ELSEVIER Palaeogeography, Palaeoclimatology, Palaeoecology 196 (2003) 209–228

PALAEO

www.elsevier.com/locate/palaeo

Tertiary palaeogeography and tectonostratigraphic evolution of the Northern and Southern Peri-Tethys platforms and the intermediate domains of the African–Eurasian convergent plate boundary zone

Johan E. Meulenkamp*, Wim Sissingh

Faculty of Earth Sciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, The Netherlands

Received 12 November 2001; accepted 23 January 2003

Abstract

The increasing effects of African–Eurasian convergence during the Tertiary resulted in the uplift and emergence of the Northern and Southern Peri-Tethys platforms. Palaeogeographic maps covering six selected time slices, including the Middle Eocene, late Early Oligocene, late Early Miocene, early Middle Miocene, early Late Miocene and Middle to Late Pliocene illustrate that environmental and depositional differentiations on the northern platform and along the bordering domains of the convergence zone were more pronounced than on the southern platform and its adjacent areas. The tectonic evolution of the northern platform included an overall eastward-directed trend in the onset of basin uplift and emergence, which started at about the Eocene–Oligocene transition, at 34 Ma. Tectonostratigraphic analyses indicate a striking contemporaneity of the events which defined the temporal and spatial development of both the domains of the convergent plate boundary zone and the bordering platforms. Five episodes of major regional change in palaeogeographic and tectonic setting are distinguished. They occurred in the Late Eocene (37–34 Ma), early Late Oligocene (30–27 Ma), latest Early to earliest Middle Miocene (17–15 Ma), early Late Miocene (9–8 Ma) and late Early to early Middle Pliocene (4–3 Ma). These episodes encompassed changes which were most probably induced by geodynamic events primarily related to the relative motions of the African/Arabian and Eurasian plates. In turn, the plate motions are assumed to have 'triggered' discrete steps in the regional kinematics and geodynamics that governed the palaeogeographic evolution of the Peri-Tethys platforms and the intermediate domains of the African–Eurasian plate boundary zone.

Keywords: palaeogeography; Tertiary; Europe; Mediterranean; North Africa; Middle East; Western/Central Asia

1. Introduction

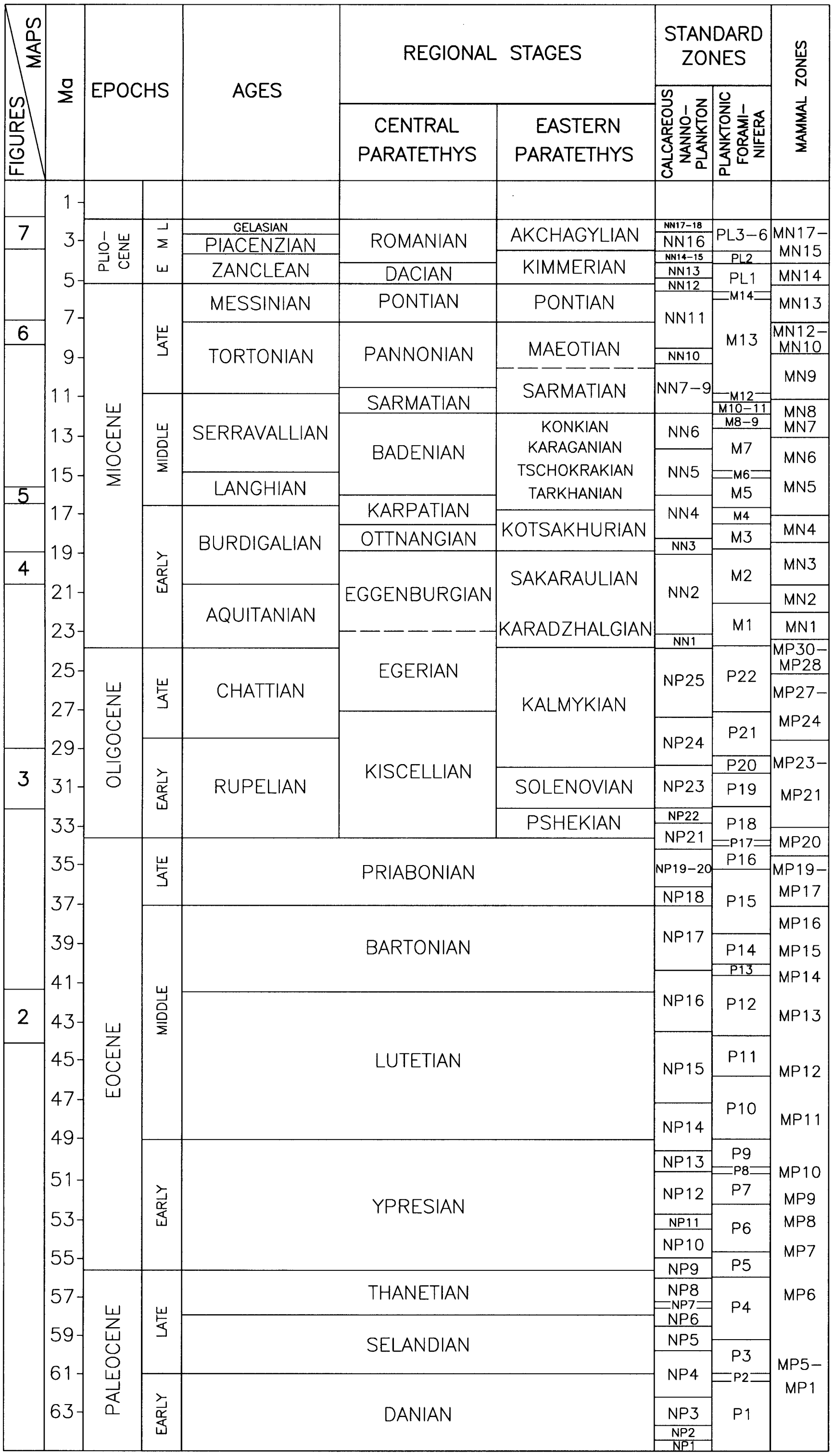
The recently published Peri-Tethys Atlas (Dercourt et al., 2000a) includes a total of 24 palaeogeographic maps at a scale of 1:10 000 000 for the Late Palaeozoic to Pleistocene time interval. Sev-

---

* Corresponding author. Tel.: +31-30-253-5181; Fax: +31-30-253-2648.

E-mail address: jmeulenk@geo.uu.nl (J.E. Meulenkamp).

0031-0182/03/$ – see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0031-0182(03)00319-5


FIGURES
MAPS
Ma
EPOCHS
AGES
REGIONAL STAGES
CENTRAL PARATETHYS
EASTERN PARATETHYS
STANDARD ZONES
CALCAREOUS NANNO-PLANKTON
PLANKTONIC FORAMI-NIFERA
MAMMAL ZONES
7
6
5
4
3
2
1
3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
41
43
45
47
49
51
53
55
57
59
61
63
PLIO-CENE
MIOCENE
OLIGOCENE
EOCENE
PALEOCENE
E
M
L
LATE
MIDDLE
EARLY
GELASIAN
PIACENZIAN
ZANCLEAN
MESSINIAN
TORTONIAN
SERRAVALLIAN
LANGHIAN
BURDIGALIAN
AQUITANIAN
CHATTIAN
RUPELIAN
PRIABONIAN
BARTONIAN
LUTETIAN
YPRESIAN
THANETIAN
SELANDIAN
DANIAN
ROMANIAN
DACIAN
PONTIAN
PANNONIAN
SARMATIAN
BADENIAN
KARPATIAN
OTTNANGIAN
EGGENBURGIAN
EGERIAN
KISCELLIAN
AKCHAGYLIAN
KIMMERIAN
PONTIAN
MAEOTIAN
SARMATIAN
KONKIAN
KARAGANIAN
TSCHOKRAKIAN
TARKHANIAN
KOTSAKHURIAN
SAKARAULIAN
KARADZHALGIAN
KALMYKIAN
SOLENOVIAN
PSHEKIAN
NN17–18
NN16
NN14–15
NN13
NN12
NN11
NN10
NN7–9
NN6
NN5
NN4
NN3
NN2
NN1
NP25
NP24
NP23
NP22
NP21
NP19–20
NP18
NP17
NP16
NP15
NP14
NP13
NP12
NP11
NP10
NP9
NP8
NP7
NP6
NP5
NP4
NP3
NP2
NP1
PL3–6
PL2
PL1
M14
M13
M12
M10–11
M8–9
M7
M6
M5
M4
M3
M2
M1
P22
P21
P20
P19
P18
P17
P16
P15
P14
P13
P12
P11
P10
P9
P8
P7
P6
P5
P4
P3
P2
P1
MN17–MN15
MN14
MN13
MN12–MN10
MN9
MN8
MN7
MN6
MN5
MN4
MN3
MN2
MN1
MP30–MP28
MP27–MP24
MP23–MP21
MP20
MP19–MP17
MP16
MP15
MP14
MP13
MP12
MP11
MP10
MP9
MP8
MP7
MP6
MP5–MP1

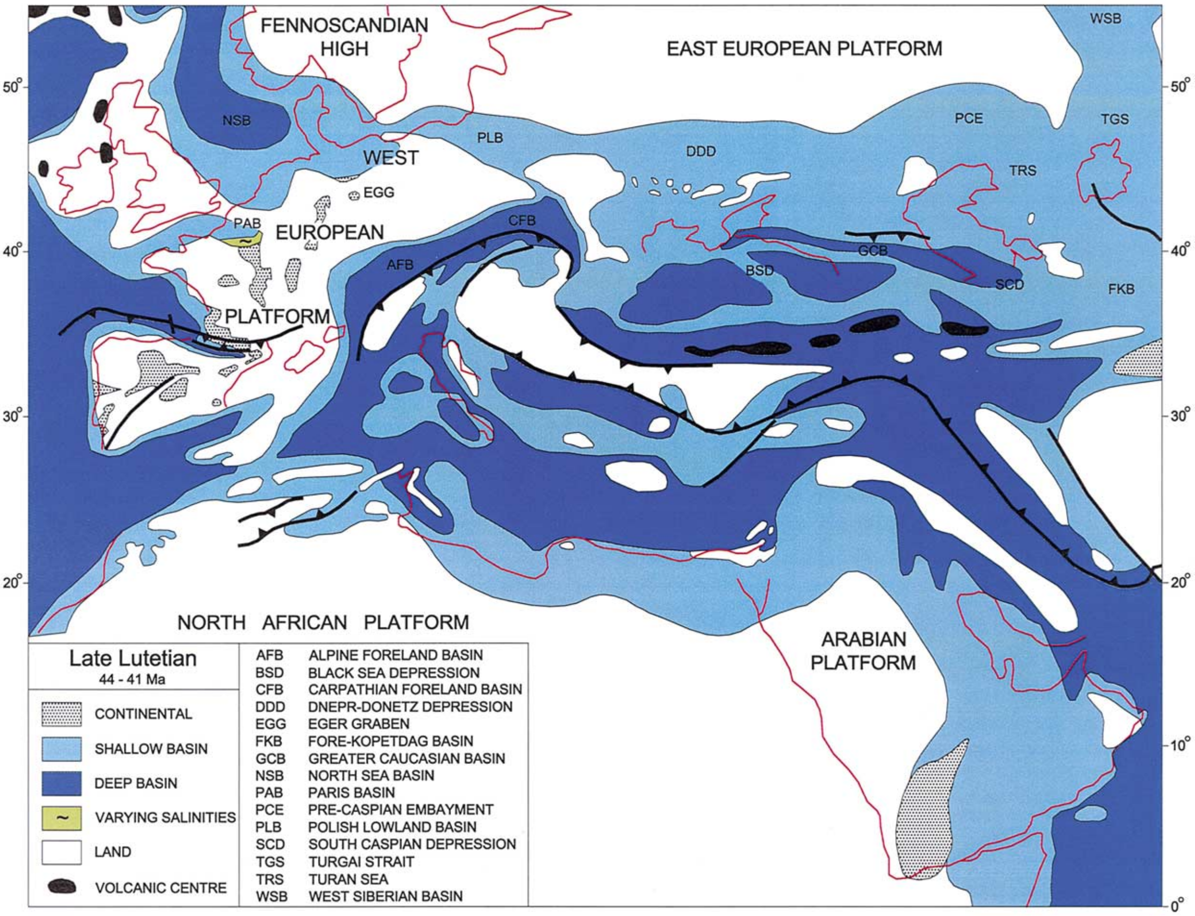


Fig. 2. Schematic palaeogeographic map for the late Lutetian, showing position of continental basins, shallow and deep marine basins and shallow and deep basins with salinities deviating from normal (modified after Meulenkamp et al., 2000a). Heavy lines denote important fault zones, while open triangles and filled triangles represent respectively thrusting and oceanic subduction.

en of these maps and their accompanying explanatory notes concern the Tertiary (Meulenkamp et al., 2000a,b). They reflect different stages of the evolution of the Northern and Southern Peri-Tethys platform areas at both sides of the African/Arabian–Eurasian convergent plate boundary, as summarised (Fig. 1) for the Early Eocene (early to middle Ypresian: 55–51 Ma), Middle Eocene (late Lutetian: 44–41 Ma), Early Oligocene (late Rupelian: 32–29 Ma), Early Miocene (early Burdigalian: 20.5–19 Ma), Middle Miocene (early Langhian: 16.4–15.5 Ma), Late Miocene (late Tortonian: 8–7 Ma) and Middle/Late Pliocene (Piacenzian/Gelasian: 3.4–1.8 Ma) in Figs. 2–7. Palaeogeographic reconstructions and tectonostratigraphic evaluations for some of the eastern and southern areas are relatively tentative due to less detailed information. For particular time intervals, the data available from some other parts of the area of study turned out to be insufficient

---

Fig. 1. Correlation chart of Tertiary epochs and ages with Paratethys regional stages, continental stages and marine and continental biozones. Numbers 2–7 in the left column refer to the positions of schematic palaeogeographic/palaeoenvironmental maps of Figs. 2–7 relative to time (modified after Meulenkamp et al., 2000b).

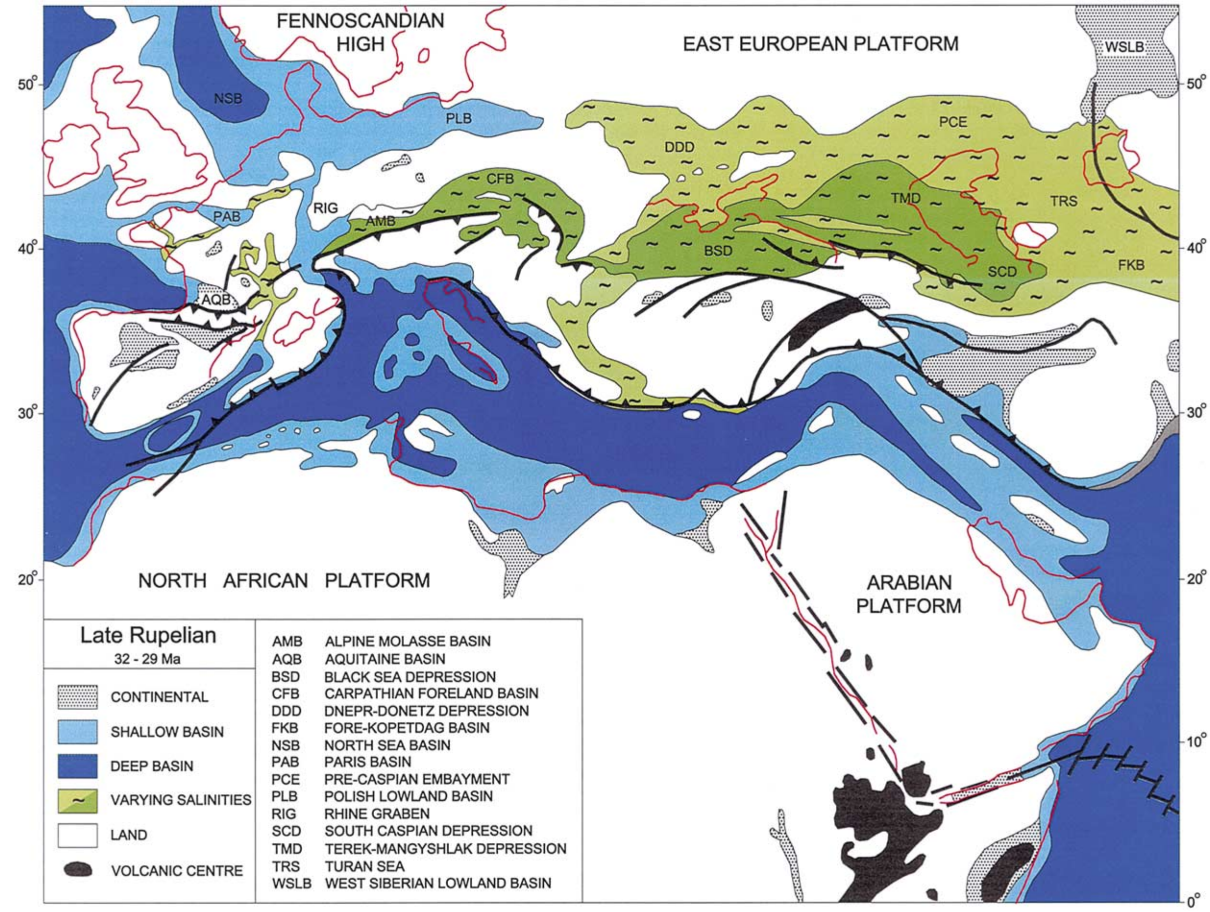


Fig. 3. Schematic palaeogeographic map for the late Rupelian, showing position of continental basins, shallow and deep marine basins and shallow and deep basins with salinities deviating from normal (modified after Meulenkamp et al., 2000a). Heavy lines denote important fault zones, while open triangles and filled triangles represent respectively thrusting and oceanic subduction.

for trustworthy reconstructions and analyses. The Tertiary evolution of the Peri-Tethys platforms was primarily controlled by the enhanced coupling of the African/Arabian, Apulian, Iberian, Eurasian and (in the easternmost part of the area of study) Indian plates (Dercourt et al., 1993, 2000a,b (and references therein); Golonka et al., 2000). This large-scale development included the effects of the later, quasi-final stages of Alpine convergence and continent–continent collision on palaeogeography and sediment distribution patterns which followed upon the break-up of Pangaea in the early Mesozoic, the subsequent formation of the Neotethys and the inception of African–Eurasian convergence from the Cretaceous onward (Dercourt et al., 1986, 1993, 2000a,b). The northward motion of the African block relative to Eurasia was fastest in the east, in accordance with the overall anticlockwise rotation of Africa/Arabia, whereas the position of the northern margin of the African Plate relative to Iberia remained fairly stable throughout the Cainozoic.

In this paper, we will summarise the palaeogeographic and palaeoenvironmental evolution of the Peri-Tethys Platform realms at either side of the African–Eurasian convergent plate boundary as inferred from Dercourt et al. (2000a,b). More in particular, the tectonostratigraphic interrelations between the coeval development of the platform

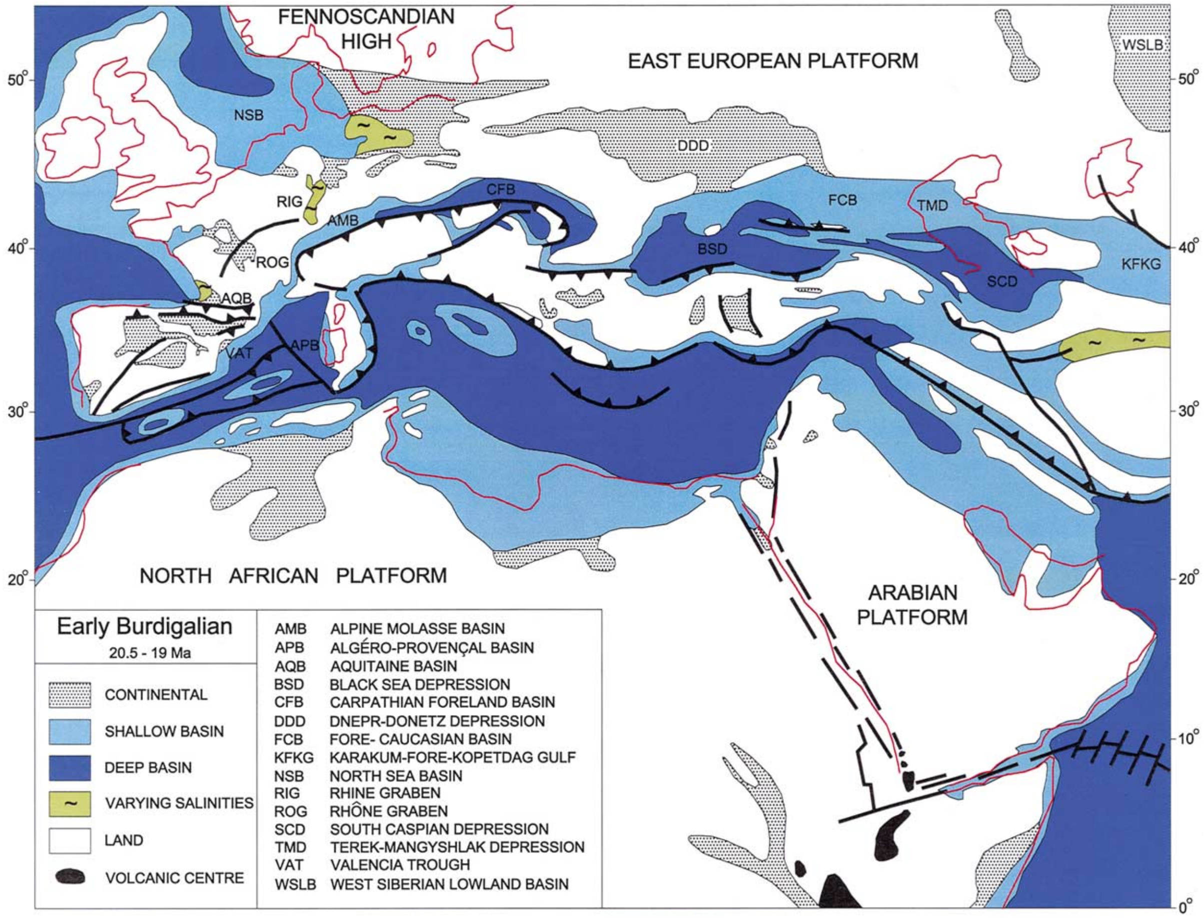


Fig. 4. Schematic palaeogeographic map for the early Burdigalian, showing position of continental basins, shallow and deep marine basins and shallow and deep basins with salinities deviating from normal (modified after Meulenkamp et al., 2000a). Heavy lines denote important fault zones, while open triangles and filled triangles represent respectively thrusting and oceanic subduction.

domains and the collision zone are explored in this paper. We will also attempt to relate some of the Tertiary episodes of major palaeogeographic change to specific geodynamic events in the collision zone.

2. Outline of Peri-Tethys palaeogeographic and palaeoenvironmental evolution

The Middle Eocene to Middle/Late Pliocene palaeogeographic and palaeoenvironmental evolution of the Tethys and Peri-Tethys realms is summarised in Figs. 2–7. The temporal development of the northern and southern platforms displays a long-term trend of decreasing marine influence and a correlative reduction in size of the marine depositional domains. The concomitant growth of the land mass reflects the impact of a large-scale, overall tectonically induced inversion process which increasingly affected both sides of the collision zone since the beginning of the Tertiary. The overall regression on the southern and northern platforms already started in the Late Cretaceous, as part of the ‘inception of Alpine times’ (Dercourt et al., 2000b). However, there are pronounced differences in timing and in regional characteristics of the observed changes between

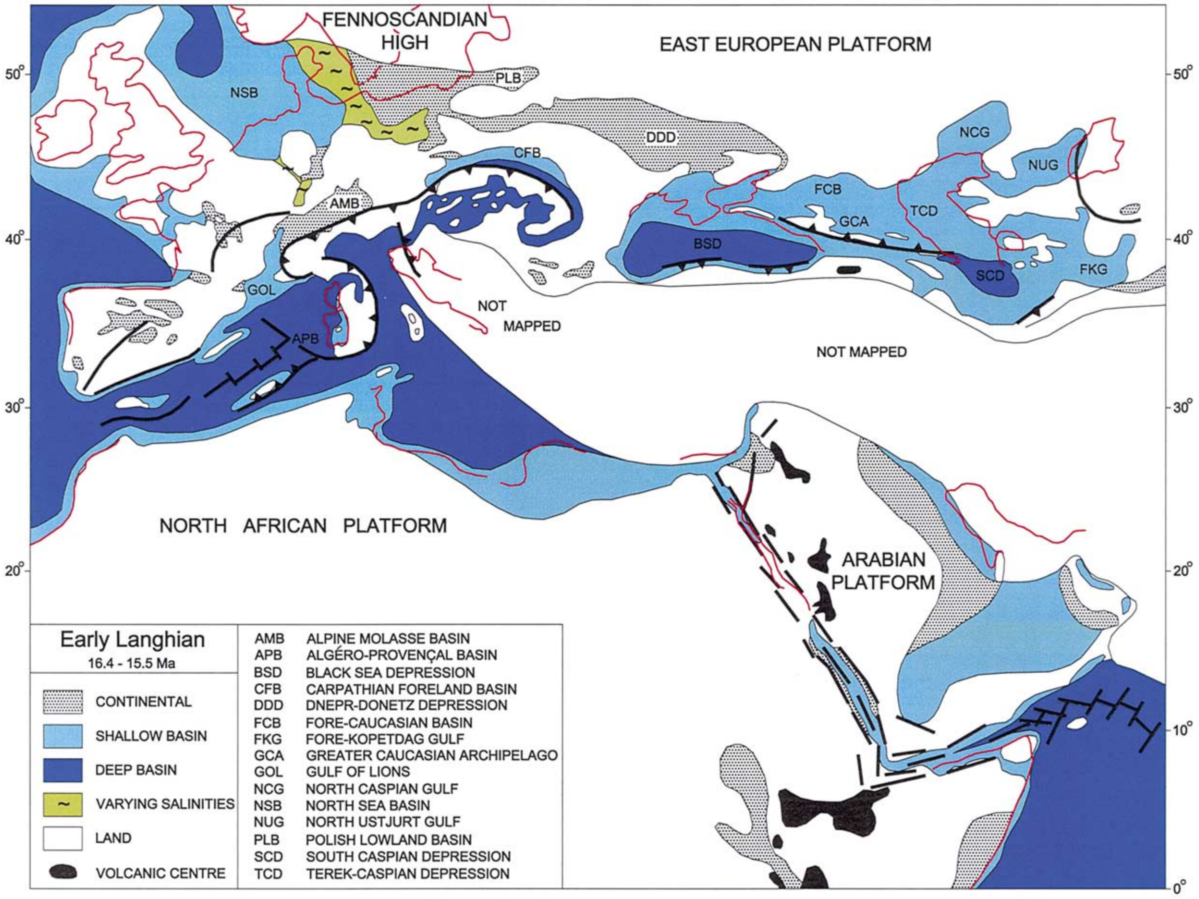


Fig. 5. Schematic palaeogeographic map for the early Langhian, showing position of continental basins, shallow and deep marine basins and shallow and deep basins with salinities deviating from normal (modified after Meulenkamp et al., 2000a). Heavy lines denote important fault zones, while open triangles and filled triangles represent respectively thrusting and oceanic subduction.

the northern and southern platforms, as well as between the western and eastern domains of the Peri-Tethys realms.

2.1. Southern Peri-Tethys Platform

Through time, the large-scale land–sea distribution patterns on the African part of the southern (African/Arabian) platform indicate a phased northward retreat of marine environments all along the platform margins. For instance, the sea extended southward as far as northern Sudan in late Palaeocene times, but the shoreline moved progressively in this area throughout the later Tertiary. In the Oligocene, fundamentally new palaeogeographic-palaeoenvironmental settings arose further to the east, in conjunction with the separation of the African and Arabian plates through the opening of the Gulf of Aden–Red Sea–Gulf of Suez Rift System. The Arabian Platform, still largely covered by the sea in Early to Middle Eocene times, was subject to a major regression in the Middle to Late Eocene. In the Early Oligocene, it was almost completely emerged. The sea re-invaded the more central parts of the Arabian Platform in the latest Early to earliest Middle Miocene, but regressed again prior to the late Middle Miocene. This implies that the (late) Middle Miocene and early Late Miocene configurations on the Arabian Platform

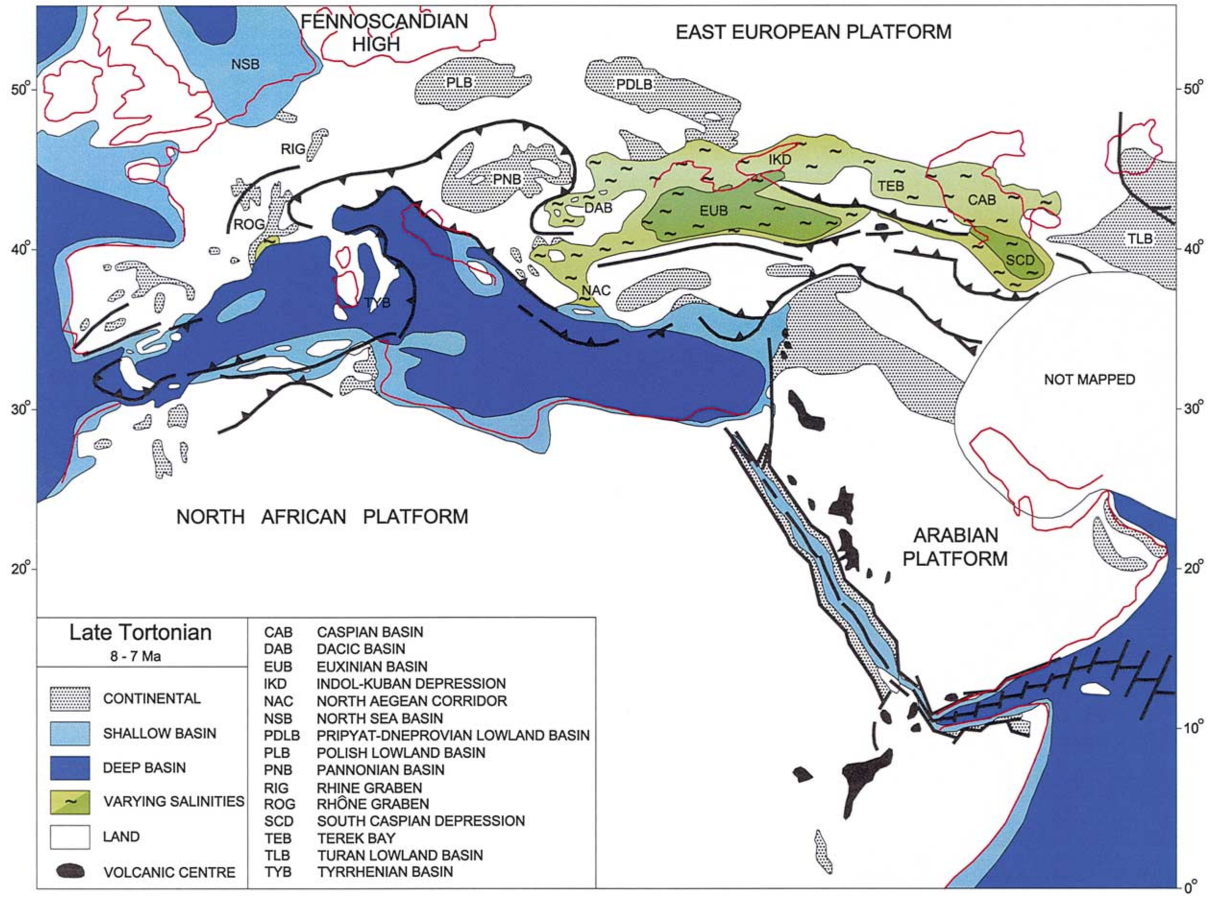


Fig. 6. Schematic palaeogeographic map for the late Tortonian, showing position of continental basins, shallow and deep marine basins and shallow and deep basins with salinities deviating from normal (modified after Meulenkamp et al., 2000a). Heavy lines denote important fault zones, while open triangles and filled triangles represent respectively thrusting and oceanic subduction.

proper did not differ fundamentally from those in the Late Miocene, as illustrated in Fig. 6.

2.2. Northern Peri-Tethys Platform

The Tertiary history of the Northern Peri-Tethys Platform is far more complex than that of the Southern Peri-Tethys Platform, due to recurrent episodes of palaeogeographic reorganisations and basin rearrangements. Regional uplift patterns on the northern platform caused the (final) closure of marine corridors, which connected the Tethys domains with the Arctic and Atlantic oceans until Late Eocene and late Early Oligocene times, respectively (cf. Rögl, 1998). In the Palaeocene and Early Eocene, the marine corridor across the Aquitaine Basin connected the Atlantic Ocean with the western part of the Tethyan domain. A N–S-trending seaway allowed the exchange of water masses between the Arctic Ocean and the Tethyan/Indo-Pacific domains via the West Siberian Basin and the Turgaj Strait until the Late Eocene (Figs. 2 and 3). In contrast, the W–E Atlantic–Tethyan/Indo-Pacific trans-European marine corridor from the North Sea Basin via the Polish Lowland Basin and the Dnepr–Donetz Depression was definitely closed in the course of the Early Oligocene (Figs. 2 and 3). In the approximately W–E-trending corridor between the Atlantic Ocean and the Tethyan Sea, as in the seaways connecting the Arctic Ocean and the Tethys, marine conditions were followed by the installment

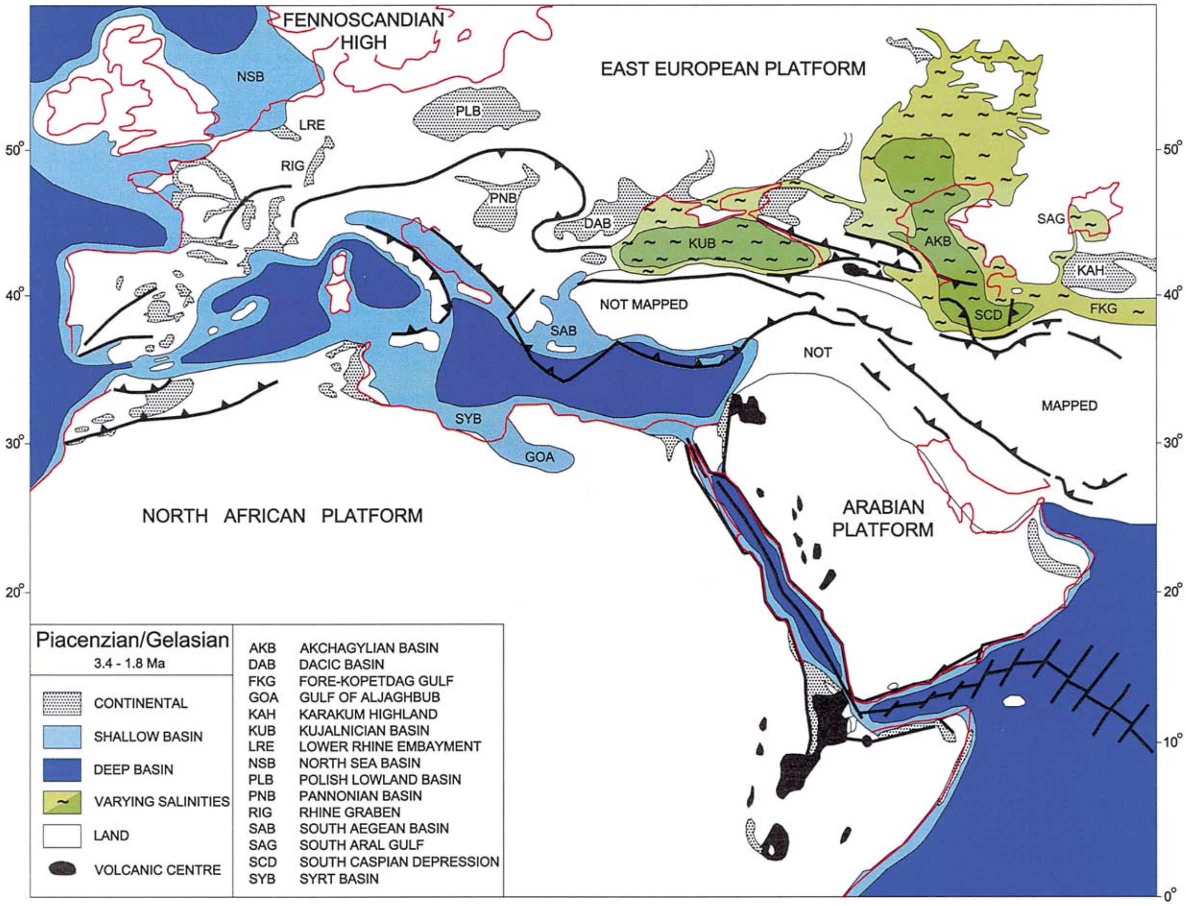


Fig. 7. Schematic palaeogeographic map for the Piacenzian/Gelasian, showing position of continental basins, shallow and deep marine basins and shallow and deep basins with salinities deviating from normal (modified after Meulenkamp et al., 2000a). Heavy lines denote important fault zones, while open triangles and filled triangles represent respectively thrusting and oceanic subduction.

of fluvio-lacustrine environments before sedimentation in most of these depositional areas came to a close (Figs. 2–7). The Tertiary uplift resulted in the withdrawal of the sea from almost all of Western Europe and from the Central and East European domains adjacent to and straddling the Tethys–Peri-Tethys transition zone, from the late Early Miocene to the Late Pliocene.

An additional, major development was the origin of the so-called Paratethys as a discrete palaeogeographic/palaeoenvironmental and, in particular, palaeobiogeographic realm at the Eocene–Oligocene transition. The enhanced emergence of the Alpine chains from the end of the Eocene onward (Figs. 3–7) resulted in the near-isolation of the basinal areas to the north and the south of these evolving chains and, consequently, the severance of marine connections. The Paratethys thus comprises domains of both the convergence zone proper and the Eurasian (Peri-Tethys) platform areas. The severance of main connections, in turn, underlies the recurrent development of vast depositional areas in the Paratethys with salinities deviating from normal.

Pronounced temporal and regional differences can be inferred from the Tertiary evolution of the basins of the Peri-Tethys and Peri-Tethys–Tethys transitional domains from west to east, i.e., from the Iberian Peninsula towards the Caspian Sea region. In the interior basins of the Iberian block, depositional systems remained remarkably constant throughout the Tertiary. Invariably, they were marked by the accumulation of fluvio-lacustrine sequences in intra-montane basins, including deposition of variable amounts of evaporites. Only in Middle/Late Pliocene times did these sequences become significantly reduced. The sedimentary record of the Pyrenees and its bordering areas indicates that marine and subsequent fluvio-lacustrine sedimentation in the Pyrenean foreland basins ended around the Eocene–Oligocene transition and in the course of the Middle Miocene, respectively. To the north, the sea withdrew from large parts of the Aquitaine Basin during the Early Miocene. The Paris Basin records the effects of regional uplift of Western Europe through the shift from marine to fluvio-lacustrine sedimentation at about the Oligocene–Miocene transition. Concurrently, a time-progressive decrease of marine influences occurred along the marginal parts of the North Sea Basin in the course of the Miocene.

From the palaeogeographic maps (Figs. 2–7) one may infer that the development of the Rhine and Rhône grabens of the European Cainozoic Rift System in Western Europe was 'superimposed' upon the overall Tertiary regressive/uplift trends. The rift system originated in the Middle Eocene. Its sedimentary record reflects the episodic nature of marine connections with either the North Sea, the Paratethys or the Mediterranean realm. After Oligocene to Early Miocene episodes of variably pronounced marine influences, the sea withdrew from the largest part of the system at about the Early–Middle Miocene boundary.

The palaeogeographic/palaeoenvironmental configurations of the Peri-Tethys–Tethys transitional domains and their adjacent areas in Southwestern and Central Europe display time-successive eastward shifts of the termination of marine foreland basin/foredeep sedimentation and subsequent accumulation of non-marine clastics from the Western Alpine towards the Eastern Carpathian regions, from the latest Early/earliest Middle Miocene to the late Middle to early Late Miocene. The end of (marine) sedimentation/inception of uplift also documents an overall eastward shift in the course of time. The net result of these developments reflects successive steps in the incorporation of the Alpine–Carpathian domain into the landmass of the European craton. In the Late Miocene, the southeastern part of the Carpathian foreland basin system (Dacic Basin) became part of the Eastern Paratethys (Fig. 6). In the latter domain and in the Peri-Tethys–Tethys transitional regions, ephemeral marine incursions from the Mediterranean occurred from the Late(st) Miocene onward. A major, intra-Pliocene palaeogeographic reorganisation in the Eastern Paratethys resulted, for instance, in a significant northward extension of sedimentation in the Caspian domain relative to the Late Miocene (Figs. 6 and 7).

In summary, it may be concluded that the overall uplift of both the Southern and Northern Peri-Tethys Platform domains in the Late(st) Eocene was followed by an Oligocene to Late Pliocene period of regional differentiation, during which the depositional and environmental conditions were further modified. This differentiation reflects a general trend of progressive termination of marine as well as terrestrial sedimentation and of regional uplift from west to east on the northern platform and along the Peri-Tethys–Tethys transitional zones.

3. Peri-Tethys–Tethys tectonostratigraphic correlations

The general trends in the palaeogeographic and palaeoenvironmental evolution of the Northern and Southern Peri-Tethys platforms did not result from gradual, sustained changes, but rather from discrete changes which apparently simultaneously affected various domains (Meulenkamp et al., 2000b and references therein). Below, we will explore the interrelationships between such changes and those which characterised the tectonostratigraphic evolution of some parts of the convergent plate boundary zone for the Middle to Late Eocene, the Oligocene to late Early Miocene, the late(st) Early to early Middle Miocene, the late Middle to Late Miocene, and the Pliocene/Pleistocene.

3.1. Middle to Late Eocene

An important event affecting the northern platform was the inception of rifting in Western Europe at about the beginning of the Middle Eocene, 50 Ma ago. This event initiated the opening of the various basins of the European Cainozoic Rift System (Sissingh, 1997, 2001). However, the main phase of rifting of the Rhine Graben started later, at about the Middle–Late Eocene transition, 37 Ma ago. The domain of the Lower Rhine Embayment did not become incorporated in the rifting process until the Eocene–Oligocene transition, 34 Ma ago.

Our data are not sufficient to put precise and unambiguous, high-resolution time constraints on the correlation between Middle and Late Eocene events inferred from the platforms' records and those pertaining to the evolution of the domains all along the collision zone. However, the available Tethys data indicate a sequence of orogenic events, 'culminating' in the Late Eocene (Priabonian) that resulted in the origin of a fairly continuous, incipient mountain chain all along the margin of the northern platform by the end of the Eocene, 34 Ma ago. Simultaneously, major Late Eocene tectonics affected the western North African margin of the Southern Peri-Tethys Platform (Frizon de Lamotte et al., 2000) and the domain of the Pyrenees ('Pyrenean orogenic phase') (Arthaud and Séguret, 1981). The available data also suggest that the Late(st) Eocene events in the Tethys are correlative to an episode of enhanced uplift of both the bordering Southern and Northern Peri-Tethys platforms, as expressed by the uplift of Arabia and the terminal Priabonian regression on the East European Platform. In the North Sea region, inversion also peaked during the Late Eocene to Early Oligocene (Ziegler, 1987).

3.2. Oligocene to late Early Miocene

The post-Eocene development of the Tethys and Peri-Tethys realms was characterised by an overall increasing regional differentiation in basin development and depositional setting. Initially, rifting on the West European Platform continued into the Oligocene, but major rifting had come to an end in part of the region between 32 and 30 Ma ago. At about the same time, the Alpine Molasse Basin opened and back-arc extension began in the Western Mediterranean (e.g., Jolivet and Facenna, 2000 and references therein). Later, but still within the Oligocene (about 27 Ma ago), rifting and subsequent foundering resulted in the origin of the Valencia Trough and in the collapse of the Gulf of Lions (Hippolyte et al., 1993; Roca, 2001). This is evidenced by the occurrence of (poorly dated) continental red beds below marine carbonates of Early Miocene (Aquitanian) age, which demonstrate that marine conditions had become firmly established in these westernmost domains at about the Oligocene–Miocene transition (24 Ma). This main incursion is probably related to the anticlockwise rotation of the Corsica–Sardinia block. In the Alpine Molasse Basin an intra-Late Oligocene ('mid-Chattian') tectonics-related break in deposition occurred (Schlunegger et al., 1996) at about 27 Ma ago corresponding to the re-introduction of saline sedimentary conditions in the Rhine Graben after an early Chattian episode of deposition of freshwater beds (Reichenbacher, 2000). Likewise related to tectonics, the northern part of the Rhône Graben (Bresse Graben) was uplifted at about the same time (Sissingh, 1998, 2001). In the West European and Western Mediterranean domains these Chattian processes were followed by the establishment of a saline corridor between the North Sea Basin and the Western Mediterranean Basin (Reichenbacher, 2000) and the establishment of (shallow) marine depositional environments in the Valencia Trough (Torres et al., 1993). Also in Aquitanian time, rifting in the Rhône Graben ended (Sissingh, 2001). By the end of the Aquitanian, the West Alpine Molasse Basin was closed in response to regional uplift. Contemporaneously, the central and northern parts of the Rhône Graben were subjected to uplift. Further to the south, the 'Upper Rhône Graben' opened, coeval with the inception of oceanisation of the Western Mediterranean (Algero-Provençal Basin) and with the initiation of the main rifting phase of the Valencia trough (Sissingh, 2001) at about the Aquitanian–Burdigalian transition, 20 Ma ago. The beginning of oceanisation of the Western Mediterranean was approximately coeval with the main phase of rotation of the Corsica–Sardinia block (Séranne, 1999; Edel et al., 2001). In the Alpine Foreland domain this event was contemporaneous with the uplift of the Rhenish Massif and the Massif Central and the initiation of deposition of fluvial clastics on top of the calcareous Aquitanian strata in the Limagne Graben, the largest basin of the Massif Central (Sissingh, 2001). Widespread and transgressive marine flooding occurred contemporaneously in the North Alpine Molasse Basin and the southernmost Rhône Graben. The increased uplift of the Rhenish Massif induced the regressive deposition of lignite-bearing coastal lowland beds in the Lower Rhine Embayment.

In the Eastern Alpine–Carpathian domains straddling the Tethys–Peri-Tethys transition, the depocentre started to migrate eastward around 27 Ma ago (Meulenkamp et al., 1996). This inception of lateral foredeep depocentre migration was superimposed upon the accelerated internal–external shift of basin axes towards the European platform since the Eocene–Oligocene transition. This occurred concomitantly with a pronounced change in the external basins from a predominance of deposition of fine-grained sediments in often anoxic environments in the Early Oligocene (Rupelian) towards the accumulation of predominantly coarser-grained terrigenous clastics in the Late Oligocene (transition Kiscellian–Egerian in terms of regional Paratethys stages; Fig. 1). From about 30–27 Ma until about 20–19 Ma ago, the foredeep depocentres had shifted along-arc over a (present-day) distance of approximately 500 km from the transition Western–Eastern Alps towards the transition zone between the Eastern Alps and the Carpathians.

Further to the east, in the basins of the southern parts of the East European Platform and those straddling the Peri-Tethys–Tethys transition zone in the Black Sea–Caucasus domain, anoxic sediments were deposited after the terminal Eocene event, about 34 Ma ago (inception of 'Maikopian stage', Ershov et al., 1998, 1999). In the deep basins anoxic conditions persisted throughout (most of) the Early Miocene, while regressive conditions developed on the platform after a short-term transgression at the beginning of the Miocene. The Oligocene to late Early Miocene (34–20 Ma) basin rearrangements and changes in overall sedimentation conditions along the Peri-Tethys–Tethys transitional zone in the east (Eastern Paratethys) seem to have been relatively minor with respect to those in Western and Central Europe (Meulenkamp et al., 2000a).

At least some of the major changes on the Northern Peri-Tethys Platform and the bordering transitional zone had unambiguous counterparts on the Southern Peri-Tethys Platform, as illustrated by the timing of the origin of the incipient Gulf of Aden–Red Sea–Gulf of Suez Rift System in the course of the Oligocene and of the subsequent onset of separation between the African and Arabian plates in the Early Miocene (see also Garfunkel and Bartov, 1977; Evans, 1988; Purser and Bosence, 1998 and references therein). Initial rifting probably started around 30–27 Ma ago and was accompanied by a major phase of volcanic activity. Its sedimentary expression was reflected in the Gulf of Suez by the local accumulation of continental, presumedly Late Oligocene proto-rift red beds, which underlie a marine sequence of Early Miocene (Aquitanian and early to middle Burdigalian, 24–18 Ma) synrift deposits, reflecting both accelerated subsidence and widening of the Gulf. Marine influence became most pronounced around the Aquitanian–Burdigalian transition, 20 Ma ago, in association with a shift from sandy towards predominantly clayey sedimentation in shallow-water and deep-water environments, respectively. This rift phase development was terminated by the 'Mid-Clysmic event' (Garfunkel and Bartov, 1977) in late(st) Burdigalian time. Concomitantly with the inception of rifting and opening of the Gulf of Suez, left-lateral displacements along the Dead Sea transform fault started in the Late Oligocene to Early Miocene.

3.3. Late(st) Early to early Middle Miocene

The tectonics-induced major changes in palaeogeography and sedimentation which had started around the Oligocene–Miocene transition culminated in the course of the late Early Miocene and ultimately resulted in a fundamental reorganisation around the Early–Middle Miocene transition. Around 16–15 Ma ago, principal rifting of the European Cainozoic Rift System had come to an end, resulting in the termination of marine-influenced sedimentation in the Rhine Graben. The termination is about coeval with a distinct episode of volcanic activity on the West European Platform (Kaiserstuhl volcanism, around 16 Ma ago; Wagner, 1976, and unpublished data). In the Alpine Foreland Basin, a discrete episode of intra-Burdigalian tectonics induced the sudden onset of widespread deposition of the Upper Marine Molasse, which had started to accumulate around the Aquitanian–Burdigalian transition. This open marine sedimentation in the Alpine Foreland Basin ended in latest Early Miocene (late Burdigalian) time, in response to continued north-vergent thrusting, coupled with increased rates of uplift of the evolving Alpine chain.

In the Western Mediterranean, the intra-Burdigalian tectonic events are related to distinct rifting along the Iberian margin, an episode of widespread volcanism, the (near) end of rifting in the Sardinia Rift (Sowerbutts and Underhill, 1998) and the Valencia Trough (Roca, 2001), and collision of the internal and external zones of the Betics (Martin-Algarra et al., 1988). The anticlockwise rotation of the Corsica–Sardinia block slowed down and ultimately came to a halt at 18–17 Ma ago (Edel et al., 2001) or slightly later (16–15 Ma ago, Chamot-Rooke et al., 1999). The end of rotation was about coeval with the end of oceanisation of the Liguro-Provençal Basin (northern Algéro-Provençal Basin) and with the onset of main rifting of the Alboran Sea, encompassed by the incipient Betic–Maghrebian chain (Comas et al., 1992; Chalouan et al., 1997, 2001).

The sedimentary strata of the Outer Carpathian domains record the culmination of a long-term trend of increasing accumulation and subsidence rates in the foreland basins/foredeeps all along the evolving Carpathian arc (Meulenkamp et al., 1996). This trend was abruptly terminated in latest Early Miocene (Karpatian, Fig. 1) time, and followed by a sharp decrease in subsidence rates around the Early–Middle Miocene transition (Badenian), about 16 Ma ago, and the concomitant inception of strongly accelerating rates of lateral, eastward migration of the foredeep depocentre until about 15 Ma ago. From this time on lateral foredeep depocentre shifts turned towards the southeast, parallel to the western margin of the East European Platform, until about the Middle–Late Miocene transition, 10 Ma ago (transition Sarmatian–Pannonian, Fig. 1). The latest Early Miocene to early Middle Miocene fundamental basin rearrangements in the Outer Carpathians were contemporaneous with the onset of the opening of the Vienna Basin and the Pannonian back-arc Basin System. Also the Peri-Tethys and Peri-Tethys–Tethys transitional domains further to the east (Eastern Paratethys) underwent a principal change in latest Early to earliest Middle Miocene time. For example, the widely distributed accumulation of Maykopian, often anoxic, sequences, which began at the Eocene–Oligocene transition, 34 Ma ago, and persisted throughout the Early/Late Oligocene and Early Miocene, stopped at the end of the Early Miocene (change from pre-foreland or Maykopian to foreland stage in the evolution of the North Caucasus Basin; Ershov et al., 1998, 1999). An accompanying tectonics-controlled reorganisation (‘Styrian phase’; see also Scherba, 1993) in latest Early to earliest Middle Miocene time in the Eastern Paratethys was the emergence of the Greater Caucasian archipelago.

Major changes of the Southern Peri-Tethys Platform include the relatively short-term latest Burdigalian to early Langhian marine transgression on the Arabian Platform, which had been emerged since about the Eocene–Oligocene transition (Figs. 3–5). This ephemeral re-invasion of the sea was contemporaneous with fundamental tectonic and sedimentary changes in the Gulf of Aden – Red Sea – Gulf of Suez Rift System as expressed by the effects of the northward progradation of the opening of the Red Sea Basin and by the impact of the Mid-Clysmic tectonic event and subsequent tectonics-induced changes in the Gulf of Suez, between about 17 and 15 Ma ago (Garfunkel and Bartov, 1977; Montenat et al., 1998). The Mid-Clysmic event represented a turning point in the geological history of the Suez rift and is considered the prelude to enhanced intrabasinal differentiation and increased isolation of the Gulf from the Mediterranean, which, in turn, resulted in the onset of the major phase of evaporite accumulation in the Gulf of Suez–Red Sea domain around 14 Ma ago (Orszag-Sperber et al., 1998). At about the Early–Middle Miocene transition, parts of the African Platform domain collapsed, as evidenced by the shift from the deposition of shallow-water platform carbonates to deep-water fine-grained clastics on Malta/Gozo and on the Iblean (Ragusa) Platform, southeastern Sicily (e.g., Theodoridis, 1984).

3.4. Late Middle to Late Miocene

In the course of the late Middle and Late Miocene, the overall uplift affecting the western and central domains of the Northern Peri-Tethys Platform caused the final break-up of the sedimentation realm across Europe. The intramontane basins on the Iberian block had started to decrease in size as compared to the early Middle Miocene extent. The Rhône Graben and the Massif Central became subject to general uplift (Sissingh, 1998, 2001) from about the Middle–Late Miocene transition onward, while, concomitantly, sedimentation virtually came to a stop in the peri-Alpine Molasse Basin. The increasing late Middle to Late Miocene continentalisation of Western Europe (and, consequently, the resultant shift towards exclusively fluvio-lacustrine environments in 'residual' basins) often prevents a precise dating of major episodes of change. The processes of uplift were particularly effective around the Middle–Late Miocene (Serravallian–Tortonian) transition (around 11 Ma ago) and within the early Late Miocene, around 8 Ma ago. At the latter time, the Rhine river system changed from the 'initial Rhine' towards the 'early Rhine' stage, contemporaneous with the inception of a major phase of uplift of the Alps.

In Central Europe, i.e., in the Central Paratethys domain of the Carpathian–Pannonian arc–back-arc system, the pronounced acceleration of lateral migration of the foredeep depocentre in the Outer Carpathians, which had started 17 Ma ago, ended at about the Middle–Late Miocene transition (Meulenkamp et al., 1996). In the intra-arc (Pannonian Basin) domains, latest Middle Miocene (Sarmatian) local uplift was followed by a short-term, early Late Miocene (early Pannonian, Fig. 1) new episode of rifting (Lankreijer, 1998) and was followed by post-rift thermal subsidence (Horvath, 1993; Csontos and Horvath, 1995; Meulenkamp et al., 1996) later in the Pannonian, 9–8 Ma ago. In terms of depositional environments, the processes affecting the arc–back-arc system in the early Late Miocene were accompanied by the termination of marine/brackish influence in the larger part of the arc and back-arc areas. In addition, the connections between the Pannonian back-arc Basin and the foreland basins of the Outer Carpathians were interrupted.

Major Late Miocene tectonic movements related to the 'Attic orogenesis' caused large-scale palaeogeographic reorganisations in the Eastern Paratethys around the Sarmatian–Maeotian transition at about 9 Ma ago (Fig. 1). The early Late Miocene movements resulted, amongst others, in the transformation of the Greater Caucasian domain into a mountain chain, which from then onward served as a major provenance area of terrigenous clastics, and in the origin of the present-day contours of the post-rift Black Sea Depression (Robinson et al., 1996). Concomitantly, the domain of the Dacic Basin (which hitherto belonged to the Central Paratethys) became incorporated in the realm of the Eastern Paratethys (Fig. 6). The subsequent ephemeral marine ingressions into the Eastern Paratethys, which probably entered from the Mediterranean in Maeotian and Pontian times, may have been related to an overall trend of regional subsidence rather than to a eustatic rise in sea level.

Hardly any high-resolution stratigraphic data are available on the Late Miocene evolution of the Southern Peri-Tethys Platform and adjacent areas. The timing of the termination of evaporite accumulation in the Red Sea Basin in the course of the Late Miocene and the presumedly associated causal(?) disrupture of marine connections with the Mediterranean are not well-constrained (Orszag-Sperber et al., 1998). In contrast, the opening of the Dead Sea Basin and the concomitant deposition of evaporitic successions can be dated at about 8 Ma ago (Meulenkamp et al., 2000b). In the western, North African part of the Southern Peri-Tethys Platform, intra-Tortonian extensional tectonics (about 8 Ma ago) resulted, for instance, in the opening of the Rifean corridor, which connected the Mediterranean Sea with the Atlantic Ocean (Bernini et al., 1994; Krijgsman et al., 1999b).

The changes on the Southern and Northern Peri-Tethys platforms and the adjacent Peri-Tethys–Tethys transitional domains during the early Late Miocene had unambiguous, time-equivalent counterparts in the circum-Tyrrhenian and Aegean regions (Meulenkamp and Hilgen, 1986; Patacca et al., 1990). In the course of the early Late Miocene, the evolving foreland basins of the Apennines were subjected to the inception of lateral, overall NNW–SSE-trending foredeep depocentre migration (Van der Meulen et al., 1998, 1999). This lateral migration was superimposed upon sustained internal–external depocentre migrations which had started in the Oligocene. It had become well-established around 8 Ma ago, coupled with the opening of the Tyrrhenian back-arc Basin and its (present-day onland) equivalent, the Tuscan Basin (Duermeijer et al., 1998; Van der Meulen, 1999). Simultaneously, the Aegean domain was subject to the inception of a major phase of arc migration of the external Hellenides and of overall subsidence in the South Aegean back-arc Basin (Meulenkamp et al., 1988, 1994).

3.5. *Pliocene–Pleistocene*

The overall uplift of Western and Central Europe continued in Pliocene–Pleistocene times. Because of the further reduction of depositional areas relative to the Late Miocene and the non-marine, clastic nature of associated deposits, it is difficult to infer and date the temporal sequence of events, which controlled the final stage of continentalisation of the European domains. However, differential tectonic movements did affect Western Europe, as evidenced by the onset of a second phase of rifting of the Rhine Graben from around 4–3 Ma ago (Early–Middle Pliocene transition) onwards, which resulted in the origin of the present-day Rhine river system (Villinger, 1998). In Central Europe sedimentation in the back-arc regions became mainly confined to local accumulations of coarse clastics; foredeep sedimentation and major folding and thrusting had also come to a close in the southeastern part of the Carpathian arc in the Middle to Late Pliocene. In contrast, new basin configurations and subsidence regimes developed in the Eastern Paratethys after a major phase of late Early Pliocene tectonics. The result was the enhanced uplift of the Greater Caucasian domain, in association with strongly increased rates of molasse foredeep sedimentation, and in the origin of the vast, NNW–SSE-trending Akchagylian Basin (Fig. 7) at the beginning of the Middle Pliocene, around 3.5 Ma ago. To the north, the basin extended far beyond the limits of the Late Miocene to Early Pliocene basins, documenting subsidence of large parts of the Eastern Paratethys in the Middle and Late Pliocene.

The major changes straddling the Early–Middle Pliocene boundary in the eastern parts of the Northern Peri-Tethys Platform (Eastern Paratethys) were coeval with an episode of major change in the Mediterranean, e.g., in the Hellenic and Tyrrhenian arc–back-arc systems. In the Aegean region, a late Early Pliocene (around 4 Ma) phase of thrusting (Sorel, 1976; Meulenkamp and Hilgen, 1986; Underhill, 1989) occurred in the external Hellenides, correlative to the outbreak of back-arc volcanism; these processes were followed by a discrete episode of extension-controlled basin rearrangements (Meulenkamp, 1985; Meulenkamp et al., 1994). The late Early to early Middle Pliocene evolution of the circum-Tyrrhenian region was characterised by the onset of a new phase of fore-arc lateral reorganisation in the Southern Apennines, which coincided with an episode of southeastward migration of the locus of maximum extension in the Tyrrhenian Basin and the onset of uplift of Tuscany (Van der Meulen, 1999) between 4.4 and 3.6 Ma ago. A next-younger reorganisation in the Central Mediterranean domain, between 2.1 and 1.7 Ma ago, included the renewed pulse in the migration of the locus of maximum extension in the Tyrrhenian back-arc Basin and a major tectonic pulse (around 1.8 Ma ago) in the southern Apennines (Duermeijer, 1999; Van der Meulen, 1999).

Events around the Plio–Pleistocene transition and subsequent episodes of change seem to have affected various other domains of the collision zone and the bordering platforms as well, but our data are insufficient to put unambiguous constraints on their timing and regional distribution. Equally, no precise age assignments are available pertaining to the evolution of the southern platform in Pliocene–Pleistocene times, but regressive trends and overall uplift prevailed all over the platform from the Early Pliocene onwards, subsequent to the earliest Pliocene flooding which ended the Messinian salinity crisis in the Mediterranean, 5.34 Ma ago (Krijgsman et al., 1999a). The flooding affected the Nile canyon, formed in Messinian time, as well as other marginal parts of the African Platform, but the Pliocene seas did not re-invade the Dead Sea Basin after the short-term Late Miocene marine ingression.

Specific problems arise with respect to the presumed latest Miocene to earliest Pliocene interplay between tectonics and eustacy-controlled changes in the Mediterranean and surrounding borderlands, when an episode of severed Atlantic–Mediterranean connections resulted in the Messinian salinity crisis (for a review, see Krijgsman et al., 1999a). This crisis was terminated by the reinstallment of normal marine conditions through the opening of the Strait of Gibraltar at the very beginning of the Pliocene. As yet, the impact of tectonics relative to eustacy remains unclarified, but it seems that the tectonic reorganisations around the Messinian salinity crisis proper were subordinate relative to the earlier and later major, tectonically induced changes around 9–8 and 4–3 Ma ago, respectively.

4. Discussion

The evaluation of the tectonostratigraphic interrelationships outlined in Section 3 makes it possible to infer five episodes of major change which simultaneously affected large parts of the convergent plate boundary zone and the bordering Northern and Southern Peri-Tethys platforms during the last 40 million years.

The first of these episodes, ranging from 37 to 34 Ma ago, concluded a Late Cretaceous to Eocene period of overall regressive trends on the platforms and of a series of (early) Alpine tectonic 'pulses' in the evolution of the fold and thrust belts developing along the convergent plate boundary zone. The resulting development of a fairly continuous system of incipient Alpine chains all along the margins of the Northern Peri-Tethys Platform by the end of the Eocene (34 Ma) and the concomitant uplift of large parts of the Northern and Southern Peri-Tethys platforms may be considered the palaeogeographic expression of the major geodynamic change at the Eocene–Oligocene transition, which initiated the transformation of the Tethyan domains into a land-locked configuration (Jolivet and Facenna, 2000). The inception of major rifting on the West European Platform during the Late Eocene was probably somehow related to the stronger coupling of the African/Apulian and Eurasian plates assembly in the west relative to the coupling effects of initial collision in the east.

The second episode of major change, between 30 and 27 Ma ago, was characterised by the beginning of a pronounced regional differentiation between the palaeogeographic and tectonostratigraphic evolution of the Peri-Tethys platforms and of the intermediate Tethys domains. This beginning differentiation was related to the onset of widespread extension in the Mediterranean realm (Jolivet and Facenna, 2000). The Early Oligocene time interval of about four million years between the end of the first (34 Ma) and the beginning of the second (30 Ma) episode of major change might constrain the time lag hypothesised by Jolivet and Facenna (2000) between the (geodynamic) onset of large-scale extension and its expression in the geological record. This expression included the inception of Late Oligocene to Early Miocene rifting and subsequent oceanisation in the west (Western Mediterranean), as well as the contemporaneous development of the Gulf of Aden–Red Sea–Gulf of Suez Rift System in the east, associated with the anticlockwise rotation of the Arabian block (Le Pichon and Gaulier, 1988).

In the Alpine–Carpathian domain of the African–Eurasian convergence zone, the intra-Oligocene (30–27 Ma) episode of major change was characterised by the beginning of eastward-directed lateral depocentre migration in the foreland basins. The Late Oligocene to Early Miocene palaeogeographic changes and basin rearrangements in the Western Mediterranean formed the response to the inception of arc migration sensu Malinverno and Ryan (1986), related to the onset of subduction roll-back about 30 Ma ago (Carminati et al., 1998a,b; Wortel and Spakman, 2000). A similar mechanism may account for the onset of lateral foredeep depocentre migration in the Alpine–Carpathian region.

The third, late(st) Early Miocene to early Middle Miocene episode of major change lasted from about 17 to 15 Ma ago. In the west, this episode resulted in regional uplift of the West European Platform and adjacent parts of the Peri-Tethys–Tethys transitional zone and was associated with the end of principal rifting of the Rhine Graben. At about the same time, the anticlockwise rotation of the Sardinia–Corsica block and the oceanisation of the Liguro-Provençal Basin came to a halt, which marks the end of a discrete phase in the geodynamic evolution of the Western Mediterranean (Carminati et al., 1998a,b; Wortel and Spakman, 2000). The palaeogeographic and tectonostratigraphic changes in Central Europe around the Early–Middle Miocene transition included the pronounced acceleration of lateral foredeep depocentre migration in the Outer Carpathians and the coeval opening of the Pannonian back-arc Basin System. These features are thought to reflect the onset of lateral migration of slab detachment in the Carpathian region (Wortel and Spakman, 2000). The contemporaneous emergence of the Greater Caucasian archipelago and the end of deposition of Maikopian facies in the adjacent foreland basin may be related to the inception of the main phase of collision along the Caucasian part of the convergent plate boundary zone (Ershov et al., 1998, 1999 and references therein). The major, tectonics-induced basin reorganisations and changes in sedimentation in the Gulf of Aden–Red Sea–Gulf of Suez Rift System in latest Early to early Middle Miocene time may, at least in part, be related to the about four-fold increase in the rate of (anticlockwise) rotation of the Arabian block (Le Pichon and Gaulier, 1988), which corresponds in time to the onset of deposition of the Kareem-Belayim evaporitic sequence, dated at 15 Ma ago (Evans, 1988 and own, unpublished data).

The fourth episode of major change occurred in the early Late Miocene, around 9–8 Ma ago. Its resultant modifications included enhanced uplift and emergence of large parts of Western and Central Europe in association with the end of (basinal) sedimentation in the northern Alpine foreland, the end of lateral foredeep depocentre migration in the Outer Carpathians and the approximately concomitant inception of post-rift thermal subsidence in the Pannonian Basin. In the east, a new phase of basin development affected the domain of the Caucasus (Sarmatian–Maeotian transition, about 9 Ma ago, Ershov et al., 1998), as part of an overall reorganisation of the East European domains and of the area straddling the Peri-Tethys–Tethys transition in the Northern Aegean. Major developments in the Mediterranean included the inception of lateral, N–S depocentre migration along the evolving Apennines and the opening of the Tyrrhenian back-arc Basin in response to the beginning of lateral migration of slab detachment in the region of the Apennines–Calabrian arc, 9–8 Ma ago (Van der Meulen et al., 1998; Van der Meulen, 1999; Wortel and Spakman, 2000). The beginning or acceleration of arc migration in the Southern Aegean region was related to a correlative phase of roll-back at the Hellenic subduction zone. A comparison between the Carpathian–Pannonian and circum-Tyrrhenian regions suggests a time lag of about eight million years between the inception of lateral migration of slab detachment in the respective domains (17–16 versus 9–8 Ma ago).

The palaeogeographic and tectonostratigraphic features which characterise the fifth episode of major change (4–3 Ma ago) included in the Mediterranean the beginning of a new (slab detachment-related) phase of arc migration in the Aegean and Tyrrhenian regions (Ten Veen, 1998; Van der Meulen, 1999). In general, the latest

Early to early Middle Pliocene episode of change was marked by the onset of widespread, differential vertical movements of the fragmented Peri-Tethys platforms and the intermediate domains of the African–Eurasian collision zone. These movements ultimately resulted in today's geographic and topographic features. Relatively significant, regional changes on the West European Platform included the beginning of renewed rifting of the Rhine Graben, following a period of about 10 million years when extension in this basin played a minor role, if any. Uplift predominated in Central Europe and sedimentation in the Carpathian–Pannonian region became confined to the local accumulation of continental clastics. In contrast, farther to the east major changes around 4–3 Ma ago resulted in new basin configurations and uplift/subsidence regimes, as seen by the enhanced uplift of the Greater Caucasus chain and the development of the N–S-trending Akchagylian Basin subsequent to major late Early Pliocene tectonics.

5. Conclusions

The Tertiary palaeogeographic and palaeoenvironmental evolution of the Northern and Southern Peri-Tethys platforms and the domains of the African–Eurasian convergent plate boundary zone was defined to a large extent by a sequence of contemporaneous tectonic events. In combination, these events resulted in five episodes of major change, which occurred in the Late Eocene (37–34 Ma), the Late Oligocene (30–27 Ma), the late(st) Early to early Middle Miocene (17–14 Ma), the Late Miocene (9–8 Ma) and the late Early to early Middle Pliocene (4–3 Ma). These episodes of contemporaneous change were superimposed upon overall W–E-directed trends of time-progressive uplift and emergence of the Northern Peri-Tethys Platform and the bordering domains of the convergence zone. The Late Eocene and Oligocene episodes of change can be related to the transformation of the convergence zone into a land-locked configuration and to the subsequent inception of large-scale extension. Some of the features of the Oligocene to Pliocene episodes of overall major change can be related to discrete stages in the regional geodynamic evolution of parts of the convergence zone, controlled by subduction roll-back and slab detachment. However, such temporal and regional relationships do not account for the contemporaneity of the episodes of major change along the entire convergence zone and the bordering platforms. Therefore, it is tentatively concluded that this contemporaneity can only be understood in terms of the coeval response to geodynamic events at the scale of the African and Eurasian plates. Such events may have 'triggered' the inception or termination of successive development stages in the regional evolution of domains in different geodynamic settings. This corroborates the conclusion by Jolivet and Facenna (2000) with respect to a common cause underlying the onset of large-scale Oligocene extension, related by the latter authors to changes in plate motion velocities.

Acknowledgements

We wish to thank all colleagues who contributed to the realisation of the Peri-Tethys palaeogeographic maps and the accompanying explanatory notes. Dr J. Golonka (Jagiellonian University, Cracow), Dr P.Th. Meijer (Utrecht University) and one anonymous reviewer are acknowledged for their critical reading of the manuscript and for their valuable suggestions. The illustrations were made by T. van Hinte. This is a contribution of the Vening Meinesz Research School of Geodynamics (VMSG) and contribution no. NSG 20030407 of the Netherlands Research School of Sedimentary Geology (NSG).

References

Arthaud, F., Séguret, M., 1981. Les structures pyrénéennes du Languedoc et de Golfe du Lion (Sud de la France). Bull. Soc. Géol. France 23, 52–63.

Bernini, M., Boccaletti, M., Mokhtari, J., Gelati, R., Moratti, G., Papani, G., 1994. The Neogene Taza-Guercif Basin. Excursion Guidebook, Interim Colloquium Neogene Basin Evolution and Tectonics in the Mediterranean Area, Florence, 57 pp.

Carminati, E., Wortel, M.J.R., Spakman, W., Sabadini, R., 1998a. The role of slab detachment in the opening of the western-central Mediterranean basins: some geological and geophysical evidence. Earth Planet. Sci. Lett. 160, 651–665.

Carminati, E., Wortel, M.J.R., Meijer, P.Th., Sabadini, R., 1998b. The two-stage opening of the western–central Mediterranean basins: a forward modeling test to a new evolutionary model. Earth Planet. Sci. Lett. 160, 667–679.

Chalouan, A., Saji, R., Michard, A., Bally, A.W., 1997. Neogene tectonic evolution of the southwestern Alboran Basin as inferred from seismic data off Morocco. AAPG Bull. 81, 1161–1184.

Chalouan, A., Michard, A., Feinberg, H., Montigny, R., Saddiqi, O., 2001. The Rif mountain building (Morocco): a new tectonic scenario. Bull. Soc. Géol. France 172, 603–616.

Chamot-Rooke, N., Gaulier, J.-M., Jestin, F., 1999. Constraints on Moho depth and crustal thickness in the Liguro-Provençal basin from a 3D gravity inversion: geodynamic implications. Geol. Soc. London Spec. Publ. 156, 37–61.

Comas, M.C., Garcia-Dueñas, V., Jurado, M.J., 1992. Neogene tectonic evolution of the Alboran Sea from MCS data. Geo-Mar. Lett. 12, 157–164.

Csontos, L., Horvath, F., 1995. Tertiary structural evolution of the intra-Carpathian area: a report on integrated basin studies, Pannonian Basin. E.C. Project, Proceedings of the XV Congress of the Carpatho-Balcan Geological Assocation. Geol. Soc. Greece Spec. Publ. 4, 12–17.

Dercourt, J., Zonenshain, L.P., Ricou, L.E., Kazmin, V.G., Le Pichon, X., Knipper, A.L., Grandjacquet C., Sborshchikov, I.M., Geyssant, J., Lepvrier, C., Pechersky, D.H., Boulin, J., Sibuet, J.C., Savostin, L.A., Sorokhtin, O., Westphal, M., Bazhenov, M.L., Lauer, J.P., Biju-Duval, B., 1986. Geological evolution of the Tethys Belt from the Atlantic to the Pamirs since the Lias. In: Aubouin, J., Le Pichon, X., Monin, A.S. (Eds.), Evolution of the Tethys. Tectonophysics 123, 241–315.

Dercourt, J., Ricou, L.E., Vrielynck, B. (Eds.), 1993. Atlas Tethys, Palaeoenvironmental Maps. Gauthier-Villars, Paris, 307 pp, 14 maps, 1 pl.

Dercourt, J., Gaetani, M., Vrielynck, B., Barrier, E., Biju-Duval, B., Brunet, M.F., Cadet, J.P., Crasquin, S., Sandulescu, M. (Eds.), 2000a. Atlas Peri-Tethys, Palaeogeographical Maps. CCGM/CGMW, Paris, 24 maps and explanatory notes, I–XX, 269 pp.

Dercourt, J., Gaetani, M., Vrielynck, B., 2000b. General features of the Atlas. In: Crasquin, S. (Coord.), Atlas Peri-Tethys, Palaeogeographical Maps – Explanatory Notes. CCGM/CGMW, Paris, pp. XI–XX.

Duermeijer, C.E., 1999. Neogene to Recent tectonic evolution of the Central Mediterranean: an integrated paleomagnetic approach. Geol. Ultraiectina 176, 1–167.

Duermeijer, C.E., Van Vugt, N., Langereis, C.G., Meulenkamp, J.E., Zachariasse, W.J., 1998. A major late Tortonian rotation phase of the Crotone Basin; implications using AMS as tectonic tilt correction and first indication of timing in opening of the Tyrrhenian Basin. Tectonophysics 287, 233–249.

Edel, J.-B., Dubois, D., Marchant, R., Hernandez, J., Cosca, M., 2001. La rotation miocène inférieur du bloc corso-sarde. Nouvelles contraintes paléomagnétiques sur la fin du mouvement. Bull. Soc. Géol. France 172, 275–283.

Ershov, A.V., Brunet, M.-F., Nikishin, A.M., Bolotov, S.N., Korotaev, M.V., Kosova, S.S., 1998. Evolution of the eastern Fore-Caucasus basin during the Cenozoic collision: burial history and flexural modelling. In: Crasquin-Soleau, S., Barrier, E. (Eds.), Peri-Tethys Memoir 4: Epicratonic Basins of Peri-Tethyan Platforms. Mem. Mus. Natl. Hist. Nat. 179, 111–130.

Ershov, A.V., Brunet, M.-F., Korotaev, M.V., Nikishin, A.M., Bolotov, S.N., 1999. Late Cenozoic burial history and dynamics of the Northern Causasus molasse basin: implications for foreland basin modelling. Tectonophysics 313, 219–241.

Evans, A.L., 1988. Neogene tectonic and stratigraphic events in the Gulf of Suez rift area, Egypt. Tectonophysics 153, 235–247.

Frizon de Lamotte, D., Saint Bezar, B., Bracene, R., 2000. The two main steps of the Atlas building and geodynamics of the Western Mediterranean. Tectonics 19, 740–761.

Garfunkel, Z., Bartov, Y., 1977. The tectonics of the Suez Rift. Geol. Surv. Israel Bull. 71, 1–44.

Golonka, J., Oszczypko, N., Slaczka, A., 2000. Late Carboniferous–Neogene geodynamic evolution and paleogeography of the circum-Carpathian region and adjacent areas. Ann. Soc. Geol. Polon 70, 107–136.

Hippolyte, J.-C., Angelier, J., Bergerat, F., Nury, D., Guieu, G., 1993. Tectonic-stratigraphic record of paleostress time changes in the Oligocene basins of the Provence, southern France. Tectonophysics 226, 15–35.

Horvath, F., 1993. Towards a mechanical model for the formation of the Pannonian basin. Tectonophysics 226, 333–357.

Jolivet, L., Facenna, C., 2000. Mediterranean extension and the Africa–Eurasia collision. Tectonics 19, 1095–1106.

Krijgsman, W., Hilgen, F.J., Raffi, I., Sierro, F.J., Wilson, D.S., 1999a. Chronology, causes and progression of the Messinian salinity crisis. Nature 400, 652–655.

Krijgsman, W., Langereis, C.G., Zachariasse, W.J., Boccaletti, M., Moratti, G., Gelati, R., Iaccarino, S., Papani, G., Villa, G., 1999b. Late Neogene evolution of the Taza-Guercif Basin (Rifian Corridor, Morocco) and implications for the Messinian salinity crisis. Mar. Geol. 153, 147–160.

Lankreijer, A., 1998. Rheology and Basement Control on Extensional Basin Evolution in Central and Eastern Europe: Variscan and Alpine–Carpathian–Pannonian Tectonics. PhD Thesis, Free University, Amsterdam, 158 pp.

Le Pichon, X., Gaulier, J.-M., 1988. The rotation of Arabia and the Levant fault system. Tectonophysics 153, 271–294.

Malinverno, A., Ryan, B.F., 1986. Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere. Tectonics 5, 227–245.

Martin-Algarra, A., Sanz de Galdeano, C., Estevez, A., 1988. L'évolution sédimentaire miocène de la région au nord de la Sierra Arana (Cordillères bétiques) et sa relation avec la mise en place du bloc d'Alboran. Bull. Soc. Géol. France, sér. 8 4, 119–127.

Meulenkamp, J.E., 1985. Aspects of the late Cenozoic evolution of the Aegean region. In: Stanley, D.J., Wezel, F.-C. (Eds.), Geological Evolution of the Mediterranean Basin. Springer-Verlag, New York, pp. 307–321.

Meulenkamp, J.E., Hilgen, F.J., 1986. Event stratigraphy, basin evolution and tectonics of the Hellenic and Calabro-Sicilian arcs. In: Wezel, F.-C. (Ed.), The Origin of Arcs. Developments in Geotectonics 21, Elsevier, Amsterdam, pp. 327–350.

Meulenkamp, J.E., Wortel, M.J.R., van Wamel, W.A., Spakman, W., Hoogerduyn Strating, E., 1988. On the Hellenic subduction zone and the geodynamic evolution of Crete since the late Middle Miocene. Tectonophysics 146, 203–215.

Meulenkamp, J.E., van der Zwaan, G.J., van Wamel, W.A., 1994. On Late Miocene to Recent vertical motions in the Cretan segment of the Hellenic arc. Tectonophysics 234, 53–72.

Meulenkamp, J.E., Kovac, M., Cicha, I., 1996. On Late Oligocene to Pliocene depocentre migrations and the evolution of the Carpathian–Pannonian system. Tectonophysics 266, 310–317.

Meulenkamp, J.E., Sissingh, W. et al., 2000a. Early to Middle Ypresian, late Lutetian, late Rupelian, early Burdigalian, early Langhian, late Tortonian, Piacenzian/Gelasian. In: Dercourt, J., Gaetani, M. et al. (Eds.), Atlas Peri-Tethys, Palaeogeographical Maps. CCGM/CGMW, Paris, maps 17–23.

Meulenkamp, J.E., Sissingh, W. et al., 2000b. Tertiary. In: Crasquin, S. (Coord.), Atlas Peri-Tethys, Palaeogeographical Maps – Explanatory Notes. CCGM/CGMW, Paris, pp. 153–208.

Montenat, C., Ott d'Estevou, P., Jarrige, J.J., Richert, J.-P., 1998. Rift development in the Gulf of Suez and the northwestern Red Sea: structural aspects and related sedimentary processes. In: Purser, B.H., Bosence, D.W.J. (Eds.), Sedimentation and Tectonics of Rift Basins: Red Sea-Gulf of Aden. Chapman and Hall, London, pp. 97–116.

Orszag-Sperber, F., Harwood, G., Kendall, A., Purser, B.H., 1998. A review of the evaporites of the Red Sea-Gulf of Suez rift. In: Purser, B.H., Bosence, D.W.J. (Eds.), Sedimentation and Tectonics of Rift Basins: Red Sea-Gulf of Aden. Chapman and Hall, London, pp. 409–426.

Patacca, E., Sartori, R., Scandone, P., 1990. Tyrrhenian Basin and Apenninic arcs: kinematic relations since Late Tortonian times. Mem. Soc. Geol. Ital. 45, 425–451.

Purser, B.H., Bosence, D.W.J. (Eds.), 1998. Sedimentation and Tectonics in Rift Basins, Red Sea-Gulf of Aden. Chapman and Hall, London, 663 pp.

Reichenbacher, B., 2000. Das brackische lakustrine Oligozän und Ober-Miozän im Mainzer Becken und Hanauer Becken: Fischfaunen, Paläokologie, Biostratigraphie und Paläogeographie. Cour. Forsch.-Inst. Senckenberg 222, 1–143.

Robinson, A.G., Rudat, J.H., Banks, C.J., Wiles, R.L.F., 1996. Petroleum geology of the Black Sea. Mar. Petrol. Geol. 13, 195–223.

Roca, E., 2001. The Northwest-Mediterranean basin (Vallencia Trough, Gulf of Lions and Liguro-Provençal basins): structure and geodynamic evolution. Mém. Mus. Natl. Hist. Nat. 186, 671–706.

Rögl, F., 1998. Palaeogeographic considerations for Mediterranean and Paratethys Seaways (Oligocene to Miocene). Ann. Naturhist. Mus. Wien 99A, 279–310.

Scherba, I.G., 1993. Stages and Phases of Cenozoic Development of Alpine Fold Belt. Nauka, Moscow, 229 pp.

Schlunegger, F., Burbank, D.W., Matter, A., Engesser, B., Mödden, C., 1996. Magnetostratigraphic calibration of the Oligocene to Middle Miocene (30–15 Ma) mammal biozones and depositional sequences of the Swiss Molasse Basin. Eclogae Geol. Helv. 89, 753–788.

Séranne, M., 1999. The Gulf of Lion continental margin (NW Mediterranean) revisited by IBS: an overview. Geol. Soc. London Spec. Publ. 156, 15–36.

Sissingh, W., 1997. Tectonostratigraphy of the North Alpine Foreland Basin: correlation of Tertiary depositional cycles and orogenic phases. Tectonophysics 282, 223–256.

Sissingh, W., 1998. Comparative Tertiary stratigraphy of the Rhine Graben, Bresse Graben and Molasse Basin: correlation of Alpine Foreland events. Tectonophysics 300, 248–284.

Sissingh, W., 2001. Tectonostratigraphy of the West Alpine Foreland: correlation of Tertiary sedimentary sequences, changes in eustatic sea-level and stress regimes. Tectonophysics 333, 361–400.

Sorel, D., 1976. Etude néotectonoique dans l'Arc Egéen externe occidental les îles Ioniennes de Kephallonia et Zakinthos et l'Elide occidentale. Thèse 3ème cycle, Université de Paris-Sud, 196 pp.

Sowerbutts, A.A., Underhill, J.R., 1998. Sedimentary response to intra-arc extension: controls on Oligo-Miocene deposition, Sarcidano sub-basin, Sardinia. J. Geol. Soc. London 155, 491–508.

Ten Veen, J.H., 1998. Neogene outer-arc evolution in the Cretan segment of the Hellenic arc: tectonic, sedimentary and geodynamic reconstructions. Geologica Ultraiectina 160, 191 pp.

Theodoridis, S., 1984. Calcareous nannofossil biozonation of the Miocene and revision of the Helicoliths and Discoasters. Utrecht Micropaleontol. Bull. 32, 1–272.

Torres, J., Bois, C., Burrus, J., 1993. Initiation and evolution of the Valencia Trough (Western Mediterranean): constraints from deep seismic profiling and subsidence analysis. Tectonophysics 228, 57–80.

Underhill, J.H., 1989. Late Cenozoic deformation of the Hellenide foreland, western Greece. GSA Bull. 101, 613–634.

Van der Meulen, M.J., 1999. Slab detachment and the evolution of the Apenninic arc (Italy). Geol. Ultraiectina 170, 1–136.

Van der Meulen, M.J., Meulenkamp, J.E., Wortel, M.J.R., 1998. Lateral shifts of Apenninic foredeep depocentres reflecting detachment of subducted lithosphere. Earth Planet. Sci. Lett. 154, 203–219.

Van der Meulen, M.J., Kouwenhoven, T.J., van der Zwaan, G.J., Meulenkamp, J.E., Wortel, M.J.R., 1999. Late Miocene uplift in the Romagnan Apennines and the detachment of subducted lithosphere. Tectonophysics 315, 319–335.

Villinger, E., 1998. Zur Flussgeschichte von Rhein und Donau in Südwestdeutschland. Jber. Mitt. Oberrhein. Geol. Ver. N. Ser. 80, 361–398.

Wagner, G.A., 1976. Spaltspurendatierung an Apatit und Titanit aus den Subvulkaniten des Kaiserstuhls. N. Jahrb. Mineral. Mon.heft., 389–393.

Wortel, M.J.R., Spakman, W., 2000. Subduction and slab detachment in the Mediterranean-Carpathian region. Science 290, 1910–1917.

Ziegler, P.A., 1987. Late Cretaceous and Cenozoic intra-plate compressional deformations in the Alpine Foreland – a geodynamic model. Tectonophysics 137, 389–420.