodology that allowed consistent comparisons of age to be made for the tectonic events in the different basins. To present the subsidence curves for all the basins, we used the same time scale (Odin, 1994; chosen at the beginning of PTP) and a backstripping method similar to that of Steckler and Watts (1978). In fact, the tectonic subsidence analysis and modelling reached very different levels in each of the studied areas. This depended on the amount of data and modelling tools available for the teams, and whether a study of the area had been undertaken before PTP. The results presented are a synthesis of the geological data on the

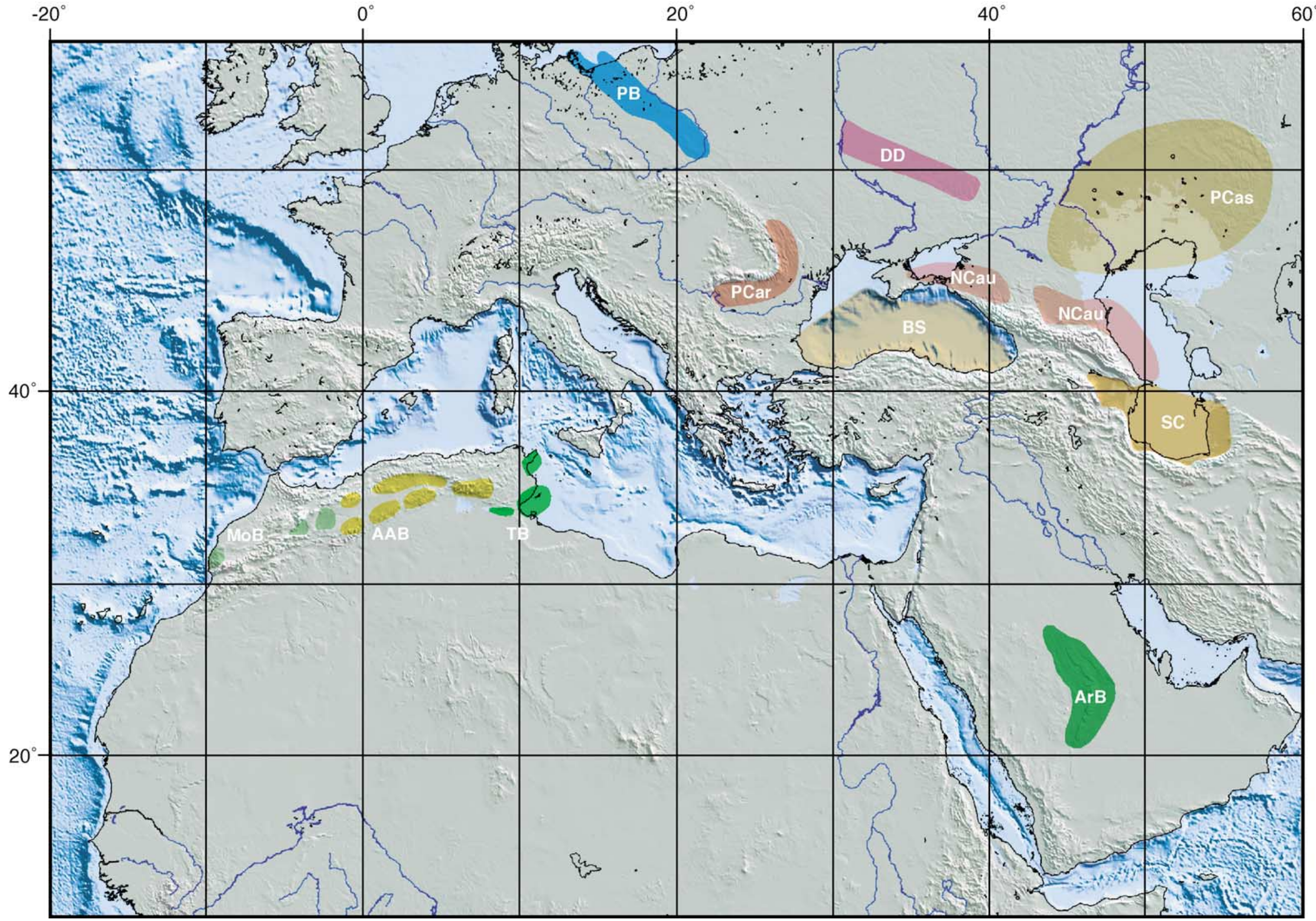

Fig. 1. Location of the basins studied by the PTP group «Basins Geodynamics»: West of northern margin, participating teams: Vrije Universiteit Amsterdam, Ukrgeofisika Kiev, University of Bucarest, Polish Institute of Geology Varsovia, PB: Polish Basin; PCar: Pre-Carpathian basins; BS: Black Sea; DD: Dniepr-Donets basin; East of northern margin, participating teams: CNRS-Univ. P. & M. Curie Paris, Russian Academy of Sciences and University of Moscow, BS: Black Sea; PCas: Precaspian basin; Ncau: North Caucasus basins; SC: South Caspian basin. Southern margin, participating teams: IFP, BRGM, SONATRACH Algeria, ETAP Morocco, Geological Survey of Arabia, MoB: Moroccan basins; AAB: Algerian Atlas basins; TB: Tunisian basins; ArB: Arabian basin.

formation and evolution of the basins with tectonic subsidence curves, cross sections and structural maps for Algeria, Morocco, Tunisia and Precaspian basins. Models have also been initiated for Arabia including a simple thermal model of deep metamorphism, and for the South Caspian basin giving an order of magnitude of the elastic flexure under compression during Plio-Quaternary. More advanced models were used for the Polish Basin and the Romanian Pre-Carpathians, Dniepr-Donets, Black Sea and Fore-Caucasus basins.

A number of features of the basins provided sources of uncertainty in the subsidence analysis, reflected also in the hypothesis presented.

Dealing with very deep basins, not fully drilled, and where steep margins hamper seismic correlations, we were confronted several times with an unknown age for the beginning of sedimentation. This was particularly the case for the Black Sea, South Caspian and the Precaspian basins. For these same basins, we discussed the nature of the basement: whether it was thinned continental crust or oceanic crust.

The estimation of the palaeobathymetry was another source of uncertainty in deep environments and most of the teams chose to present the subsidence curves without this type of correction when a part of the basin history was in such a condition. However, it should be noted that this parameter, and correlated sea-level variations can greatly change the interpretation of the tectonic events timing when the water-depth is varying.

The presence of a thick salt layer, and above all salt movements also provided important complications in the reconstruction of the basins evolution, particularly also in the Dniepr-Donets, Precaspian, Polish, Algeria and Tunisia basins. Salt displacements have to be taken into consideration when dealing with subsidence. Initial salt thickness must be reconstructed so that it is possible: to avoid underestimating the amount of subsidence during salt deposition and overestimating posterior subsidence (e.g. in rim-synclines), or to recognise when salt has been redeposited at another age after migration. To ignore salt migration can lead to an underestimate of the first phases of evolution and give too much significance to subsequent phases. It might even lead to the inclusion of phases that may not exist, when the displacement of salt has been reconstructed.

In association with the «Tectonics» Group (Barrier et al., in press), another role for the «Basins Geodynamics» Group has been to show the tectonic context of the Peri-Tethyan platforms on the PTP Atlas maps (Dercourt et al., 2000) (i.e. their rifting, inversion, regional extension or compression and subsidence). To this purpose, three types of complementary tectonic data have been shown on the maps characterising the tectonic context: major structural features: palaeostresses, and basins regional depocentre trends (i.e. types of subsidence: in active extension, post-rift passive thermal, flexural in active compression). A combination of these factors has allowed us to characterise the tectonic context more precisely. This is particularly true for the basins and their boundaries: (i.e. active normal faults or strike-slips, axes of syn-extensional subsidence for rifts; pull-apart or back-arc basins; axes of thermal subsidence for post-extensional times; thrusts and axes of flexural basins in collisional contexts). On the maps, the tectonic data were superimposed upon the palaeoenvironmental and palaeogeographic data (with indications of lithologies), thus providing a general view of the basins through the Tethyan evolution.

In some cases, the results obtained were not represented on the maps for the following reasons. They were not adapted to the scale of 1/10 000 000. They were not accurate enough. They dealt with events occurring in the interval of times between two maps, or simply because of a hypothesis of work different from the one retained for the map. Complementary to the Atlas, the detailed studies of the different basins examined in PTP are presented in the papers of this Special Issue. Below, we summarise some main features on the evolution of these basins (for location, see Fig. 1).

3. The basins studied

3.1. Northern margin

Situated in the East-European Platform, the Pripyat-Dniepr-Donets basin (Stephenson et al., 2001) continues towards the east in the Karpinsky folded belt which borders the Precaspian basin to the southwest (Fig. 1). A rifting phase occurred during Late Devonian. The major subsidence phase during Late

Carboniferous, which led to the formation of the prosperous coal basin, had already been interpreted although with some difficulties. Movement of Devonian evaporites created diapirs and the formation of salt-withdrawal basins during the Carboniferous (Stovba et al., 2003), progressively filled by Carboniferous continental sediments (Izart et al., 1998). Carboniferous subsidence needs only to be explained, then, by three factors: post-rift thermal subsidence, diapirism of Devonian salt and the regional subsidence of the East-European Platform.

The Precaspian basin contains a thickness of more than 20 km of sediment and is one of the basins for which the age of origin, and even the real nature of the crust, is not fully resolved. Volozh et al. (2003) propose a Riphean age for the beginning of sedimentation. They explain a part of the basin subsidence by the presence of a dense layer at the base of the crust which they interpret as eclogites. The geological evolution of the basin is presented as a series of regional cross sections. The most important part of subsidence is due to the re-establishment of isostatic equilibrium with a thin and high-density crust underlying the basin. This crust was thinned during a probably Riphean and largely Devonian phase of rifting. During the remainder of its evolution, the basin underwent post-rift subsidence causing the filling of a deep basin. This allowed the deposition of several kilometres of Lower Permian salt. The formation of numerous salt diapirs covering all the basin surface prohibits a detailed analysis of the posterior subsidence history.

Polish Basin subsidence (Stephenson et al., 2003) can be explained in terms of a crustal extension/transtension followed by a lithospheric cooling. Structural orientation was strongly influenced by the preexistence of the structure of the Tornquist-Teisseyre Zone (TTZ = northeast boundary of the Trans European Suture Zone (TESZ)). A rifting phase occurred during the Late Permian–Early Triassic and an accelerated subsidence phase took place during Late Jurassic (Oxfordian–Kimmeridgian), linked to rifting of the Arctic–North Atlantic system and to Tethyan margin rifting. Subsidence accelerated at the beginning of Cenomanian and marks the beginning of the compressive deformations, which culminated with basin inversion at the end of the Cretaceous- and beginning of Tertiary. The timing of this cannot be precisely defined. Moho depths, predicted on the basis of tectonic subsidence studies, are broadly compatible with those observed from recent refraction seismic studies of the Polish Basin area, taking into account important inferences about palaeo crustal thickness changes across the TTZ.

Subsidence analysis has shown that the flexural basin of the southern Carpathians in Romania (Matenco, 1997; Matenco et al., 2003), was a consequence of the progressive thrusting of the Carpathian chain onto the platform. In the Early Miocene, subsidence increased in the west of the Moesian platform/Getic depression concert with the opening of a rift basin of WSW–ENE orientation. However, most important subsidence phase is dated to Late Miocene time and is associated with the completion of the emplacement of the external Carpathian nappes onto the East-European Platform. It appears that the subsidence is tightly linked to fractures that existed before thrusting. The relationship is especially strong between the intra Moesian and Trotus faults, resulting from Moesia colliding with the East-European Platform and the process by accelerating the subduction process in the SE corner of the Carpathians. In this location, subsidence continued during the Pliocene.

To the south of eastern Europe, the Black Sea, North Caucasus and South Caspian basins show a general NW to SE alignment. Geophysical data and modelling permit a reconstruction at the crustal/lithospheric scale for this complex domain.

To the north of Great Caucasus, from west to east a series of sedimentary basins exist being part of the thinned margin of the Great Caucasus basin opened during Jurassic in a back-arc position associated to the northwards Tethyan subduction below the Eurasian Platform. During Late Miocene–Pliocene foreland flexural basins exist to the north of the eastern and western Caucasus. They develop during the collision and uplift of the chain. A numerical modelling taking into account a thin elastic plate, gravimetry and topography (Ershov et al., 1999, 2003) showed that subsidence is supported at the east and west by the presence of lithospheric roots below the low topography of the chain. The absence of flexural basin (Stavropol high) to the north of the Caucasus central part (highest one) may be interpreted by detachment of a lithospheric root which is still existing on the edges of the chain.

The South Caspian basin is the eastern termination of the Caucasus trough opened in back-arc position during the Jurassic. From an analysis of subsidence on the basins margins, Brunet et al. (2003) suggest ocean crust generation in this area commencing towards the end of Callovian–Oxfordian (i.e. after an Early–Middle Jurassic phase of rifting). The role of the partial closure of the Caucasus trough during the pre-Callovian is not resolved in this area as well as the lateral presence of basins underlain by oceanic crust. Other accelerations of subsidence occurred during the Aptian–Albian and also, very significantly, during the Plio-Quaternary. This latter phase is interpreted to represent a flexural subsidence phase resulting from compression between Arabia and Eurasia, reflecting both their collision, and the loading of blocks and chain around the basin. Subduction took place northwards South Caspian basin.

Two teams worked on the Black Sea evolution. Their views differed on the age of the opening of the eastern Black Sea, Nikishin et al. (2003), favoured Cretaceous back-arc basin opening simultaneously with the rifting of the western Black Sea basin. They present a summary of the geological history of the area and propose a scenario of Cretaceous opening of the two basins, followed by a period of compression in the Santonian–Campanian preceding a tensional Eocene event in the eastern area. They attribute the Neogene-Quaternary rapid subsidence to a compression-induced flexural deepening. A Palaeocene opening of the eastern Black Sea is retained by Cloetingh et al. (2003) for their modelling. Their comparison between the western Black Sea and eastern domain supports a very different lithospheric behaviour and mechanical properties for the two basins. This is reflected in very different levels of necking and pre-rift strength and has important consequences for the development of rift shoulders and the mode of stress propagation from the basin margins to the basin centre.

3.2. Southern margin

The Moroccan basins studied by Ellouz et al. (2003) are located at the junction between the Atlantic and the Mediterranean domains. The subsidence analysis by Ellouz et al. (2003) focuses on the Essaouira, Missour basins, the Middle and High Atlas and the Hauts Plateaux and links them to the evolution of the Atlantic and Tethyan oceans. During the Triassic–Jurassic, Essaouira basin and Atlas intra-marginal rifted basins show accelerated subsidence in the context of the transition of rifting to oceanic accretion of the neighbouring oceans. Since the Late Cretaceous, the evolution is mainly linked to Tethyan closure. Emplacement of nappes in the North and spectacular tectonic inversion of the rifted basins from Miocene to Present times are the most prominent expression of the strong horizontal shortening. The Missour basin and the Hauts Plateaux became identifiable units only after inversion of the Atlas region. The data available does not allow the timing of the Atlas uplift (between the Cretaceous and the Present) to be precisely specified, and no definitive argument can be given at this stage to support the most likely, whether Late Cretaceous or Tertiary, for the beginning of this uplift.

Integration of surface and subsurface data in the Algerian basins has allowed different subsidence phases to be emphasised (Bracene et al., 2003). A rifting stage phase under Tethyan and Atlantic tectonic control took place during Triassic and Liassic times. This phase is characterized by the movement of tilted blocks and the onset of diapiric events during Liassic. The post-rift subsidence took place from Middle Jurassic up to Late Cretaceous. A phase of Late Jurassic is linked to diapirism and salt withdrawal. Subsidence in eastern Algeria during the Cretaceous resulted from a rifting event in the Gulf of Gabès and Sirte area (Van der Meer and Cloetingh, 1993; Abadi, 2002). The Tellian foreland in Algeria was a part of the southern Tethyan margin during the Mesozoic.

Tertiary flexural subsidence in foreland basins, and phases of inversion, are related to the Africa–Europe plate convergence episode.

The Tunisian Hammamet, Gabès and Chotts basins were studied by Patriat et al. (2003). Their behaviour was different according to inherited structures and to their location. The position of Tunisia situated at the junction of the western and eastern Mediterranean domains led to longer rifting phases cumulating both histories.

Extension occurred during Trias–Liassic (Tethyan rifting) with a subsequent extensional period lasting from Liassic to Early Cretaceous (Neocomian) with a clearly defined subsidence episode occurring in all the basins. From Aptian to Late Cretaceous transition phase took place. Post-rift thermal subsidence was interrupted by the onset of extensional and compressional pulses. Halokinetic movements gave anomalous subsidence rates in some basins. A phase of acceleration subsidence occurred across the entire Maghreb during the Cenomano-Turonian, due to changes in plate kinematics with a change in the relative movement between Africa and Eurasia, with the sinistral transtensional regime becoming a dextral one. Cainozoic time was dominated by the beginning of collision between Europe and Africa accompanied by emplacement of the Tellian nappes and both, uplift and subsidence in the Hammamet basin.

Subsidence analysis of the Arabian Platform from Permian to Tertiary has been performed with curves and transects reconstructed from outcrop data (Le Nindre et al., 2003). These authors demonstrated the control of sedimentation by the presence of permanently active structural features. Several major tectonic events occurred during the Late Permian, Early Triassic, Norian, Middle Toarcian and Dogger. The relative influence of tectonics and eustasy (see also Cloetingh et al., 1985) on sedimentation is discussed for the different formations. Late Jurassic sedimentation is controlled by eustasy and tectonic/eustatic influences are combined during Cretaceous and Early Cainozoic times. Le Nindre et al. (2003) propose a mechanism invoking deep crustal metamorphism as the major control on the Jurassic subsidence of the Arabian Platform.

4. Key geodynamic aspects

The influence of pre-existing structural features was underlined by most of the authors of this issue (see also Cloetingh and Lankreijer, 2001; Ziegler et al., 2001b). The presence of old structural features is generally focused on the location and orientation of subsequent subsidence depocentral trends. In this way, the NW–SE Trans European suture zone appears to be a major element at the boundary between western and eastern Europe and influences the subsidence of the Polish and Pre-Carpathian basins. Suture zones between platforms and accreted terranes also often determine reopening of the Precaspian, Great Caucasus, and South Caspian basins.

Each region is also affected by the nearest major ocean opening or closing. At the crossroads situated between two oceans, the influence is mixed. This is the case in Morocco, located at the junction of the Atlantic and western Tethys. Here in the subsidence evolution, some phases of the two domains can be observed as well as main orientation of structures.

The first common strong rifting period in the platform areas occurs during the Late Devonian in the Dniepr-Donets and the Precaspian basins (Stovba et al., 2003; Volozh et al., 2003) probably in a back-arc setting resulting from Palaeo-Tethys and Uralian subductions. This is followed by a phase of mainly thermal subsidence during the Carboniferous. Rifting takes place in the Polish Basin in Late Permian–Early Triassic, also followed by cooling (Stephenson et al., 2003). More widespread rifting occurs in the Late Triassic–Liassic, linked to the Atlantic and Tethyan rifting. This is mainly observed on the southern Tethyan margin: Morocco, Algeria, Tunisia (Ellouz et al., 2003; Bracene et al., 2003; Patriat et al., 2003). A deep Jurassic metamorphism resulting from a thermal event is proposed at the same time for Arabia (Le Nindre et al., 2003) and a Late Triassic–Early Jurassic intrusive heating is advocated for the North Fore-Caucasus basins (Ershov et al., 2003).

In the northeast margin, extension seems to begin later, in the Liassic, following the Cimmerian orogeny resulting from accretion of the Cimmerian blocks in Middle Triassic. After their detachment from Gondwana during the Permian, these blocks migrated towards the north as a consequence of northwards Palaeo-Tethys subduction below Eurasia. After collision, the subduction zone jumped to the south of the accreted terranes with disappearance of Neo-Tethys oceanic crust beneath them. This Neo-Tethys subduction eventually resulted in opening of a back-arc basin: the Great Caucasus trough (Nikishin et al., 2001) and in extension on the margins of the South Caspian Basin (Brunet et al., 2003).

In Late Jurassic, extensional reactivation occurs in the Polish Basin (Stephenson et al., 2003), Oman (Le Nindre et al., 2003) whereas the South Caspian Basin is proposed to be spreading (Brunet et al., 2003).

At the end of Early Cretaceous, repeated reactivation occurs in the Great Caucasus trough (Nikishin et al., 2001), on the margins of the South Caspian Basin (Brunet et al., 2003). At this time, rifting of western

Black Sea is very active before its spreading from Cenomanian to Coniacian (Nikishin et al., 2003). In Cenomanian, the anti-clockwise rotation starts of the newly created African plate.

At the end of Cretaceous and probably beginning of Cainozoic, a compression stress regime prevails and numerous areas are uplifted and basins inverted (see also Cloetingh and Lankreijer, 2001). This is, for example, the case for the Dniepr-Donets (Stovba et al., 2003), the Black Sea area (Cloetingh et al., 2003; Nikishin et al., 2003), the Polish Basin (Stephenson et al., 2003) as well as for Moroccan basins, in the latter case without firm proof of the exact age (Ellouz et al., 2003).

During Eocene, extension occurred in the southeast of the Black Sea (Nikishin et al., 2003) to the south of the Lesser Caucasus and of the Alborz (Brunet et al., 2003).

The Tethys ocean closed with collision of Africa-Arabia and Eurasia. However, shortening went on with continuing northwards movement of Arabia. This process caused the development of numerous flexural basins either simply induced by compression (South-Caspian, Black Sea) or also due to the loading of thrust sheets or nappes (Pre-Carpathians, Fore-Caucasus, Algeria, Tunisia, Morocco). This is mainly the case for the Late Miocene to Pliocene-Quaternary with development of very rapidly subsiding flexural basins.

Therefore, it appears that the past overall evolution of the basins studied here was to a large extent driven by the birth, evolution and closure of the Tethys Ocean superposed on structural fabrics resulting from old extension/orogenic cycles and influenced by the Atlantic history.

The geodynamic evolution is still poorly constrained in several of the basins, especially for the area between the eastern Black Sea and the South Caspian Sea. The age of formation of these basins is largely controversial. New fieldwork has to be carried out in accessible areas of Greater and Lesser Caucasus and in Iran.

Work on the eastern part of the Peri-Tethyan domain, in the Middle East and in the South of eastern Europe is a major goal for future research. The limited knowledge of the tectonic history of the area located between the two large continental masses of Eurasia and Africa is a key factor for the understanding of the tectonic evolution of the Peri-Tethyan and Tethyan domains.

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