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Syn-kinematic palaeogeographic evolution of the West European Platform: correlation with Alpine plate collision and foreland deformation

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Abstract

Sequence stratigraphic correlations indicate that intermittent changes of the kinematic far-field stress-field regimes, and the associated geodynamic re-organisations at the plate-tectonic contacts of the African, Apulian, Iberian and European plates, affected the Tertiary palaeogeographic evolution of the West European Platform through a combination of intra-plate tectonics and fluctuations of relative sea level. A temporal sequence of first-order stages in structural, palaeotopographic and palaeohydrographic development of the platform can be distinguished from the Paleocene onwards. These formative stages are closely linked to major plate-boundary events involving the development of the Pyrenean and Alpine orogens, and can be traced throughout the West European Platform.

Keywords: Alpine Foreland Basin, Aquitaine Basin, European Cenozoic Rift System, palaeogeography, plate-kinematics, Paris Basin, West European Platform

Introduction

The Late Cretaceous to Tertiary collision of Africa and Europe is generally recognised as the prime driving force of the Alpine orogeny in Western and Central Europe. The integration of data on the timing and directions of these plate motions has allowed the reconstruction of the general convergence path of the African and European plates, as well as the relative motions of the intermediary, penetrative Iberian and Apulian microplates (Bergerat, 1987; Le Pichon et al., 1988; Dewey et al., 1989). The data used include palaeostress indicators in the brittle and ductile deformations of the Alps and Pyrenees and their surrounding areas, palaeogeographic reconstructions of the orogenic Tethyan belt in the Mediterranean realm, and plate-tectonic events as deduced from the Indian and Atlantic sea-floor spreading axes (magnetic anomalies). However, kinematic interpretations are commonly controversial. In Tertiary times, the continental crust of the West European Platform responded in a complex manner to the inferred N-S to NW-SE trending convergence motions and compressions. Re-activation of pre-existing normal faults and development of new crustal fractures was common and widespread. In this manner, upthrusting of major basement blocks (e.g. Bohemian Massif; Malkovsky, 1987) and inversion of Mesozoic (trans)tensional hanging-wall basins occurred north of the present Pyrenean and Alpine fold-and-thrust belts (most notably in the region ranging from southern England to northern Germany; Ziegler, 1987; Ziegler et al., 1995, 1998). Overall, basin inversions accompanied the Alpine orogeny from the mid-Cretaceous onwards. Inversions characterise the Sub-Hercynian (Santonian-Campanian), Laramide (Paleocene) and Pyrenean (Late Eocene-Early Oligocene) orogenic phases. Major, causally-related deformation, uplift and erosion of Mesozoic sediments occurred along the western margin of the Bohemian Massif and in the adjacent proximal part of the North Alpine Foreland (and in its southward extension underneath the north-verging, partly basement-cored Alpine nappes) during the latest Cretaceous and earliest Tertiary (Bachmann et al., 1987; Nachtmann & Wagner, 1987; Schröder, 1987; Bachmann & Müller, 1991). Inversions occurred throughout the mid-Cretaceous-Tertiary period in the foreland of the west-verging Western Alps and north-verging Pyrenees (Gillcrist et al., 1987; de Graciansky et al., 1989; Roure & Colletta, 1996), indicating persistent compressional propagation of the Alpine-Pyrenean orogenic system towards and across the passive southern margin of Europe. The development of these structures was not controlled by the same geodynamic conditions as the typical intra-plate inverted basins. The accompanying crustal shortening was locally rooted in the basement and possibly translated into the nearby orogens via a lower crustal detachment. The South German Block (southern Germany) and the Ardennes, West Rhenish and Burgundy blocks (northeastern and central France), however, were little affected by inversion tectonics. This tectonic activity was probably induced by divergent and convergent wrench-faulting initiated by compressional and transpressional re-activation of Permo-Carboniferous (and Mesozoic) fracture systems. The root cause being the northwestward-advancing Alpine orogenic wedge. The evolving orogen transmitted stresses from the Alpine collision zone between mobile Africa and cratonic Europe, into the Alpine foreland. The northward drift of Africa formed part of a larger pattern of seafloor spreading and block movement along transform faults in the Indian and South Atlantic oceans.

The African-European collision forces mostly dominated over the deviatoric Mid-Atlantic ridge-push forces, and were the formative stress source in the West European Platform (Sissingh, 2006). Generally, the intensity of the intra-platform basin inversions, basin-fill extrusions and crustal shortenings decreases with increasing distance from the Alpine thrust front (Ziegler, 1987; Ziegler et al., 1998). This reflects a (mainly) collision-related compressive stress regime in the Alpine foreland due to a mechanical coupling of the advancing orogenic wedge and the cratonic foreland plate at the Alpine collision zone. It also testifies of a decoupling of the upper crust from the lithospheric mantle, which enabled movement of crustal fragments along both pre-existing and new fractures above a relatively ductile lower crust. A west-to-east increasing collision-resistance force acting along the southern margin of the European Plate, has been suggested for the Recent (Gölke & Coblentz, 1996). This gradient would be a consequence of the continuing dextral oblique convergence and counter-clockwise rotation of Apulia (Africa) relative to Europe, contemporaneous with tangential transmission of inplane collisional stresses into the Alpine foreland. Though compression from the south was most likely the main driving force for the Tertiary (re)structuration of the Alpine foreland, the ridge-push forces generated by the northward-propagating opening of the Atlantic Ocean may also have been significant. These interacted with the forces derived from the plate-scale Alpine collision (Gölke & Coblentz, 1996). The stress field of the West European Platform therefore evolved through a temporally and spatially variant combination of forces generated by the collisional coupling of the African and European plates and the progressive opening of the Atlantic (Sissingh, 2006). Past and present stress-field characteristics of the West European Platform can ultimately be explained in terms of plate-boundary events and ridge-push forces that originated by seafloor spreading in the Indian and Atlantic oceans.

Pre-existing crustal fractures and fracture patterns played an important role during the Tertiary kinematic and tectonic development of the sedimentary basins of Western Europe (Encls 1 and 2; Appendix 1; Kronberg, 1991). They responded to intra-plate changes in stress regime depending on their susceptibility to re-activation. Therefore, fault (re-)activation did not necessarily require a major change in the stress field. The main fracture zones of the metastable West European Platform strike NNE-SSW, NNW-SSE, WNW-ESE and NW-SE. These trends are generally inherited from Variscan (late Palaeozoic) and older basement structures. In the proximal North Alpine Foreland, numerous minor normal faults are WSW-ENE striking (Nachtmann & Wagner, 1987; Herb, 1992). They reflect Tertiary flexural subsidence and tension of the crust caused by the loading of the passive southern margin of Europe by northward-advancing Alpine nappes. This syn-flexural subsidence induced the development of the North and West Alpine Foreland basins along the Alpine fold-and-thrust belt (Fig. 1; Encls 1 and 2; Appendix 1). In the more distant foreland region, differential lateral movements of crustal blocks resulted in the comparatively complex European Cenozoic Rift System (Figs 2 and 3; Encls 1 and 2), the origin of which is still enigmatic (see below). These two sedimentary basin complexes, together with the North Pyrenean Foreland Basin/Aquitaine Basin along the Pyrenees and the saucer-shaped intracontinental Paris Basin in central France, are the most prominent tectonic features of the West European Platform (Encls 1 and 2; Appendix 1). Each of these basins has its own, unique structural setting and tectonic history. However, their coeval, but different stratigraphic fills, record identical events such as the far-field kinematic 'pulses' related to the African-European plate convergence.

Time and again changes in intra-plate stress regimes induced differential vertical and horizontal movements of crustal blocks along pre-existing and newly established fracture systems of the West European Platform. Block movements were often (sub)parallel to the Variscan and pre-Variscan basement structures. Thus, the characteristics of the intra-plate stress fields and the internal geometry of the pre-existing fracture patterns determined to a large extent the occurrence of fault re-activations and the formation of new faults in the platform region. The highly fragmented crust of the West European Platform remained significantly compressed in plane-horizontal directions by the African-European continent/continent collision forces and the counteracting Atlantic ridge-push forces (Sissingh, 2006). Decoupled from the lithospheric mantle by the relatively weak, ductile lower crust, the lateral plate-boundary forces moved the fragments of the upper crust more or less independently from each other and the lithospheric mantle (Müller et al., 1997). Fault-plane solutions of earthquakes and geodetic data indicate that adjustive morpho-tectonic activity and positional adjustments of upper crustal blocks in the West European stress province continue till the

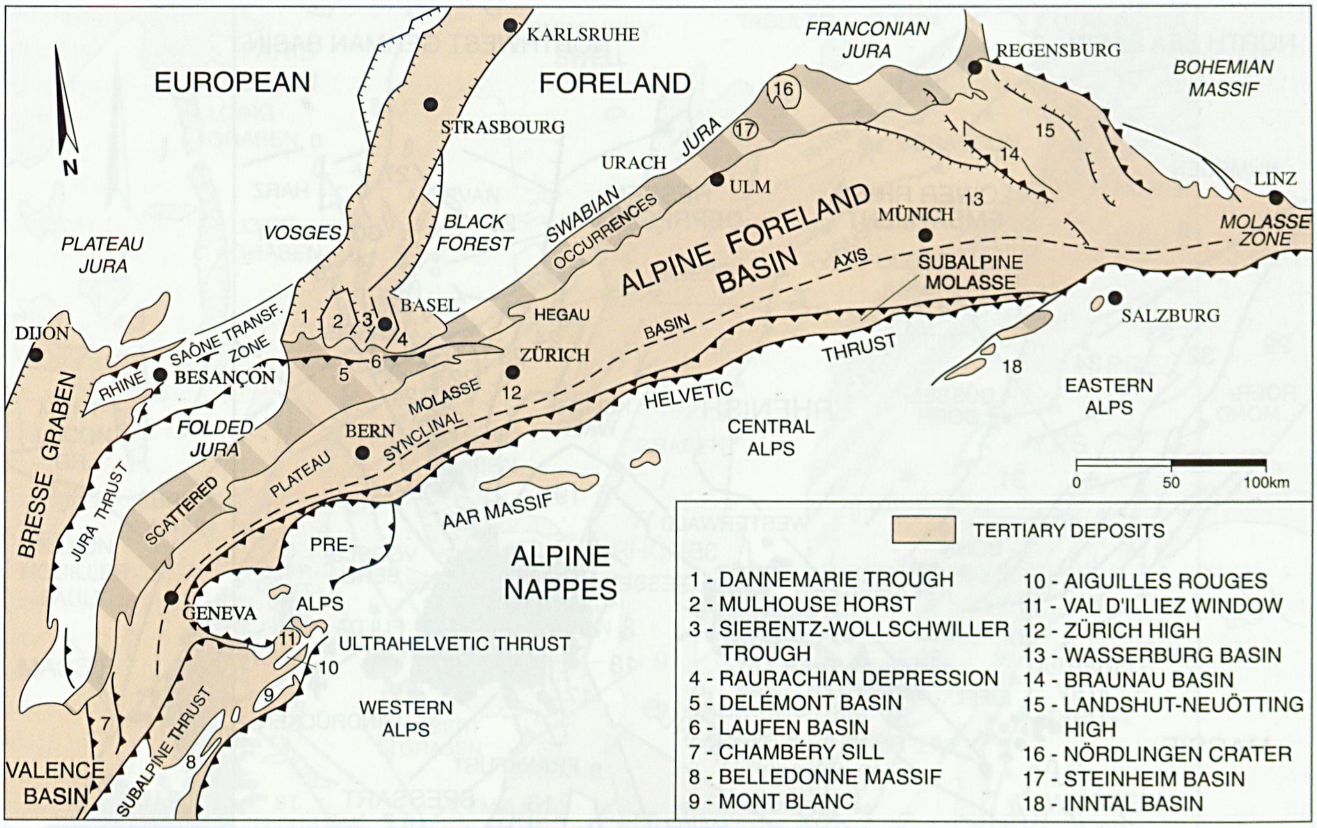

Fig. 1. Structural sketchmap of the North Alpine Foreland Basin (modified after Sissingh, 1997).

present day. The temporal variations in intra-plate stress regime and faulting of the West European Platform were an important control on the subsidence and sedimentation patterns of the platform basins.

In addition to tectonic events that were mostly related to plate-kinematic fluctuations in stress condition, the geological evolution of the West European Platform was also affected by the environmental dynamics induced by eustatic and non-eustatic changes in sea level, and by climatic changes. Changes in relative sea level were an important control on the erosion/sedimentation cycles of the platform basins. During the Cenozoic the relative significance and interaction of tectonics, sea-level fluctuations and climate changed continuously. Over time, their relative importance as controls on topographic and hydrographic developments changed, which in turn affected sedimentation and erosion processes. This resulted in deposition of very diverse stratigraphic sequences in the basins on the geomorphologically complex platform. As will be discussed in this paper, marine sedimentation in the central part of Europe ceased towards the end of the Cenozoic under influence of orogenic uplift of the platform. The resulting exhumation/denudation processes gave rise to the diverse geographic features of the present West European Platform.

The principal focus of this paper is to describe the Tertiary development of the West European Platform in the plate-kinematic and tectonic context outlined above. Previous tectonostratigraphic analyses of the basins of the North and West Alpine Foreland domains indicated that deposition was controlled in part by essentially synchronous tectonic events driven by the Alpine orogeny (Sissingh, 1997, 1998, 2001, 2003a,b, 2006; Meulenkamp & Sissingh, 2003; see below for tectonostratigraphic synchroneity between the Paris and Aquitaine basins). The stratigraphic records of combined tectonic, sedimentation and erosion processes in the platform basins appear to allow elucidation of the spatial-temporal interrelationship between kinematic processes in the evolving Alpine orogenic wedge and sequence stratigraphic developments in the adjacent Alpine foreland. This paper analyses this synkinematic correlation in basin developments and the palaeogeographic evolution of the West European Platform.

General plate-kinematic development and tectonic setting

Though caused by the northward drift of Africa, the actual onset of the Alpine orogeny in Western Europe was the full-scale collision of the Apulian and Iberian microplates with the European craton. This collision was diachronous. The initial impact was approximately north of the present-day Adriatic and propagated westward towards the Western Alps and eastward towards the Carpathians. In particular, the northwestward-directed movement and indentation of the Apulian block into the relatively ductile European Plate west of the Tornquist-Teisseyre Zone (Appendix 2) was an important event in

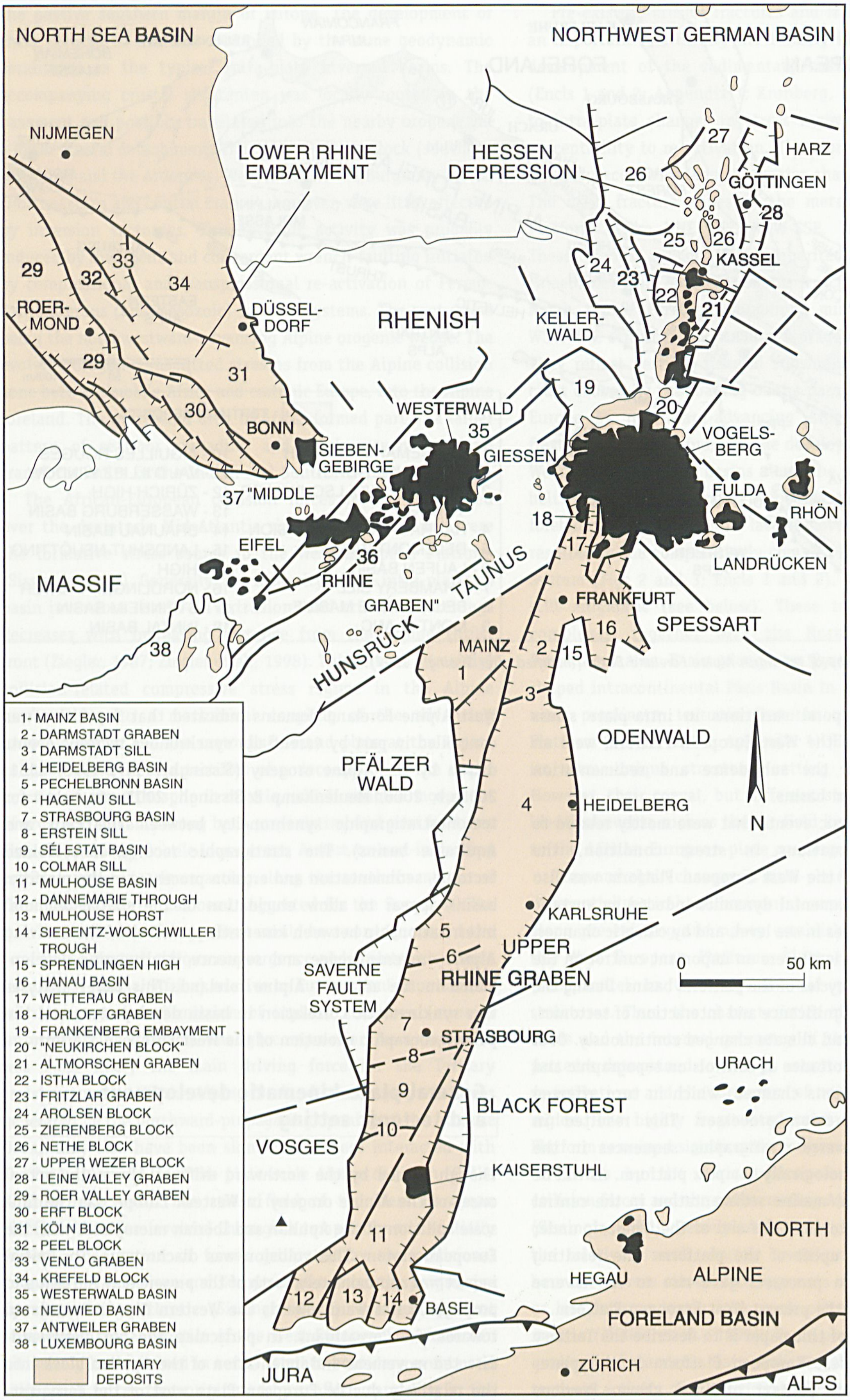

Fig. 2. Structural sketchmap of the Upper Rhine Graben (modified after Sissingh, 2003a).

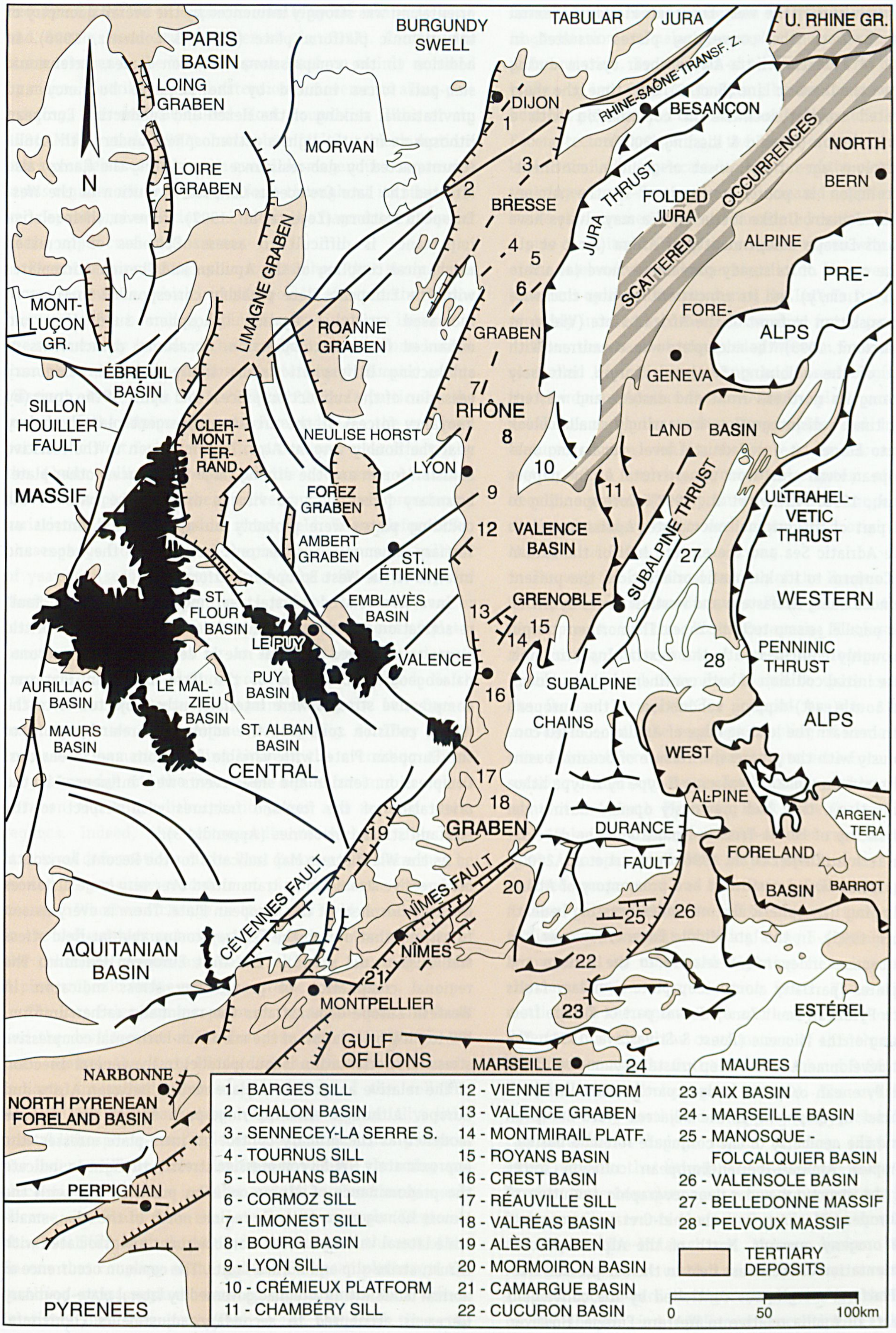

Fig. 3. Structural sketchmap of the Rhône Graben (modified after Sissingh, 2001).

the Alpine evolution of the West European Platform. Dextral translations between the converging plates resulted in development of a dextral, intra-Alpine shear system during the Oligocene: the Insubric Line (Encl. 2). Over time, the shear system rotated counter-clockwise in combination with a northward translation (Schmid & Kissling, 2000).

The Cretaceous age of the onset of Apulian continent-continent collision is poorly constrained in the Alpine-Mediterranean domain. Unlike Iberia, Apulia may always have moved towards Europe independently of Africa (Platt et al., 1989). In the course of its steady convergent move (at a rate of about 0.5 - 1 cm/y) and its concurrent counter-clockwise rotational translation in front of the African Plate (Vialon et al., 1989; Marchant, 1993), the microplate was, concurrent with deformation of the adjoining European margin, intensely deformed along its northern front and eastern and western flanks. Over time, a disintegrating, increasingly smaller block impinged into Europe at a mid-crustal level, separating subducted European lower crust from upper crustal Alpine nappes (Ziegler et al., 1996; Pfiffner et al., 1997). Corresponding to the central part of the original microplate, Apulia nowadays includes the Adriatic Sea and the eastern half of the Italian peninsula. Conform to its kinematic orientation, the present block is bounded along its eastern and western flanks by NW-SE striking, sub-parallel seismo-tectonic zones. The northern margin of Apulia roughly coincides with the dextral Insubric Line. Following the initial collision of both continental plates, down-flexing and south(east)-dipping subduction of the European plate margin beneath the leading edge of Apulia occurred contemporaneously with the progressive closure of oceanic basins in the Mediterranean domain (replacing B-type by A-type lithosphere subduction), that had previously opened during the Mesozoic break-up of Permo-Triassic Pangea and the development of the Tethys (Ziegler et al., 1996; Dercourt et al., 2000).

Initially, Iberia moved northward as a promontory of Africa, its north-dipping lithospheric flexure underthrusting beneath Europe (Bois, 1993). In the late Middle Eocene, however, the microplate became independent relative to the African and European plates (partially along steep plate-boundary faults of the North Pyrenean Fault Zone). It was part of Europe from the beginning of the Miocene (Roest & Srivastava, 1991). The convergent development of the deep crustal asymmetry of the Alpine and Pyrenean orogenic wedges partly controlled both the superficial development of the adjacent West European Platform and the geometry of the conjugate foreland basins.

The complex Apulian-Iberian-European collision forces influenced the structural and palaeogeographic evolution of the West European Platform from the mid-Cretaceous onset of the Alpine orogeny onwards. North of the Alpine collision zone the orientation of the stress field in the compressed West European Platform margin was controlled by the convergent displacements of Apulia relative to Western Europe. However, further north in the interior of Western Europe the stress-field orientation was strongly influenced by the overall geometry of the cratonic platform plate (Gölke & Coblentz, 1996). In addition to the compressional collision forces, extensional slab-pull forces induced by the negative buoyancy and gravitational sinking of the flexed and subducting European lithosphere into the lighter asthenosphere underneath Apulia (counteracted by slab-resistance forces along the flanks) also affected the Late Cretaceous-Cenozoic evolution of the West European Platform (Zeyen et al., 1997). However, their relative importance is difficult to assess. Episodes of increased mechanical coupling of the Apulian and Iberian microplates with the European Plate probably corresponded to times of increased resistance against lithosphere subduction and enhanced foreland compression. Occasional detachments of subducting lithospheric slabs likely induced temporary cessation of the subduction process and uplift of the crust (by buoyancy forces) at the arcuate convergent plate boundary near the doubly-vergent Alps. In comparison to the resistive collision forces and the driving ridge-push forces, other plate-boundary forces such as viscous drag at the base of the colliding plates were probably unimportant as controls on Tertiary kinematic and tectonic settings at the edges and interior of the West European Platform.

Inversion-related crustal warping, syn-kinematic fault re-activation and development of new fractures in the brittle upper crust played a crucial role in determining the tectono-palaeogeographic setting of the West European Platform. Compressive stresses were intermittently projected from the Alpine collision zone into the adjoining foreland regions of the European Plate, with variable directions and intensities. Compression, tension and shear events were influenced by the orientation of the foreland fractures with respect to the foreland stress trajectories (Appendix 3).

As the World Stress Map indicates for the Recent, horizontal compressive stress can be transmitted over very large distances in the lithosphere of the European Plate. There is every reason to assume that during the Tertiary comparable far-field stress transmission did occur in the West European Platform. The regional compilation of present-day stress indicators in Western Europe demonstrates the regionally rather uniform, NW to NNW orientation of the maximum horizontal compressive stress. This orientation is (sub)parallel to the general direction of the relative and absolute plate motion between Africa and Europe. Although Atlantic ridge-push forces can also be modelled as the primary control on intra-plate stresses, the approximately NW-SE compressive stress is thought to indicate the predominance of Alpine collision push. In line with the almost homogenous tectonic regime north of the Alps, small-scale lateral variations of tectonic regimes are associated with thrust, strike-slip and normal faults. The common occurrence of normal faults within a regime governed by lateral plate-boundary forces is attributed to secondary adjustments (horizontal displacements, rotations) of upper crustal fragments which are decoupled from the lithospheric mantle by the relatively weak and ductile lower crust (Müller et al., 1997). Compressive stress releases in the West European Platform mainly occurred by means of strike-slip and extensional movements along pre-existing, near-vertical crustal block boundaries (Illies et al., 1981; Müller et al., 1997). Intra-plate faulting, block motions and stress releases within the overall homogenous compressive stress regimes affected the platform throughout its structural and depositional evolution and reflect the fragmented character of the upper crust in this area.

Recent tectonostratigraphic studies show that many plate-kinematic events, which simultaneously affected the Alpine orogen and its bounding Alpine foreland, left an imprint in the sedimentary records of the West European Platform basins. Examples include superimposed eustatic and climatic events (Sissingh, 1997, 1998, 2001, 2003a,b, 2006). In particular, the records of the Alpino-Pyrenean Foreland (i.e., the southern part of the West European Platform that was most affected by the Alpine collision), testify of the occurrence of crustal deformation phases that were marked by relatively pronounced variations of the intra-plate stress field. These deformation phases range from (first-order) episodes lasting many millions of years to (second-order) ones of only a few million years' duration. Their delimiting events probably occurred more or less instantaneously in relation to re-organisations of plate-boundary conditions. As far as known, they occurred most frequently in the Alpino-Pyrenean Foreland and North Atlantic-West Mediterranean regions during the Late Eocene and later phases of the Alpine orogeny (Fig. 4). They reflect increased kinematic coupling between the overriding Alpine orogenic wedge and the overridden Alpine foreland as well as between the larger lithospheric plates and regional stress regimes. Indeed, the tectonosedimentary basin fills and structural deformations of the West European Platform may be viewed as sensitive recorders of plate-kinematic stressfield changes. Whether a change in the stress field is recognisable in the sedimentary record partly depends on the intensity of the collisional events associated with the coupling of the Alpine orogenic wedge with its cratonic foreland.

The Late Paleocene inception of the Alpine Foreland Basin and the development of the European Cenozoic Rift System, from around the Early-Middle Eocene transition onwards, indicate intensified mechanical coupling of the colliding Apulian and European plates (Appendix 3). Initially, little crustal lithosphere was displaced ahead of the leading edge of the indenter. Plane-stress lithosphere folding, thrusting and thickening of both the indenter and the foreland margin only became significant from the Late Eocene onwards (Ziegler et al., 1996; Pfiffner et al., 1997). It was not until the end of the Eocene that coupling of the Apulian-European plates and the resulting stress regimes were episodically modified with a relatively high frequency (Fig. 4). At the same time, the Alpine continental collision started to have more effect on the development of the West European Platform by inducing tectonic fragmentation and palaeogeographic and palaeoenvironmental differentiation. By the end of the Eocene, the platform had broken up into major sedimentary basins surrounded by fault-bounded plateaus and cratonic massifs (Appendix 3). The post-Eocene tectonic 'pulses' from the Alpine orogenic wedge did not lead to similarly large scale deformation of the platform. During the orogen's post-Eocene phase of increased nappe emplacement, strike-slip stresses were accommodated within the emergent Alpine chain itself. This is the probable reason why deformation of the foreland was no longer significant. However, widespread basement uplifts did occur during the Late Tertiary. These were probably induced by other, an-orogenic forces (see below).

Thus, the shape of present-day Western Europe was largely controlled by collisional events and forces originating from the European-Apulian-Iberian-African plate assembly. The development of its surface topographic and hydrographic features occurred within the plate-kinematic and tectonic setting of an evolving, syn-orogenic system of Meso- and Neoalpine plates. The imprint on the West European Platform of plate-boundary events and forces which originated at the Mid-Atlantic Ridge, is not as strong.

The way the collisional welding of the Iberian and Apulian microplates with the European Plate affected the tectonic development of the West European Platform changed significantly in the course of the Alpine orogeny. Broad-scale Pyrénéo-Provençal tectonism related to space constraints of the Iberian Microplate, as induced by the Africa-Europe convergence, and the resultant coupling of Iberia and Europe were most influential during mid-Cretaceous-Eocene time. The suturing of Iberia to Europe was accompanied by the development of the North Pyrenean Fault Zone (coinciding with a 10 - 15 km Moho jump with the thicker crust at the Iberian side). Accompanying effects on the platform were northward-directed compression and shortening, E-W striking anticlinal folding corresponding to north-vergent fault-propagation folding, north-vergent thrusting along S-dipping shear zones accompanied by northward-migrating flexuring, and strike-slip re-activation of pre-existing faults. These effects were restricted to the region north and east of the doubly-vergent Pyrenees, including the continuation of this thrust belt into the Provence and the Gulf of Lions (Arthaud & Séguret, 1981; Tempier, 1987; Rocher et al., 2000). The overall gradual subsidence and northward-onlapping propagation of the Late Paleocene-Middle Eocene Alpine Foredeep (Sissingh, 1997, 1998) indicates that lithospheric subduction at the European-Apulian plate-boundary zone was less hampered by collisional plate-coupling events than during the later development of the Alpine 'Pre-Molasse' and Molasse basins. Widespread, increased (re-)structuration of the platform occurred during the Late Eocene-earliest Oligocene phase of increased coupling of the Iberian and Apulian microcontinents with Europe (classic Pyrenean orogenic phase; Mattauer, 1968). From that

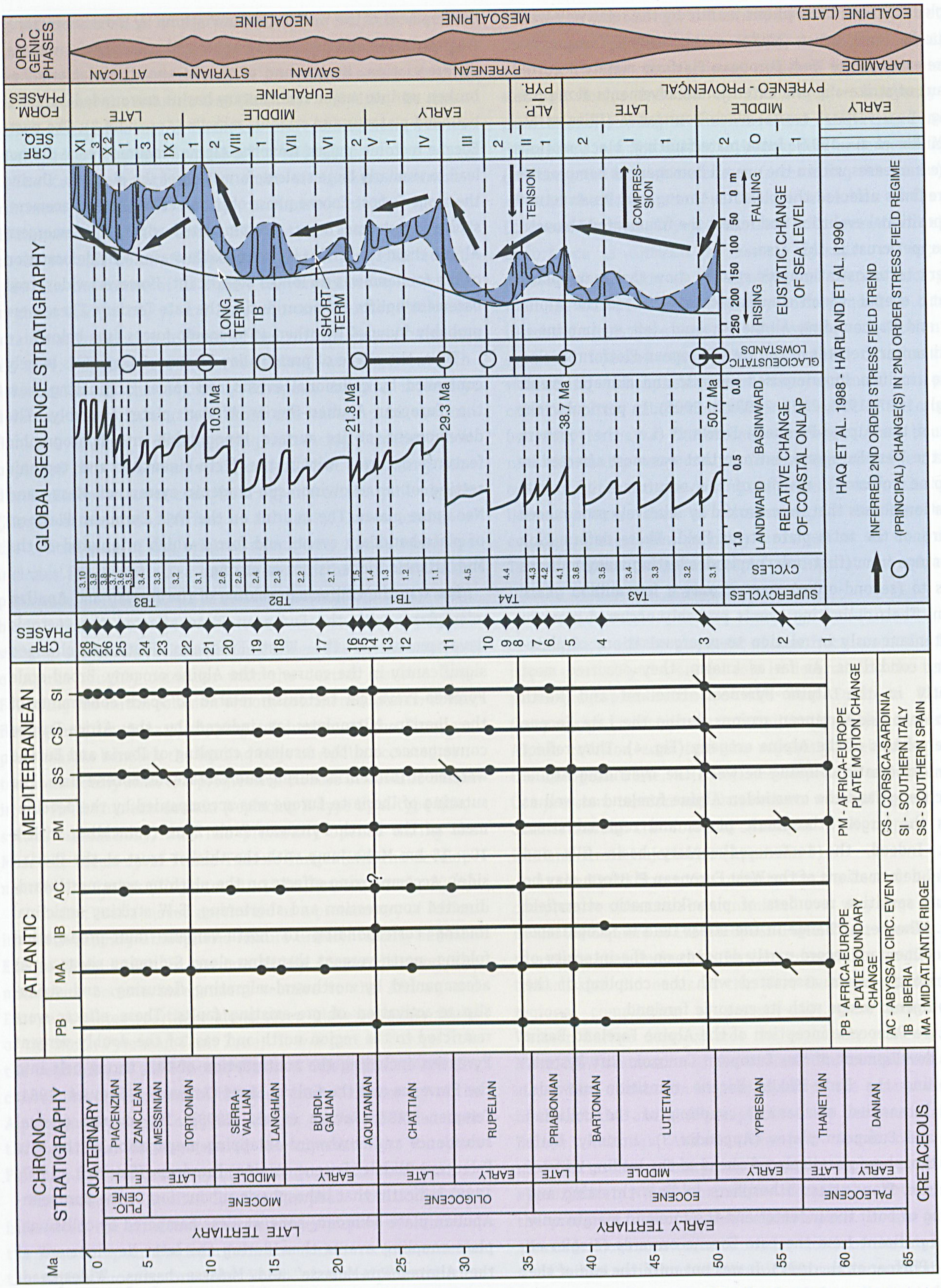

Fig. 4. *Kinematic relationship between Mediterranean and Atlantic plate-boundary events and phases, CRF sedimentary sequences and phases of the West European Platform, Alpine formative platform phases, Alpine orogenic phases and global sequence stratigraphy (after Sissingh, 2006). Fluctuations in global sea level are interpreted to be related to compressional and tensional changes in intra-plate stress (after Cloetingh, 1986). Arrows indicate second-order stress-field trends. Open circles denote eustatic changes in sea level related to principal changes in second-order stress-field regimes.*

time onwards, the shaping of the platform was increasingly through episodic collisional events, as horizontal propagation of the Alpine orogenic wedge was replaced by vertical growth due to episodic crustal imbrication. After the Oligocene, orogenic platform deformation was mainly due to Apulian-European collision events, with deformation being most pronounced north and west of the emergent Alps. Based on plate-kinematic and tectonic key events in the North Atlantic and Alpine-Mediterranean domains, the following main formative phases can be distinguished for the Late Paleocene-Recent evolution of the West European Platform (Fig. 5).

Middle Pyrénéo-Provençal Phase (Late Paleocene -Ypresian)

Subduction-dominated Alpine orogenic phase corresponding to relatively slow, strongly westward-directed convergent motion of Apulia relative to Europe. Initiated in the North Atlantic with the formation of the Azores-Biscay Rise and terminated in this domain with the origin of the King's Trough-Azores-Biscay Rise-North Spanish Trough Fracture Zone. Initiation and termination in the Alpine foreland domain coincided respectively with the origin of the Alpine Foredeep and the initial development of the European Cenozoic Rift System (middle to late part of Phase 3 of Dewey et al., 1989).

Late Pyrénéo-Provençal Phase (Lutetian-Bartonian)

Subduction-dominated Alpine orogenic phase corresponding to very slow, northward-directed motion of Apulia, inducing basement-cored Penninic and Austro-Alpine thrusting in the nascent Alpine orogenic wedge. In the North Atlantic domain this termination corresponded to a southward jump of the Europe-Iberia plate boundary from Boundary B to the King's Trough-Azores-Biscay Rise-North Spanish Trough Fracture Zone. Ended with the HP Lepontine (green-schist) metamorphic phase in the Alpine collision zone and the onset of the main rifting phase of the European Cenozoic Rift System (early to middle part of Phase 4 of Dewey et al., 1989).

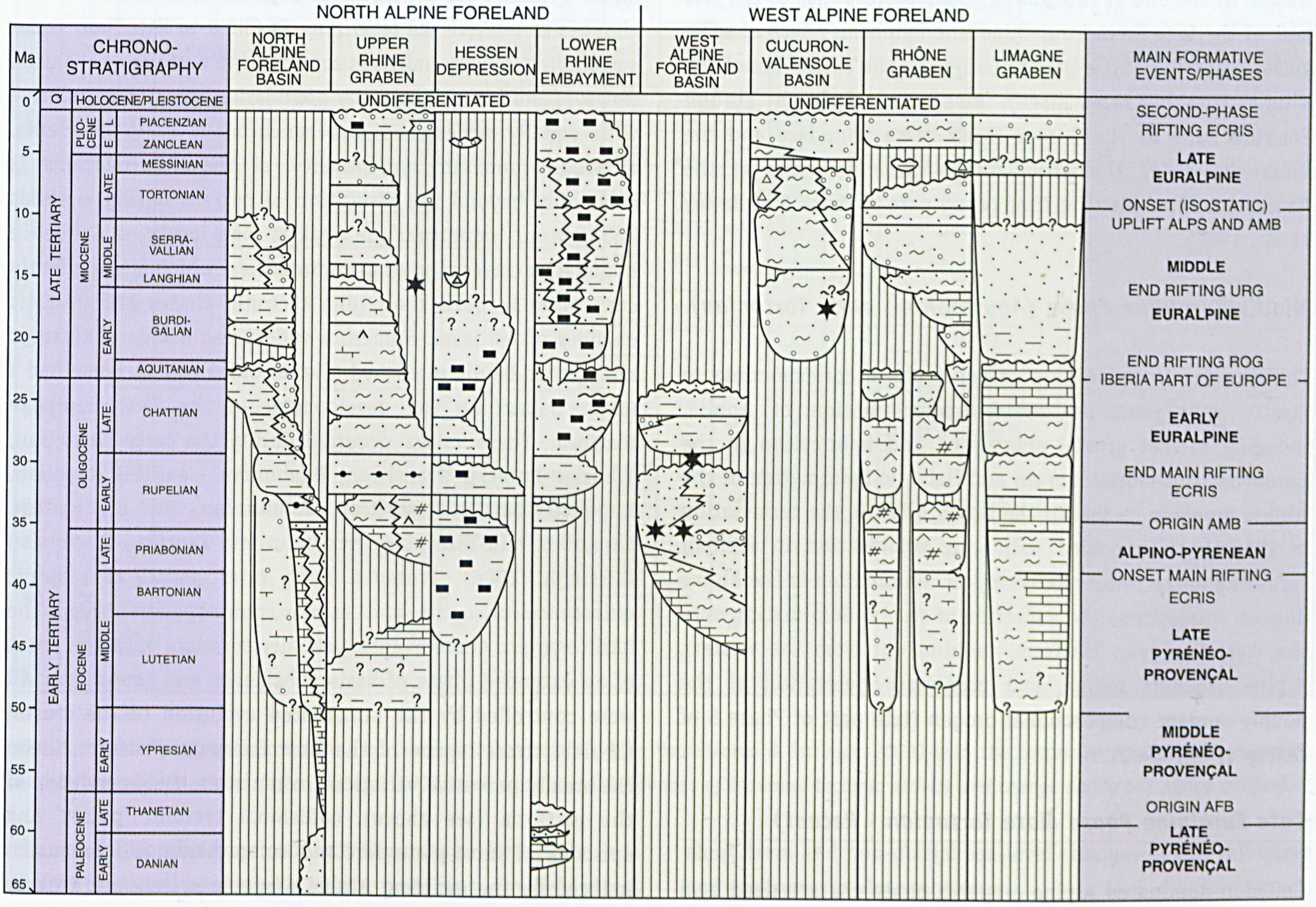

Fig. 5. Tectonostratigraphic relationship between the sedimentary sequences of the North and West Alpine Foreland basins and the main formative events and phases of the West European Platform (after Sissingh 2003b, 2006). Successively, the syn-kinematic Tertiary deformation and palaeogeography of the platform was affected by the collisional convergence of Iberia and Europe (Middle to Late Pyrénéo-Provençal phases of initial foreland flexuring and folding), the increase in convergent mechanical coupling of Iberia and Apulia with Europe (Alpino-Pyrenean Phase of main foreland rifting and flexuring) and the continuing, though eventually decreasing convergence of Apulia and Europe (Early to Late Euralpine phases of late foreland rifting and 'post-compressional' uplift). AFB = Alpine Foreland Basin; AMB = Alpine Molasse Basin; ECRIS = European Cenozoic Rift System; URG= Upper Rhine Graben; ROG = Rhône Graben.

Alpino-Pyrenean Phase (Priabonian - earliest Rupelian)

Collision-dominated Alpine orogenic phase corresponding to very slow, northward-directed motion of Apulia and enhanced mechanical coupling of the Apulian, Iberian and European plates leading to the development of the 'Pre-Molasse' Basin in front of the Alpine orogenic wedge during final Penninic and Austro-Alpine thrusting. In the North Atlantic domain this termination corresponded to compression and subduction of the North Spanish Trough. Ended in the Alpine domain with the onset of the Helvetic thrusting phase and the origin of the Alpine Molasse Basin (late part of Phase 4 of Dewey et al., 1989).

Early Euralpine Phase (Rupelian-Chattian)

Collision-dominated Alpine orogenic phase corresponding to slow, northward-directed motion of Apulia resulting in major crustal shortening associated with enhanced imbrication of the European continental margin and pronounced Helvetic folding, thrusting and overthickening of the Alpine orogenic wedge. At the end of this phase, which corresponds to the late part of the Late Cretaceous-Oligocene Pyrenean phase of some authors, Iberia became part of Europe by the extinction of the King's Trough-Azores-Biscay Rise-North Spanish Trough Fracture Zone as the Europe-Iberia plate boundary and the establishment of the Africa-Europe plate boundary at the Azores-Gibraltar Fracture Zone (early part of Phase 5 of Dewey et al., 1989).

Middle Euralpine Phase (Aquitanian - early Tortonian)

Collision-dominated Alpine orogenic phase corresponding to mostly very slow, northward-directed motion of Apulia, inducing further crustal shortening and imbrication of the European continental margin and Helvetic deformation of the Alpine orogenic wedge. In the North Atlantic the termination of this phase coincided with a re-organisation in seafloor spreading in the Mohn's Ridge region. Termination in the Alpine domain corresponded to migration of crustal deformation onto the West European Platform, fanning out from the western Alpine orogenic wedge, and pronounced elevation of the doubly-vergent compressional orogen (late part of Phase 5 of Dewey et al., 1989).

Late Euralpine Phase (late Tortonian - Recent)

Collision-dominated Alpine orogenic phase characterised by a very slow, northwestward-directed motion of Apulia, imbrication and overthrusting by the Alpine orogenic wedge of the southern parts of the North Alpine Molasse Basin, northward displacement and uplift of the North Alpine Molasse Basin and folding and thin-skinned thrusting of the Jura and Subalpine Chains (Phase 6 of Dewey et al., 1989).

Tectonostratigraphic basin development

The temporal significance of the lithological surfaces bounding the sedimentary sequences of a basinal stratigraphic record reflects basically the combined effect of tectonic events, sea-level fluctuations and climatic changes. Correspondingly, the limiting stratigraphic horizons tend to be as diachronous as the their causal forces and sources. Conventional sequence stratigraphy is based on a global sea-level model that assumes a synchronous, globally interconnected behaviour of sea level and a depositional model that assumes globally synchronous accumulation of sedimentary sequences, with each sequence corresponding to a single global sea-level fluctuation (Haq et al., 1988). Both models are thought to be plausible based on the presence of widely recognizable and correlative sea-level events and sedimentary sequences. The Tertiary basins of the West European Platform, including the pro-wedge Alpine Foreland Basin, the retro-wedge Aquitaine or North Pyrenean Foreland Basin, the European Cenozoic Rift System and the Paris Basin (Figs 1 to 3; Encl. 2; Appendix 1), appear to contain ample evidence for synchronous deposition of sequences and changes in relative sea level (Fig. 6: CRF 0 to XI). Their widespread synchroneity indicates control by an eustatic mechanism. However, numerous sequence boundaries are also correlative with equally widespread and synchronous tectonic events, although proof of synchroneity of these correlations is commonly beyond the resolution of current dating methods and tectonic 'signatures' are weak at some localities. Sequence boundaries correspond to unconformities, which are frequently correlative to both short-term tectonic phases and eustatic changes of sea level. Numerous widespread events of tectonic change can be distinguished (Fig. 6: CRF 1 to 28). Some had a major impact on the development of the West European Platform. These 'crises' occurred during the early Thanetian, Ypresian-Lutetian transition, Priabonian - earliest Rupelian, Rupelian-Chattian transition, Aquitanian, mid-Burdigalian, Langhian, mid-Tortonian, Messinian and Zanclean-Piacenzian (Sissingh, 2006). Preceded by a brief period of tectonic quiescence or uplift and erosion/non-deposition near the basin margin, these events generally correlate with the onset of an extended phase of basin subsidence and deposition. All were controlled by the punctuated evolution of the crustal far-field stress regime of the West European Platform. Given the areally pervasive variations in the stress-field condition of the platform (see above), collisional tectonic 'pulses' and episodes of intra-plate foreland compression and extension induced by the evolving Alpine orogenic system are a likely second control on the distribution of significant lithological breaks in the stratigraphic record. The contribution of climate changes though is much more difficult to prove. Surprisingly commonly, the onsets of relative sea-level changes and tectonic activity appear to be synchronous over large areas. Though platform-wide synchroneity of eustacy-controlled sea-level

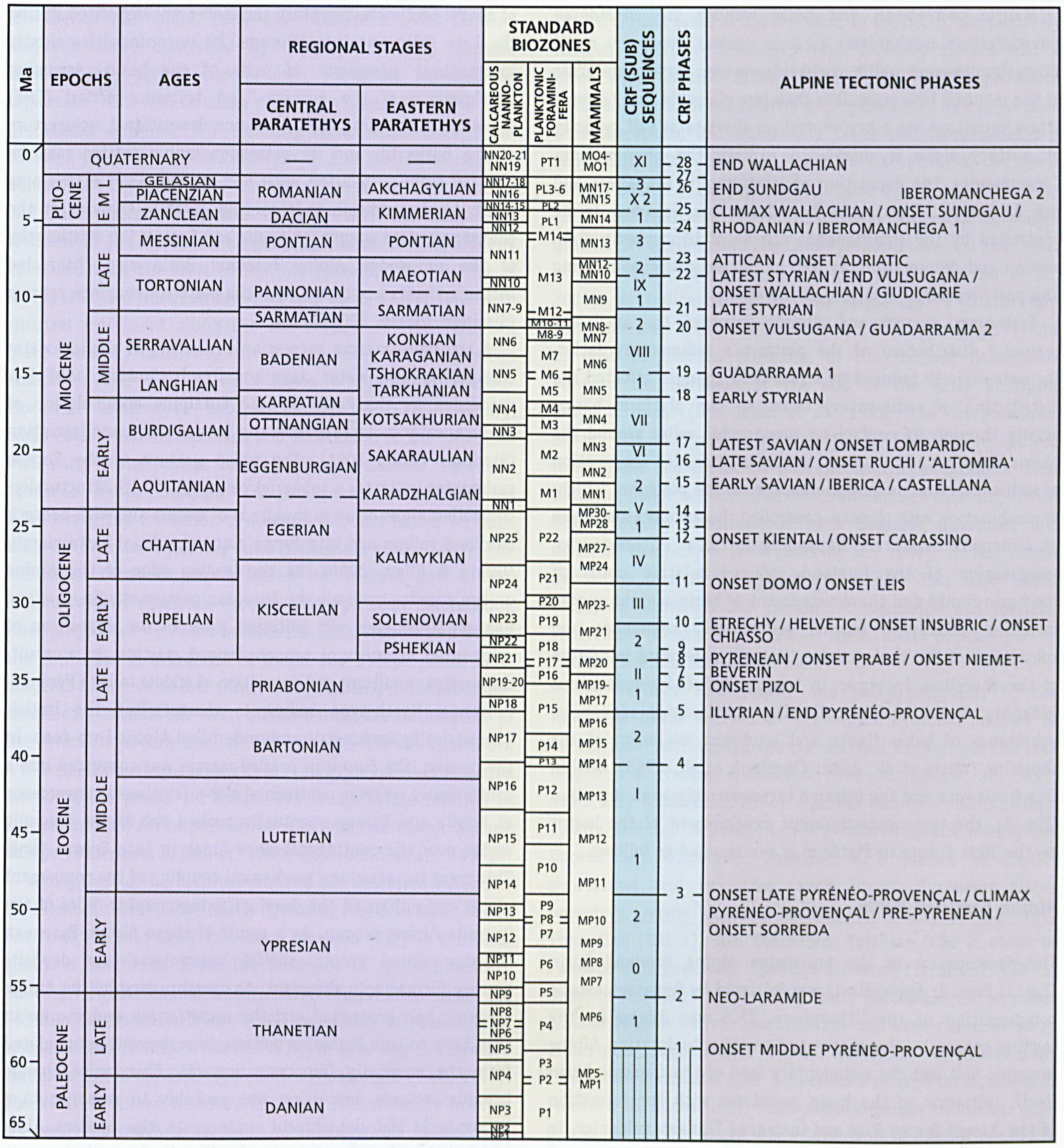

Fig. 6. Chronostratigraphic correlation of Cenozoic biozonations (after Meulenkamp & Sissingh, 2003) with the succession of tectonostratigraphic (sub)sequences and phases (after Sissingh, 2006) and associated brief periods of increased tectonic activity and change during the Alpine orogeny.

change and foreland tectonic activity may be fortuitous, it is in fact predicted by plate-kinematic modelling. Far-field stress variations induced by Indian and Atlantic mid-ocean seafloor spreading and plate-boundary re-organisations are most probably the ultimate control on the apparently coeval changes in stress- and eustacy-related depositional conditions of the West European Platform. The following geophysical mechanisms have commonly been invoked to explain rapid, short-term and non-glacial sea-level changes of the Vail curve and epeirogenic plate motions:

1. Stress-induced changes in lithosphere folding (Cloetingh et al., 1985, 1987)
2. Mantle convection (Officer & Drake, 1985)
3. Polar wander (Sabadini et al., 1990)
4. Stress-induced changes in lithosphere density (Cathles & Hallam, 1991).

Mantle convection and polar wander are considered unsatisfactory mechanisms as it is unclear how they could drive simultaneous uplift or subsidence over large plate areas at the required time scale. It is therefore plausible that tectonic stress variations are a key control on short-term Vail cyclicity as eustacy alone is unable to explain the phenomenon. Consequently, the deposition of stratigraphic sequences and the formation of sequence boundaries are assumed to be controlled by the simultaneous effects of lithospheric plate motion and deformation, as well as syn-depositional faulting and post-depositional tilting of the strata.

Tectonism, eustacy and climate governed the areal and temporal distribution of the platform's sedimentary facies. Tectonic activity induced by stress-field changes affected the distribution of sedimentary facies in the platform basins mostly through its control on topographic relief around the basins. Together with eustacy, tectonics controlled the creation of sedimentary accommodation space on the platform, which, in combination with climate, controlled the amounts and types of sediments deposited. Depending on local circumstances, compression of the foreland induced relative uplift of the basin flanks and the development of basin-margin unconformities, offlapping basinal sedimentary sequences and subsidence of the basin centre, as well as seaward migration of the shoreline. Increases in tension induced simultaneous widening of the basins, onlapping stratigraphic sequences, subsidence of basin flanks and landward migration of the shoreline (Watts et al., 1982; Cloetingh et al., 1985). Within this framework and the inferred tectonostratigraphic zonation (Fig. 6), the tectonostratigraphic development of the basins on the West European Platform is summarised as follows.

Alpine Foreland Basin

The development of the pro-wedge Alpine Foreland Basin (Fig. 1; Encl. 2; Appendix 1) was initiated by flexural isostatic compensation of the lithosphere. This was driven by the loading caused by the north- and westward-migrating Alpine orogenic belt and the sedimentary load of the flanking basin itself. Initiation of the basin correlates with the formation of the Azores-Biscay Rise and increased Thulean volcanism in the Rockall-Faeroe-Shetland Trough area, indicating a causal relationship with plate-tectonic activity in the North Atlantic domain (Sissingh, 2006). Long-term subsidence of the basin started during the Late Paleocene (Allen et al., 1991; Kempf & Pfiffner, 2004). It continued in the North and West Alpine Foreland basins until respectively the Late Miocene (Sissingh, 1997, 2001) and the Early Miocene (Sissingh, 2001), when uplift initiated regional erosion and non-deposition. The sedimentary fill of the remnant pro-wedge foreland basin comprises mainly clastic deposits which progressively onlap the basal unconformity in northern and western directions (Sissingh, 1997, 2001). A widely recognizable (CRF) succession of coeval tectonosedimentary sequences was deposited during the Late Paleocene-Late Miocene. Its unconformities signify intermittent emergence of parts of the basin. Assuming synchroneity of the eustacy- and tectonics-related (CRF) sequence subdivision, the pre-erosion depositional architecture of the basin fill and its palaeogeographic setting may be inferred from correlation with non-eroded (CRF) equivalents (Encl. 5). In addition to recording eustatic changes at the convergent plate margins of Apulia and Europe, the stratigraphy of the pro-wedge Alpine Foreland Basin also chronicled tectonic events associated with the plate convergence process (Sissingh, 2003b, 2006).

A tripartite marine succession consisting of shallow-water carbonates, deep-water clays and flysch (Sinclair, 1997a) is succeeded by the Early to Late Euralpine accumulation of shallow-water molasse around the Eocene-Oligocene transition (Sissingh, 1997, 2001). The onlap pattern of the Eocene carbonates indicates a subaerial palaeorelief with structurally-controlled highs of up to hundreds of meters and with bedrock confined valleys and interfluves along the distal basin margin (Gupta & Allen, 2000). As the leading edge of the Alpine orogenic wedge overrode the European passive margin, foreland flexural subsidence was initiated prior to the deposition of substantial amounts of orogen-derived clastics. As a result, deep-water conditions and deposition of Middle to Late Pyrénéo-Provençal flysch-type sediments characterised the initial, geometrically asymmetric and underfilled Alpine Fore-deep. In the process, the European passive margin was converted into a continuously evolving continental slope. Continued convergence of Apulia and Europe eventually pushed the Alpine orogenic wedge over the continental slope-break in Late Eocene time. This event increased the mechanical coupling of the convergent plates and enhanced the developing topographic relief of the juvenile Alpine orogen. As a result of these Alpino-Pyrenean collision-related events, shelfal 'pre-molasse'-type deposits became increasingly abundant. As overthrusting by the Alpine orogenic belt proceeded and the accretionary wedge grew in size, Early to Late Euralpine molasse-type deposits accumulated from the mid-Early Oligocene onwards. This major change towards molasse deposition was probably in response to a lithospheric slab-detachment underneath the nascent Alps, which induced regional basin shoaling by isostatic tectonic uplift (Sinclair, 1997b). Deposition in the filled to overfilled North Alpine Molasse Basin may have ended in response to another uplifting slab-detachment in the early Late Miocene (Andeweg & Cloetingh, 1998).

Aquitaine Basin

The triangular Aquitaine Basin (Appendix 1) originated during a Permo-Triassic phase of extensional tectonic activity. The basin developed on top of the Aquitaine Block, west of the Massif Central (Appendix 3) and overlaps the northern edge of the Iberian Microplate. Piano-key differential block faulting and subsidence controlled by NNE-SSW trending tension, resulted into several second-order subbasins bounded by important, NNW-SSE trending strike-slip faults. From the mid-Cretaceous onwards, N-S trending compression and transpression related to the subduction of the Iberian Microplate beneath the European Plate (inducing inversion of Late Jurassic and Early Cretaceous basins together with salt diapirism) resulted in the Pyrenean orogeny. Initiation of the orogeny coincided with the start of seafloor spreading in the Bay of Biscay and the North Atlantic. It was contemporaneous with sinistral movement along the sub-vertical Iberian-European plate-boundary fault, i.e., the E-W trending North Pyrenean Transform Zone (Encl. 2), while Iberia rotated slowly counterclockwise relative to Europe. During the Early Tertiary, compression-related flexuring and shortening of the crust and increasing thrust-wedge loading by the nascent Pyrenean orogenic wedge induced, in combination with thermal subsidence, the formation of flexural foreland basins on both sides of the plate-boundary zone (Desegaulx et al., 1991). The collisional tectonics first affected the eastern part of the doubly-vergent Pyrenean orogen. The Pyrenean deformation front propagated westward towards the Cantabrian region during the continued convergence of Iberia and Europe. From here, orogenic compression and thrust-wedge loading propagated diachronously towards the west, possibly until the termination of the Pyrenean orogeny around the Oligocene-Miocene transition. A N-S trending compressive stress regime prevailed during this late orogenic phase. No longer did Iberia rotate relative to Europe; instead, Africa pushed the microplate northward against Europe (Desegaulx & Brunet, 1990; Bourrouilh et al., 1995).

Along the northern thrust-front of the emergent Pyrenees, the flexural retro-wedge North Pyrenean Foreland Basin stood out from the mid-Early Paleocene onwards (Gély & Sztràkos, 2000). It developed under the influence of syn-sedimentary faulting, thrust loading and flexural compression until the Eocene-Oligocene transition, when deposition of Palassou fan conglomerates and thick calcareous flysch gave way to extensive accumulation of molasse-type clastics (Bourrouilh et al., 1995). The North Pyrenean Foredeep migrated diachronously towards the west and north in response to thrust-wedge loading and the northward movement of the North Pyrenean thrust front. The northward-directed thrusting progressed in line with generally E-W trending foreland folding reflecting NNE-SSW trending compression, which also affected the Languedoc-Provence fold-and-thrust belt (Arthaud & Laurent, 1995) and the area south of the Pyrenean orogen (Rocher et al., 2000). This was accompanied by strike-slip re-activation of NNW-SSE trending faults. At the same time, the North Pyrenean Foredeep deposits (up to some 3000 m thick) were tectonically deformed and, subsequently, underthrust beneath and/or incorporated into the evolving thrust front (Déramond et al., 1993). The foredeep can be traced eastwards along the North Pyrenean frontal thrusts as far as the Provence. In the north, the relatively narrow, underfilled and deep-water foredeep merged with a much wider, overall filled, shelfal basin. This larger North Aquitaine Platform was relatively little disturbed by compression from the south. Its sedimentary fill of mainly carbonates is fairly thin (500 - 1000 m), with the exception of the deep-water Parentis Basin (up to about 2000 m; Appendix 1). Post-Cretaceous collisional foreland-shortening and orogenic wedge-growth climaxed during the Late Pyrénéo-Provençal and, most of all, the Alpino-Pyrenean orogenic phases (Rocher et al., 2000), as indicated by massive sequences of coarse fan-conglomerates along the southern basin margin (Fig. 7). Due to post-compression unflexing of the thinned lithosphere beneath the Pyrenees at the end of the Early Euralpine orogenic phase (Desegaulx et al., 1991), the compressional orogen and its adjoining orogenic foreland basin were uplifted from about the Oligocene-Miocene transition onwards, thus inducing major unroofing of the thin-skinned fold-and-thrust belt. Probably simultaneous with isostatic unloading and uplift of the orogen (Desegaulx et al., 1991), fluvial clastic deposition increased north of the orogen. This major event coincided with NNW-SSE trending compression and foreland shortening (Rocher et al., 2000) when Iberia became part of Europe (Roest & Srivastava, 1991).

The Tertiary stratigraphy and palaeogeography of the Aquitaine Basin evolved in a complex dynamic manner as depositional settings constantly changed throughout the area (Fig. 7; e.g. Muratet & Cavelier, 1992; Sztràkos et al., 1997, 1998; Gély & Sztràkos, 2000). Discrete tectonic 'pulses', which clearly affected deposition, were most frequent during the Eocene and Oligocene. Together with phases of crustal shortening and thrusting, such Iberian-European plate-boundary events occurred during, or close to, the early Thanetian (CRF 1), late Thanetian, Ypresian (CRF 2; onset of Palassou I deposition), Ypresian-Lutetian transition (CRF 3; onset of Palassou II deposition), early Bartonian (CRF 4; onset of Côte-Maison-Neuve Conglomerate and Lower Brassempouy Limestone deposition), latest Bartonian or Bartonian-Priabonian transition (CRF 5; tectonics-related termination of Palassou III deposition), Priabonian-Rupelian transition (CRF 8; angular unconformity; end of Palassou III deposition; onset of widespread deposition of molasse), mid-Rupelian (CRF 10; emplacement of North Pyrenean allochthonous units (thrusts)), Rupelian-Chattian transition (CRF 11; angular unconformity) and mid-Chattian (CRF 12; tectonics-related non-deposition/erosion) (Figs 6 and 7; Muratet & Cavelier, 1992; Déramond et al., 1993; Gély & Sztràkos, 2000; Rocher et al., 2000).

European Cenozoic Rift System

The European Cenozoic Rift System (Encls 1 and 2; Ziegler, 1994, Prodehl et al., 1995; Rouchy, 1997; Sissingh, 1998, 2001, 2003a, b; Michon, 2001; Michon et al., 2003; Dèzes et

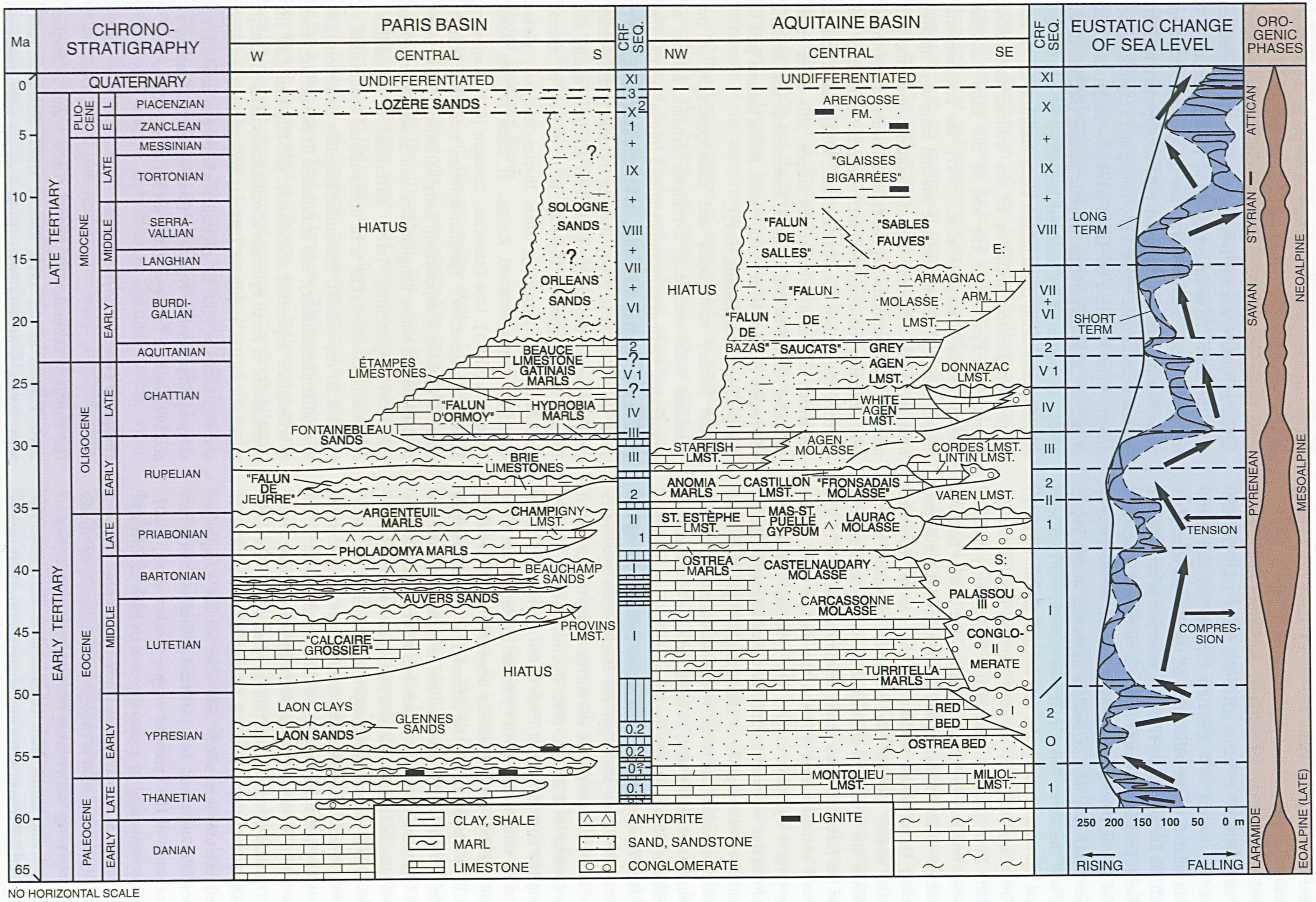

Fig. 7. Lithostratigraphic diagrams and sequence stratigraphic interpretations for the Aquitaine Basin (simplified after Pomerol, 1982; Muratet & Cavelier, 1992; Deramond et al, 1993; Dubreuihl et al., 1995) and the Paris Basin (simplified after Gély & Lorenz, 1991; Mégnien & Mégnien, 1980).

al., 2004) represents a number of discrete lithospheric failure zones. Extension, which locally still continues at present, was mostly perpendicular to the direction of shortening in the contemporaneously emergent Alps (Michon et al., 2003). Nowhere in any of its mainland European and West Mediterranean-Atlantic segments, did rifting progress to the stage of incipient oceanic spreading. Hence, it is an immature rift system, also in view of the absence of large-scale volcanism. Initiation and subsequent propagation of rifting was associated with differential block faulting and subsidence that resulted in the establishment of an extensive and complex system of rift structures, interconnected by the sinistral Rhine-Saône transform zone and the Sillon Houillier fault which follows a Variscan zone of weakness (Fig. 1; Encls 1 and 2; Lacombe et al., 1993). Development began around the Early-Middle Eocene transition, probably under influence of extensional shear induced by N-S trending compression. The Middle Eocene opening of the rift system may have been caused by Late Pyrénéo-Provençal (trans)tensional strike-slip tectonics. This followed the partially NW-SE trending structural grain of a pre-existing lithospheric weakness zone comprising Permo-Carboniferous and Mesozoic fracture systems. This regional N-S to NNE-SSW trending collisional compression of the West European Platform also induced closure of the eastern Bay of Biscay. The onset of rifting was contemporaneous with the opening of the King's Trough at the site of the later (Late Eocene-Oligocene) African-North American-European Triple Junction (Sissingh, 2006). Substantial amounts of syn- and post-rift, continental to shallow marine sediments were deposited in the filled to overfilled grabens and subgrabens (Encls 3 to 8). Kinematically, deposition was mainly controlled by extension normal to the N-S to NNE-SSW trending main graben axis. The sedimentary fill of the individual (sub)grabens is highly asymmetric. The nature of the sedimentary fills was mostly controlled by intra-basinal environmental conditions, including communication with the world ocean system, and the development and erosion of the topographic relief of the adjacent land masses such as crystalline massifs, elevated rift shoulders and framing fault scarps. Local and regional uplifts intermittently interrupted sedimentation, truncating sequences whose pre-erosional stratigraphic extent can be conceptually reconstructed (Encls 5 and 6). Syn-sedimentary rift propagation occurred in the Upper Rhine Graben from the south to the north during the Late Eocene (Sissingh, 1998, 2003a,b) and possibly in the Oligocene from the Lower Rhine Embayment farther northwestwards into the Lower Rhine Graben (Zagwijn, 1989) and from the Rhône Graben to the south (Sissingh, 2001, 2003b). Extension feathered out north of the Rhenish Triple Junction in the North Sea and North German-Polish basins, and south of the Valencia Trough with fractures traversing the Rif fold belt of northwest Africa in the direction of the Cape Verde Islands. First-phase rifting ceased in the Upper Rhine Graben and Hessen Depression during the Middle Miocene and in the Rhône and Massif Central grabens in the earliest Miocene (Sissingh, 2006). In the NW-SE striking Lower Rhine Embayment, rifting lasted from the Eocene-Oligocene transition to the Recent (Zijerveld et al., 1992; Geluk et al., 1994; Michon et al., 2003). Its Oligocene development and its later evolution, following a sudden change of the stress field near the Oligocene-Miocene transition, occurred under influence of respectively NW-SE and NNE-SSW extension (Michon et al., 2003; cf. northern Upper Rhine Graben; Schumacher, 2002). The rifting process was accompanied by rotational divergence of the flanks (Encl. 2): the eastern Rhenish Massif rotated clockwise during (at least) the Late Oligocene main phase of rifting (Schreiber & Rotsch, 1998) that coincided with accelerated subsidence of the southeastern Roer Valley Graben (Michon et al., 2003). The separate, ENE-WSW trending Eger Graben opened in the late Middle Eocene by almost N-S directed extension (Malkowski, 1987). The formative extensional tectonics that generated the pure-shear rift with axially located, abundant volcanic activity continued (presumably) until the end of the Tertiary (Sissingh, 2006). During the Pliocene, rifting of the Upper Rhine and Rhône grabens resumed, but this did not extend to the Hessen Depression. As such, the mega-structure is a partially aborted rift system. In the Upper Rhine Graben the second phase of rifting is controlled by sinistral shear motion. Continuing extension of this graben is evidenced by seismo-tectonic activity parallel to the graben axis.

The rift-forming mechanism is still poorly understood. Various explanations have been proposed, including passive and active rifting models (see Ziegler, 1994 for a review). During the last decade, the following 'single-mode' explanations of the necessary (trans)tensional stress regime have been put forward:

1. Passive foreland extension induced by convergent African-European plate interaction and plate-boundary re-organisation (Ziegler, 1994; Dèzes et al., 2004)
2. Passive foreland splitting induced by the transpressional indentation of the Apulian Microplate (Regenauer-Lieb & Petit, 1997)
3. Passive foreland extension induced by the gravitational pull of the descending slab below the overriding Alpine orogenic wedge (Michon et al., 2003)
4. Active foreland extension induced by mantle-plume upwelling (Hoernle et al., 1995; Goes et al., 1999).

Since evidence for a regional extensional tectonic stress regime covering Western and Central Europe during the Cenozoic, is lacking, it has been proposed that the formation of the European Cenozoic Rift System is related to 'crustal cracking' due to mantle-plume upwelling rather than to plate indentation or plate-boundary forces alone (Goes et al., 1999). However, the Middle Eocene and later intra-plate rifting events and plate-kinematic Alpine compressions of the meta-stable West European Platform were broadly synchronous and linked to each other through their shared but evolving regimes of far-field tectonic stress (Ziegler, 1990, 1994; Dèzes et al., 2004). The spatially and temporally distinct (sub)phases of passive rifting correlate with discrete plate-boundary events (Sissingh, 2003b). Moreover, there is no clear evidence for initial, plume-generated doming of the major rift zones, though the Limagne Graben-Forez Graben-Bresse Graben transect displays a small, symmetrical graben in between two larger, opposite half-grabens. The hot Rhine and Loire mantle domes (Appendix 2) developed by crustal thinning and thermal uplift in response to active upwelling in the asthenosphere from the Burdigalian onwards. This was accompanied by uplift of the overlying rifts, accentuation of rift shoulders, increased erosion of surrounding Variscan basement massifs (Massif Central; Vosges and Black Forest especially from the Serravallian onwards, as evidenced by the conglomeratic 'Jura Nagelfluh' (Kälin, 2000)) and volcanic activity (Sissingh, 2001, 2003b). It has been assumed that the Rhine Dome with the unique intra-graben Kaiserstuhl Volcano at its centre developed at the crossing of the N-S trending rift system and an E-W trending Alpine fore-bulge, indicating locally reduced elasticity and increased brittleness of the down-flexed lithosphere (Laubscher, 1992). Instead, it may be related to compressional folding of the foreland lithosphere (Lefort & Agarwal, 1996; Ziegler et al., 2002; Dèzes et al., 2004) as the crustal extension across the Upper Rhine Graben and the Massif Central is larger than expected from thermal up-arching alone (Ziegler, 1994). It is therefore likely that these external, plate collision-related events determined the (trans-)tensional formative stress regimes, as well as the development of the sedimentary fills of the mega-rift. Still, the rifting mechanism may have been a combination of 'passive stress-generated' and 'active plume-generated' crustal extension. Concurrent lithospheric thinning beneath the extensional belt may have been caused by a combination of plate subduction, mantle-plume upwelling and asthenospheric convection. Upwelling mantle-plume material was possibly pushed aside by subducting cool mantle material, forcing upwelling of hot material around the subduction zone. Such a mechanism is consistent with the synchronous occurrence of Late Pyrénéo-Provençal to Late Euralpine phases of orogenesis and taphrogenesis. Mantle upwelling corresponding to regional uplift of the West European Platform occurred in post-Oligocene times, well after the initial and main phases of rifting.

Paris Basin

The intracratonic Paris Basin (Appendix 1) formed due to Permo-Triassic extensional tectonics involving the Ardennes, Armorican and Burgundy blocks in a triple-junction configuration (Appendix 3). Following the initial rifting phase, semi-circular differential basin subsidence occurred during most of the Triassic-Early Tertiary, with the major geodynamic events of the Tethyan and Atlantic domains being recorded in the basin fill (Mégnien & Mégnien, 1980; Perrodon & Zabek, 1990; Guillocheau et al., 1999; Robin et al., 2000). Accordingly, a concentric topography marked by cuestas developed after the Early Miocene closure of the basin with the oldest strata at the periphery and the youngest at the centre of the basin. Beneath the basin, ridges corresponding to zones of different crustal thicknesses occur. They are concentric with the Alpine orogenic front and probably reflect Laramide buckling of the West Alpine Foreland crust due to north(west)ward compression imposed onto the foreland by the collision of Apulia and Europe (Lefort & Agarwal, 1996).

Subsidence of the basin was highest during the Triassic and Jurassic. In the Tertiary, the overall filled, flexural-sag basin subsided very slowly until the earliest Miocene closure of the basin and onset of widespread non-deposition. General uplift of the newly formed Lutetian Plateau occurred in the Quaternary (Robin et al., 2000). Altogether, the preserved Tertiary basin fill is very thin (up to some 250 m). The formative subsidence mechanism of the essentially Mesozoic basin is not clear. Long-term thermal subsidence (driven by exponential cooling of the lithosphere) played an important role. Superimposed tectonics (including intermittent extensional, compressional and transpressional phases of structural rejuvenation) may also have been important, as subsidence was irregular. The Tertiary evolution of the Paris Basin was controlled by a polyphase subsidence regime with superimposed N-S to NNE-SSW trending Pyrénéo-Provençal and weaker WNW-ESE to NW-SE trending Euralpine compression. These compressional phases were separated by an Alpino-Pyrenean phase of WNW-ESE trending extension. The latter tectonic phase induced the development of the Loire and Loing (half)grabens in the south (Debrand-Passard et al., 1992) and probably also rifting elsewhere, such as north of the Bray-Vittel Fault (Coulon, 1992) (Encl. 2). The compressional events resulted in an E-W to WNW-ESE trending, dominantly Late Pyrénéo-Provençal system of en-echelon anticlinal structures. Additionally, brief tectonic and eustatic events affected deposition in the basin (Cavelier & Pomerol, 1979; Gély & Lorenz, 1991; Debrand-Passard, 1995; Robin et al., 2000). The precise distinction of the controls on the depositional development of the basin is still problematic. However, individual phases of intra-plate deformation (with a southern or southeastern orogenic origin) are apparent for the post-Cretaceous period. A notable one is the so-called Etrechy phase of mid-Rupelian age (CRF 10; Gély & Lorenz, 1991). Other angular unconformities developed at the Thanetian-Ypresian (CRF 2), Ypresian-Lutetian (CRF 3) and Lutetian-Bartonian (CRF 4) transitions, in the Late(st) Bartonian (CRF 5 ?), at the Priabonian-Rupelian transition (CRF 8), in the earliest Rupelian (CRF 9) and at the Aquitanian-Burdigalian transition (CRF 16) (Figs 6 and 7; Gély & Lorenz, 1991; Robin et al., 2000). Evidently, punctuated tectonic forcing and eustacy were an important control on the sedimentary development of the basin (Fig. 7).

Concluding stratigraphic remarks

The stratigraphy of the sedimentary basins of the West European Platform was very much controlled by the kinematic episodicity of the Pyrénéo-Provençal, Alpino-Pyrenean and Euralpine orogenic phases (Fig. 5). Those different stratigraphic sequences form polyphase but correlative successions of Tertiary age. Though strict synchronicity cannot be demonstrated, the sequence stratigraphic interpretations imply that these successions were deposited in response to widespread plate-boundary events and global changes in sea level (Sissingh, 2006). The plate-boundary events were governed by the northward drift of Africa induced by the opening of the Indian and Atlantic oceans and by the resultant collision of Apulia and Iberia with Europe. These events repeatedly modified the tectonic stress field of the West European Platform. The changes in stress fields and plate motions, and the fluctuations in relative sea level, which together controlled the stratigraphic evolution of the platform basins as well as the palaeogeographic evolution of the West European Platform as a whole, are thought to be ultimately linked to seafloor spreading in the Indian and Atlantic oceans (Sissingh, 2006).

Palaeogeographic evolution

The Alpine and Pyrenean mountain chains and their foreland basins (Encls 1 and 2; Appendix 1) formed in response to Tethyan oceanic crust subduction and the following phase of continent-continent collision on the convergent margins of the European, Apulian and Iberian plates. During the Tertiary, the latter two plates moved northward ahead of the also northward drifting African Plate. The plate collision and the accompanying tectonic deformation of the West European Platform began in the Cretaceous, when Africa initially moved easterly and later on more northerly relative to Europe. As a result of the plate-scale, counter-clockwise convergence, the ENE-WSW striking Eastern and Central Alps, the roughly N-S trending chain of the Western Alps, and the E-W trending Pyrenees developed during the Tertiary. This was accompanied by variably S-N and E-W vergent frontal thrusting along the contemporaneously evolving North and West Alpine and North Pyrenean Foreland basins (Encl. 2; Appendix 3). The complex nappe stack of the Western Alps in particular accommodated radial compressional tectonics activated by the counter-clockwise rotating Apulia Microplate (Appendix 3). Structurally, the foreland basins are intimately linked to the Tertiary phases of the Alpine orogeny (Sissingh, 2003b, 2006). They developed in direct response to the collision of the Alpine and Pyrenean orogenic wedges with the southern margin of cratonic Europe and evolved by flexural, thrust-wedge loaded subsidence of the orogenic foreland plate. Through time, the axes of the foreland basins migrated north- and westward, ahead of the advancing Alpine and Pyrenean nappe stacks. Thrust-wedge loading and thickening occurred under largely subaerial conditions. Correspondingly, thrust-wedge erosion was substantial and provided ample clastic supply to the foreland basins. The sediment fills of these basins generally onlap the Mesozoic substratum of the European foreland in northern and western directions.

Following uplift and erosion during the so-called 'Paleocene Restoration' event, sedimentation occurred diachronously in a generally northward-migrating, deep-water Alpine Foredeep from the Late Paleocene until about the Eocene-Oligocene transition (Sissingh, 1997, 2001). Today, this basin is strongly faulted and folded, and largely buried beneath the Alpine fold-and-thrust belt, hampering palaeogeographic reconstructions by poor exposure. Representing a remnant oceanic Tethyan basin, its sediment fill onlapped the southern European continental margin, which was subjected to distal, syn-orogenic down-warping and bulging of the lithosphere by the tectonic loading induced by the northward-prograding Alpine orogenic wedge. Towards the end of the Eocene, both the North and West Alpine foredeeps were closed. By then, deep-water marls and turbiditic sands on top of mainly shallow-marine carbonates gave way to the generally shallow-water clastics of the North and West Alpine Molasse basins. Syn-orogenic tectonism of the precursor foredeeps continued though as evidenced by numerous faults that cut the molasse deposits.

From their inception onwards, the North and West Alpine Foreland basins were closely linked to the contemporaneous formation of the Alps. The stacking, erosion and lateral movements of the Alpine overthrust belt continuously changed the shape and dimensions of the foreland clastic wedges, their palaeogeographic features and their depositional settings. The episodic tectonic evolution of the impinging North and West Alpine orogenic wedges is recorded in the sequence-stratigraphic architecture of their peri-alpine offspring basins. Similarly, the North and South Pyrenean foredeeps and molasse basins would not have formed without the Pyrenean orogeny. After the Late Cretaceous paroxysmal dislocation by left-lateral plate motions associated with the opening of the North Atlantic, the Bay of Biscay and the Parentis Basin, the compressive forces exerted by Iberia against Europe restructured the entire Aquitaine Basin.

The European Cenozoic Rift System is a key feature of the Tertiary palaeogeography of the West European Platform (Appendix 1). The structural development of this mega-rift began close to the Early-Middle Eocene transition. In conjunction with northward-directed rift propagation in the Upper Rhine Graben (Sissingh, 2003a,b) and (less conclusively established) southward-directed rift propagation in the Rhône Graben

(Sissingh, 2001; n.b. the Marseille Basin opened around the Priabonian-Rupelian transition), almost all main parts of the West European rift system originated during the Eocene. Only the Lower Rhine Embayment became structurally distinct after the Eocene (Sissingh, 2003a,b). Rifting increased, decreased or ceased at different times in different parts of the structure. On the West European Platform it continued intermittently until the present-day in the Upper Rhine Graben and the Lower Rhine Embayment (Fig. 5; Sissingh, 2003b, 2006).

Like the foreland basins, the polyphase structural evolution of the rift system was controlled by the syn-orogenic convergence of the European, Apulian, Iberian and African plates. Evidently, the orogenic chains and foreland basins and the intraplate rift system are tectonically linked to each other through Alpine plate interactions and plate-boundary re-organisations.

The palaeogeography of the Paris Basin (Appendix 1) evolved during the Paleogene under partial control of continuing thermal subsidence that had started during the initial episode of Permo-Triassic rifting. Contemporaneously, plate-kinematics in conjunction with eustatic changes in sea level affected the depositional environment time and again (Fig.7). Post-Oligocene developments seem to have been governed by uplifting of the surrounding massifs or by elevation of the platform region as a whole (see below).

Below a wider-ranging but still synoptic account of the foregoing tectonopalaeogeographic sketch is given for the Middle Eocene-Pliocene period. Eight palaeogeographic summary maps have been compiled for that purpose. These maps (Appendices 4 to 11) are based on a plethora of papers, which cannot all be acknowledged in this study (see Cahuzac (1980), Plaziat (1981, 1984), Gayet (1985), Gély & Lorenz (1991), Cahuzac et al. (1995), Dubreuilh et al. (1995), Berger (1996), Sissingh (1997, 1998, 2001, 2003a), Sztràkos et al. (1997, 1998), Gély & Sztrakos (2000), Kuhlemann & Kempf (2002) and Berger et al. (2005) for extensive bibliographies). Also selectively, reference is made to Capdeville (1989), Dubreuihl (1989), Hantke (1993), Meyer (1994), Hoffmann (1996), Schröder (1996), Huckriede & Urban (1998), Standke & Suhr (1998), Villinger (1998), Unger (1999), Schröder & Peterek (2002) and Giamboni et al. (2004) for additional palaeohydrographic data. Previous palaeogeographic reconstructions of the West European Platform have been published by Ziegler (1990) and Meulenkamp & Sissingh (2000a,b).

Paleocene and Eocene

As far as known, deposition in the predominantly deep-water facies of the Alpine Foredeep was essentially continuous during the Late Paleocene-Eocene. This was simultaneous with large-scale, initially shallow-water onlap of the Alpine Foreland in northerly and westerly directions from the initial, time-transgressive development of the 'Palaeocene Unconformity' onwards (Allen et al., 1991). The origin of the onlapped unconformity surface has been attributed to uplift and erosion induced by a north- to northnorthwestward-migrating forebulge (Laubscher, 1992) and to compressional folding of the lithosphere (Ziegler et al, 2002) ahead of the encroaching Alpine thrust loads. This unconformity marks the base of the Tertiary sedimentary mega-sequence, which evolved in response to overall N-S to NNW-SSE trending compression and downflexing of the European Plate induced by the Middle to Late Pyrénéo-Provençal collision of Apulia and Europe. The collision caused widespread, north- to northnorthwestward-migrating uplift and deformation of the Alpine Foreland in advance of the evolving Alpine thrust belt (Allen et al., 1991; Crampton & Allen, 1995). Its development proceeded diachronously from the early Thanetian until at least the onset of the Rupelian, and was followed by progressive regional flooding of the subsiding, block-faulted Helvetic shelf. During this period, a transgressive and deepening succession of continental sandstones, neritic limestones and increasingly deeper-water marls and flysch was laid down on top of the basal Tertiary unconformity. Concurrent with the coeval first-order onlapping and overstepping of the distal basin margin, cyclic transgressive-regressive deposition took place towards the north and the west (Herb, 1988). Large-scale diachronous coastal-marine deposition was accompanied by migration of the deeper-marine facies belts (including Alpine flysch with interstratified chaotic wildflysch formations derived from the evolving Alpine orogen). In parallel, the basal hiatus increased in magnitude towards the external parts of the foredeep basins (Sissingh, 1997, 2001). The associated normal faulting of the foreland due to flexural fore-bulge uplift and/or compressional lithosphere folding led to subaerial exposure and to localised deposition of lacustrine limestones and iron-rich and kaolinitic terrestrial clastics that reflect tropical weathering conditions. Overall, areal marine submergence seems to have increased in rate during the Eocene. This was accompanied by syn-depositional flexural normal faulting due to local re-activation of rift margin structures. This resulted in half-grabens separated by intra-basinal basement highs, which were subjected to erosion resulting in second-order hiatuses in the early foreland basin. The submergence was accompanied by northward-directed propagation of early Alpine nappes and deep-marine deposition of Ultrahelvetic turbidites and debris flows in front of submarine canyons that had cut into a narrow shelf fringing the Alpine orogenic wedge to the south (Appendix 4; Herb, 1988; Lihou, 1995, 1996a,b; Menkveld-Gfeller, 1995; Oberhauser, 1995; Lihou & Allen, 1996). In the West Alpine Foredeep, the Briançonnais (a discrete crustal block that belonged to the Iberian Microplate (northern part) or the European Plate (distal margin) until the Late Jurassic-Early Cretaceous), was incorporated into the Alpine accretionary prism as a partially obducted, exotic terrane during the Middle Eocene. By Late Eocene time, however, it was entirely subducted beneath the orogenic prism in front of the leading edge of the Apulian Microplate (Appendices 3 and 4; Stampfli et al., 1998; Michard & Martinotti, 2002). Deposition of Eocene neritic sediments was generally controlled by transgressive phases, which alternated with regressions that caused limited erosion. At the migrating distal basin margins, the overall time-transgressive drowning of the basal shore-face sandstone-carbonate complex can be related to tectonically-induced, rapid basin subsidence and an increased input of fine-grained terrigenous clastics. These clastics represent the most distal facies of the Alpine flysch that accumulated in deep water in the proximal parts of the generally underfilled, flexural foredeep basin, i.e., in front of the advancing Alpine orogenic wedge (Sinclair, 1997a). During the Ypresian and Lutetian, a shallow-marine gulf was present north of the foredeep proper (extending into the region comprising the Bonnes Plateau, the Aravis Chain and the Bauge and Platé massifs; Appendix 4). Communication between this basin and the foredeep was temporarily interrupted by the end of the Lutetian. It became permanently integrated into the deeper-marine foreland basin during the late Bartonian (Kerckhove, 1980; Cavelier, 1984). During the Priabonian, foredeep deposition was strongly controlled by collisional tectonics associated with the HP Lepontine collision metamorphism that was climactic near the Bartonian-Priabonian transition (Sissingh, 1997). Prior to the early Rupelian when deposition of the typical molasse started, the North Helvetic Flysch (including the Taveyannaz and Val d'Illiez sandstones which contain andesitic clasts derived from a volcanic arc that has never been located; Sinclair, 1992; Waibel, 1993) of Priabonian-early Rupelian age (cf. Sinclair, 1992; Ruffini et al., 1997; pers. comm. J.-P. Berger, Fribourg) was deposited in a 'Pre-Molasse' Basin (Appendix 5). In the eastern part of this intermediary basin, deeper-marine mass flow deposits accumulated next to shelfal to lagoonal carbonates and fluvio-lacustrine clastics (Wagner, 1996). Thus, the Priabonian sediments accumulated during a transitional sedimentary cycle under partly underfilled and partly steady-state foredeep conditions of deposition that were characterised by the absence of classical molasse. Via the intermediary 'Pre-Molasse' Basin setting and under the influence of the evolving Alpine mountain belt and syn-sedimentary foreland faulting, the mainly deep-water and underfilled North and West Alpine Foredeep basins were ultimately transformed into the largely shallow-marine and continental, filled to overfilled North and West Alpine Molasse basins. These large-scale changes in palaeogeographic and basinal settings had as their prime cause the mechanical coupling of the converging Apulian, Iberian and European plates that together constitutes the Alpino-Pyrenean orogeny. The principal collisional event probably corresponded to an increased mid-crustal penetration of Apulia in underthrusted Europe and to accelerated growth and thrusting of both the Alpine and the Pyrenean orogenic wedges onto the European Plate. This major event resulted in thrust-wedge loading on a major scale of the European crust, in combination with intra-orogen nappe stacking, uplift and erosion.

During the Early Pyrénéo-Provençal collision of Iberia against Europe, a wide, E-W trending deep-marine passage was present until the latest Cretaceous in between the Atlantic and Tethyan oceanic domains. Continuing narrowing of the passage induced regression of the sea towards the west. During the Paleocene, compression resulted in the development of a dynamically evolving marine-lagoonal gulf that extended eastwards into the Languedoc. This gulf existed until the Early Eocene (Plaziat, 1981, 1984; Pomerol, 1982). Foredeep subsidence persisted along the incipient Pyrenees with Middle Pyrénéo-Provençal collision deformation concentrated along the eastern part of the plate-boundary zone. As a result, a westward-propagating Pre-Pyrenean thrust-and-fold belt developed by the beginning of the Eocene in between the narrow South and North Pyrenean Foreland basins (Appendix 4). Successive compressional tectonics and accompanying flexural subsidence in the Eocene displaced the westwards plunging basin axis and depocentre of the Aquitanian Basin, which formed part of the North Pyrenean Foreland Basin. As a result, the basin became subdivided by an increasingly complex system of evolving submarine ridges and troughs enhanced by halokinesis. Thick continental series of syn-tectonic Palassou conglomerates reflecting erosion of newly created Pre-Pyrenean palaeorelief accumulated along the southern margin of the northern foreland basin (Crochet, 1991; Deramond et al., 1993). Deep-marine clays and flysch accumulated farther to the west, whereas deposition of shallow-marine carbonates (near the Atlantic coast) and more widespread fluvio-lacustrine clastics and carbonates prevailed in the North Aquitanian Basin (Fig. 7; Plaziat, 1981, 1984; Dubreuihl, 1989; Sztràkos et al., 1998). The paroxysmal Alpino-Pyrenean phase of thrusting and folding, which in essence shaped the present-day Pyrenees, generated additional molassic conglomerates. In addition, platform carbonates and, most prominently, fluvial clastics continued to accumulate during the Priabonian, the latter in conjunction with playa evaporites which indicate an arid climate (Fig. 7; Appendix 5; Plaziat, 1981, 1984).

The European Cenozoic Rift System (Encl. 2; Appendix 1) developed episodically from the climactic compressional event at the Middle-Late Pyrénéo-Provençal boundary that occurred close to the Early-Middle Eocene transition (Sissingh, 2003b). The oldest, Lutetian graben-fill sediments are unevenly distributed in the Upper Rhine Graben. They include the Messel, Eocene Basal Clay and Siderolithic formations. The late Lutetian is most notably represented by the Ubstadt-Bouxwiller beds, a sequence consisting of limestones, dolomitic marls, clays and lignites (Sissingh, 2003a,b). These strata were deposited under a warm and humid climate in non-restricted lacustrine depocentres. The Lutetian complex of continental sediments accumulated in palaeogeographically restricted depressions, lakes or river valleys (Appendix 4). It reflects an initial phase of rifting with regionally differentiated, pull-apart subsidence related to strike-slip block movements along pre-existing faults. This was induced by N-S trending compression of the Late Pyrénéo-Provençal formative phase of the European Foreland (Sissingh, 1998, 2003a,b). The paucity of coarse conglomerates indicates that the palaeorelief was modest, with the exception of the southern segment of the Upper Rhine Graben. The different sites of sedimentation received variable amounts of clastics. This probably depended mainly on the local rate of tectonic subsidence, which, in general, seems to have been in balance with the rate of sediment input. In the Hessen Depression (Kassel Basin) Lutetian clays, sands and lignites accumulated under comparable conditions (Meiburg & Kaever, 1986). Middle Eocene continental deposition in the Upper Rhine Graben ceased with the development of a widespread stratigraphic hiatus that may be attributed to a Bartonian period of non-deposition and erosion that was induced by uplift (Sissingh, 2003b). This event may be correlative to widespread uplift of the European crust that originated through lithospheric unflexing. This was caused by the detachment of a lithospheric slab from the European Plate which was subducted underneath the juvenile Alpine orogen at the onset time of the HP Adamello metamorphic phase (Sissingh, 1997). Alternatively, it was a direct response to N-S trending compression originating from the Alpine collision zone. It was apparently also contemporaneous with the onset of plate-kinematic independency of Iberia relative to Europe and Africa (Roest & Srivastava, 1991). The uplift of the Upper Rhine Graben was (near-)coincident with the opening of the Eger Graben as well (Kasiński, 1991). The next Alpino-Pyrenean main phase of northward-propagating rifting under influence of E-W crustal extension induced pronounced subsidence. During the early part of this second rifting phase, a thick, cyclic succession of evaporitic deposits with brackish-marine horizons accumulated in the southern Upper Rhine Graben (Nickel, 1996; Blanc-Valleron & Schuler, 1997; Rouchy, 1997). Meanwhile lignite-bearing strata accumulated in the land-locked Hessen Depression (Appendix 5), which also experienced enhanced extensional tectonics.

In the Rhône Graben (Bresse Graben to Camargue Basin; Encl. 2; Appendix 1) terrestrial deposits accumulated under conditions comparable to those of the Upper Rhine Graben from about the Ypresian-Lutetian transition until the Bartonian-Priabonian transition (Appendix 4; Sissingh, 2001, 2006). The Lutetian-Bartonian Rhône Graben was characterised by a series of lakes in which calcareous lacustrine sediment accumulated in association with localised fluvial deposition (Cavelier, 1984). The palaeorelief divided the graben into a number of lacustrine subbasins, sills and fluvial source areas. The lakes received clastics from low-lying landmasses along the eastern and western margins of the initial rift, as well as from intra-graben highs. As in the Upper Rhine Graben, major cyclic evaporite sequences accumulated in the Rhône Graben during the Priabonian-early Rupelian main phase of E-W trending rifting (Appendix 5; Curial & Moretto, 1997; Dumas, 1986; Dromart & Dumas, 1997; Rouchy, 1997). The coeval development of major evaporitic basins in the proximal European Foreland and the development of the 'Pre-Molasse' basins nearer to the Alpine orogenic wedge, signifies a paroxysmal plate-kinematic change in the regional stress field. This induced re-activation of faults and allowed subsurface Triassic evaporites to be recycled by leaching into the Rhône and Upper Rhine grabens (Sissingh, 2001, 2003a). Indeed, the Triassic evaporitic series may have been actively involved in the Alpino-Pyrenean extensional faulting (terminal Eocene diapiric intrusion occurred in the Vocontian area of southern France). Hypersaline and evaporative lakes were a dominant feature during this phase of rift development. Seawater and marine organisms (such as nannoplankton, foraminifera and molluscs) occasionally entered the Rhône Graben from the West Alpine Foredeep during the Priabonian-early Rupelian. Similarly marine influence reached the Upper Rhine Graben via the Burgundy Passage (Figs 8 to 10; Appendices 5 and 6; Sissingh, 2003b).

In the Massif Central rifting and accompanying sedimentation started in a land-locked palaeogeographic setting at around the same time as in the Upper Rhine and Rhône grabens (Appendix 4; Sissingh, 2001). In the Limagne Graben, the initial basin fill comprises a fluvio-lacustrine sequence of sandy, marly and more calcareous sediments, whereas fluvial arkoses predominate in the coeval Puy Basin (Rey, 1971; Autran & Peterlongo, 1980). During this first phase of syn-rift deposition, the surrounding Massif Central was still a peneplained area of erosion and non-deposition. Volcanism was confined to a few centres (Appendix 4; Sissingh, 2001). Until the Priabonian, fluvial clastic transport occurred from the Limagne Graben northwards in the direction of the Paris Basin (Appendices 4 and 5). At the same time, E-W trending extension of the eastern Massif Central accelerated.

Paleocene-Eocene cyclical deposition in the flexural, steadily subsiding Paris Basin resulted in calcareous and clastic sediments (Fig. 7; Gély and Lorenz, 1991). During the Danian-latest Bartonian mega-cycle (Robin et al, 2000), maximum marine transgression at the beginning of the Lutetian followed a period of basin-wide uplift and erosion that was caused by enhanced N-S intra-plate compression at the transition of the Middle and Late Pyrénéo-Provençal tectonic phases. The transgression came from the north and the west. I.e., from the North Sea, Western Approaches and Channel basins, across the submarine, NW-SE trending Artois Axis, which was temporarily emergent during Ypresian (Pomerol, 1982). This resulted in deposition of, amongst others, the Calcaire Grossier (Fig. 7). This tectonic activity marks the end of clastic sedimentation sourced from the Massif Central (until the Burdigalian) and the onset of limestone deposition. Carbonate sedimentation was probably enhanced by erosion of the calcareous Mesozoic

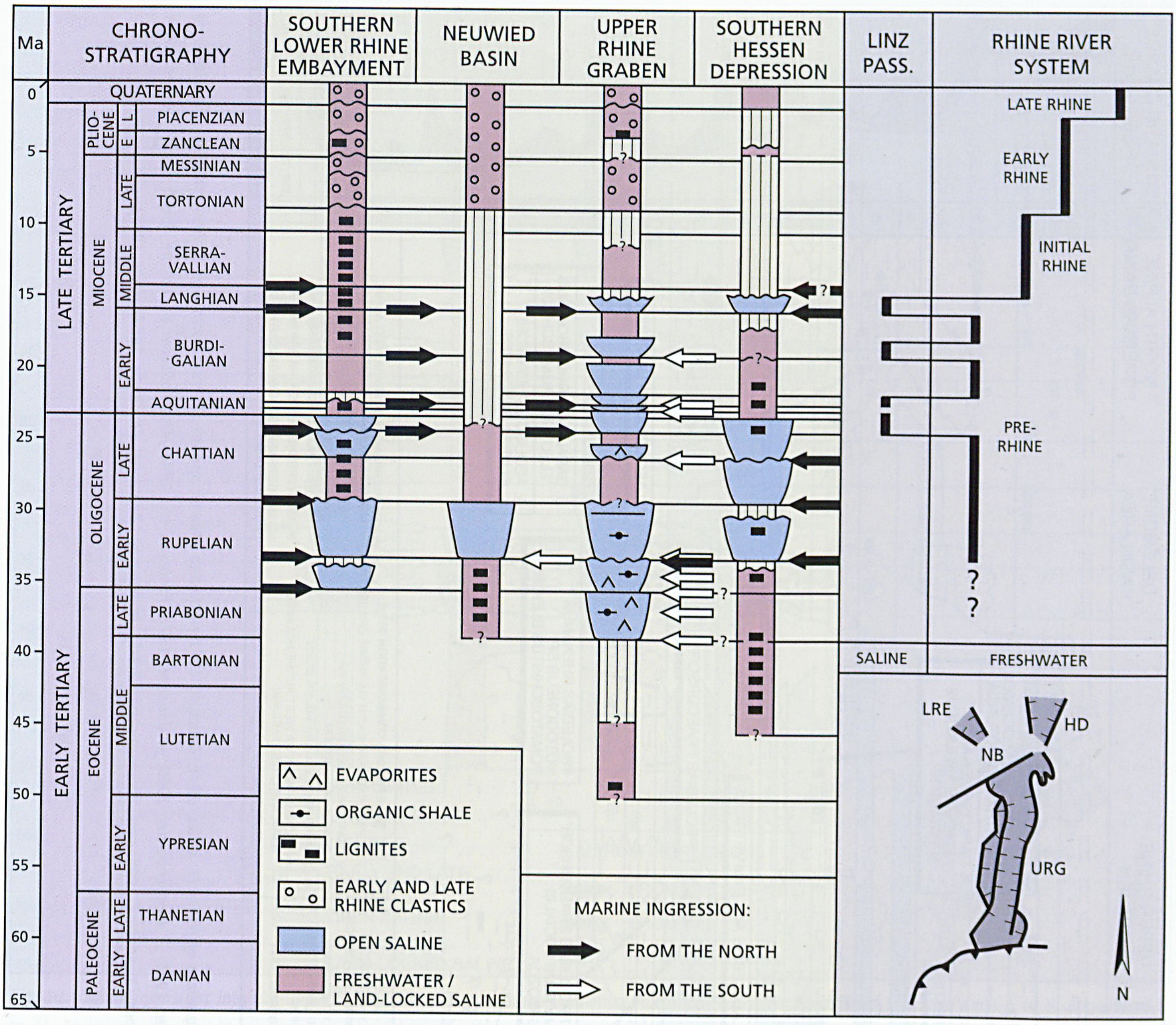

Fig. 8. Saline incursions into the Upper Rhine Graben and developmental stages of the river Rhine at the Rhenish Triple Junction (see also Fig. 9; Encls 5 to 8; Appendices 1 to 4). Incursions from the north occurred from the North German-Polish Basin via the Hessen Passage and from the North Sea Basin via the Linz Passage. Incursions from the south occurred from the Rhône Graben via the Burgundy Passage and from the Alpine Foreland Basin) via the Raurachian Passage (see also Fig. 10). During the Rupelian, a brackish-marine passage probably existed connecting the Paris Basin and the graben via the Luxembourg Basin and Vordereiffel Passage. Note that saline deposits are not known from the southern(most) Lower Rhine Embayment, which is consistent with incursions via the Linz Passage during the Aquitanian, Burdigalian and Langhian (see also Fig. 11; Sissingh, 2003a,b).

exposed in the surrounding land areas. Earlier during the Tertiary, a variety of shallow marine, lagoonal-lacustrine and fluvio-lacustrine deposits accumulated in the intra-cratonic, gulflike basin. The Lutetian incursion passed through the pre-existing Vexin Passage in between the Bray Island and the Variscan (Cadomian) Armorican Massif (Appendix 4), but did not submerge the post-Danian Bray Anticline. By mid-Lutetian time the Artois Axis emerged, permanently disrupting marine communication between the Paris Basin and the North Sea Basin (Appendices 4 to 7; Pomerol, 1982). Temporarily, marine circulation through the Vexin Passage was reduced. However, following another widespread break in sedimentation, marine conditions returned briefly in the early Bartonian. In later Eocene times the basin was overall reduced in size (with a relatively pronounced Bray Island at the centre and poor communication with the open marine realm in the west) and environmentally restricted as evidenced by the occurrence of continental-lagoonal evaporites (especially those deposited subsequent to the last major transgression of the Eocene, i.e., the deposition of the Pholadomya Marls (Fig. 7). This basal Priabonian transgression was governed by Alpino-Pyrenean tectonic activity which also affected late Eocene deposition in general (Fig. 7; Appendix 5; Mégnien & Mégnien, 1980; Gély & Lorenz, 1991).

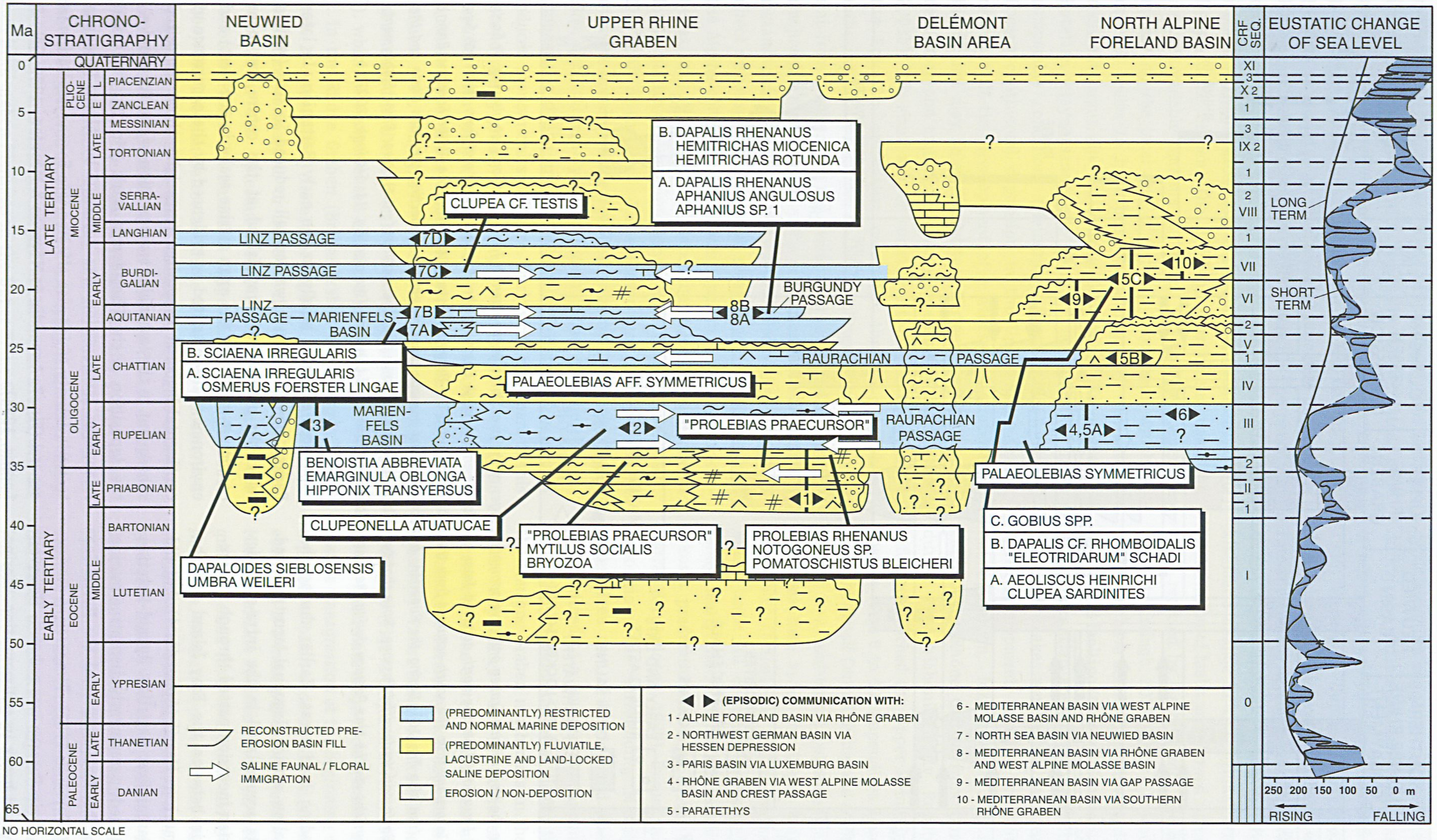

Fig. 9. Saline incursions into the Upper Rhine Graben as evidenced by immigrations of fishes (1: Gillet, 1944; Gaudant, 1981 (including endemic species ?); from North German Basin into Neuwied Basin via Hessen Depression (2) and northernmost Upper Rhine Graben: Reichenbacher, 1995; 2: Reichenbacher, 2000; 4: Gaudant, 1977; Fontes et al., 1996; Reichenbacher & Philippe, 1997; Reichenbacher, 2000; 5, 7 (a-c), 8: Martini, 1990; Pharisat, 1991: Reichenbacher, 2000), gastropods (3: Amitrov, 1996; pers. communication 2003), bivalves and bryozoans (1: Doebl, 1969; Thery, 1996).

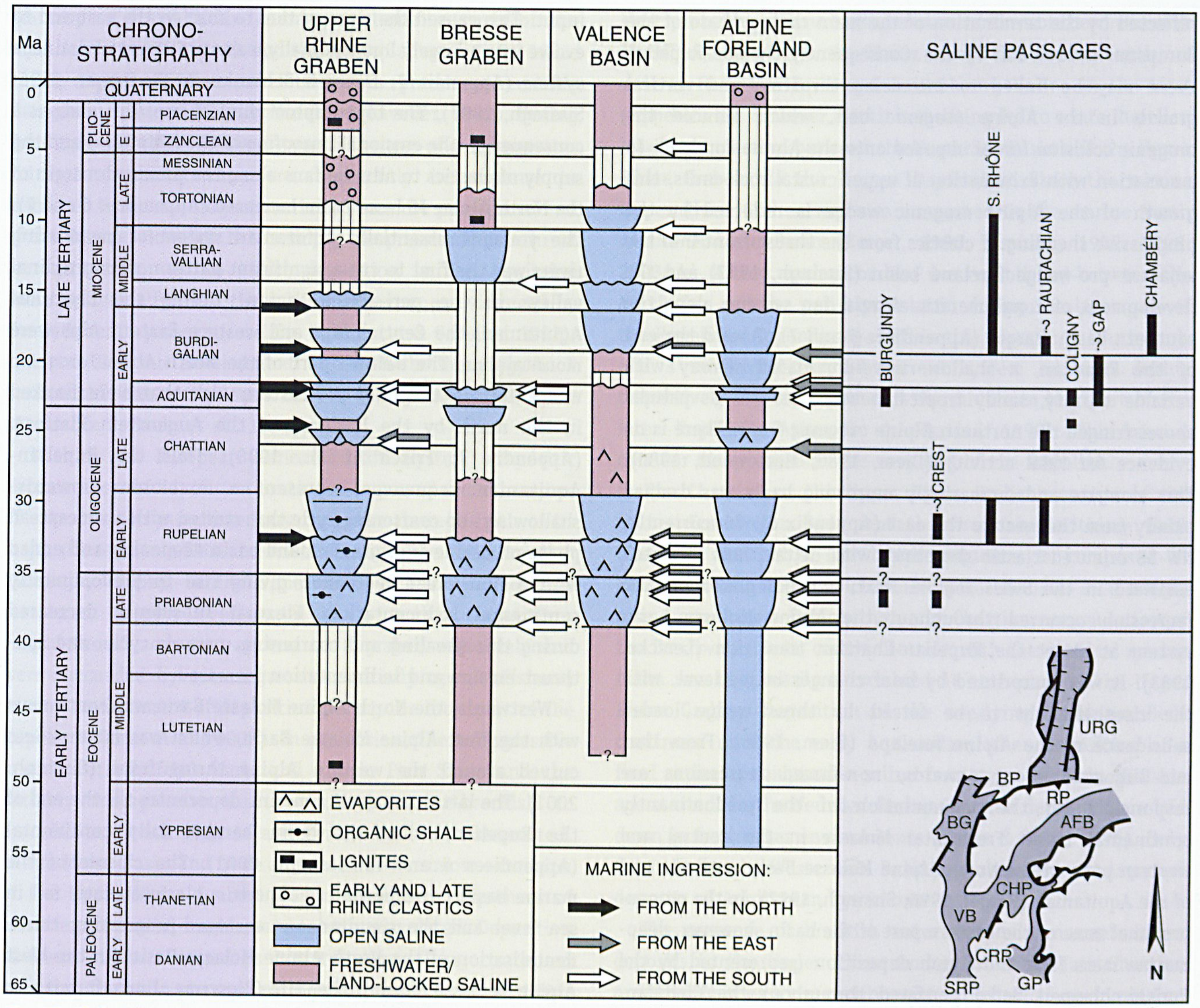

Fig. 10. Saline incursions into the Upper Rhine Graben, Bresse Graben, Valence Basin and Alpine Foreland Basin (see also Encls 5 to 8; Appendices 1 to 4). Incursions into the Rhine Graben occurred from the North German-Polish Basin via the Hessen Passage, North Sea Basin via the Linz Passage, Alpine Foreland Basin via the Raurachian Passage and Rhône Graben via the Burgundy Passage (see also Figs 8 and 9). Incursions into the Bresse Graben occurred via the Crest and Coligny passages from the Alpine Foreland Basin and from the Mediterranean Basin through the South Rhône Passage. Incursions into the Valence Basin occurred from the Alpine Foreland Basin via the Crest and Gap passages and from the Mediterranean Basin through the Marseille, Apt and South Rhône passages. Incursions into the Alpine Foreland Basin from the south occurred from the Mediterranean Basin via the Aix and Cucuron passages. In the east the basin was connected to the Paratethys (see also Fig. 11; Sissingh, 2003b).

Oligocene

Following the closure of the North and West Alpine foredeeps, the initial post-Priabonian phase of deposition in the North and West Alpine Molasse basins coincided with a major eustatic rise in sea level during the earliest Rupelian. In the northern basin, deep-water Fish and Engi shales were deposited. Their deposition was accompanied by further rapid flexural subsidence and faulting, and a northward shift of the central axis and the northern margin of the basin. Part of the basin had poor circulation during the early Rupelian, as indicated by anoxic shales. Deposition of these shales occurred simultaneously with that of orogen-derived turbiditic clastics (i.e., the Deutenhausen Beds). Prior to additional transgressive onlap of the Alpine Foreland during the deposition of the Lower Marine Molasse (Sissingh, 1997, 2003b) and western time-equivalent clastics (Sissingh, 2001), a regressive period, probably in response to both an eustatic fall in sea level and tectonic uplift, gave rise to an intra-Rupelian hiatus (Sissingh, 1997, 2001). This break is correlative with the HT Lepontine metamorphic phase, which has been related to a temporary unflexing of the European plate induced by a lithospheric slab detachment underneath the Alpine orogen (Sinclair, 1997b; Sissingh, 2006). The break-off was also followed by increased heat flux and magmatism that climaxed with the Bergell intrusion. It corresponded to a major foreland stress relaxation reflected by the termination of the main rifting phase of the European Cenozoic Rift System. Consequently, the mid-Rupelian event may be linked to increasing thrusting and vertical growth in the Alpine orogenic belt, which reduced the orogenic collision forces imposed onto the Alpine Foreland. In association with exhumation of upper crustal rock-units, this growth of the Alpine orogenic wedge is reflected by the progressive shedding of clastics from the thrust front into the adjacent pro-wedge foreland basin (Sissingh, 1997) and the development of conglomeratic alluvial fan systems along the southern basin margin (Appendices 6 and 7). Toward the end of the Rupelian, a shallow, wave-dominated seaway with variable salinity, sandy tropical beaches as well as paludal shores fringed the northern Alpine orogenic front. There is no evidence for tidal activity (Diem, 1986; Homewood, 1986). This elongate and increasingly narrowing basin was drained axially from the west to the east (Appendix 6). Concurrently, NW-SE oriented clastic shorelines with deltaic fans migrated eastward in the Swiss region. Next, a major glacio-eustatic regression occurred throughout the Alpine Molasse basin system at about the Rupelian-Chattian transition (Lemcke, 1983). It was overprinted by brief changes in sea level, with the rises thought to be forced by thrust-wedge loaded subsidence of the Alpine foreland (Diem, 1986). From that mid-Oligocene event onwards, non-forced regressions are responsible for the accumulation of the predominantly continental Lower Freshwater Molasse in the central and western parts of the North Alpine Molasse Basin until the end of the Aquitanian (Berger, 1996; Sissingh, 1997). In the orogen-proximal zone of the eastern part of the basin, however, deep-marine mass flow and flysch deposition (represented by the Puchkirchbergen Beds) persisted throughout the Chattian-Aquitanian (Sissingh, 1997). Following the mid-Oligocene marine regression, continental deposition prevailed in much of the northern basin and thick, mainly conglomeratic alluvial-fan deposits accumulated. Northward-flowing, marginal intra-Alpine streams formed a number of laterally interfingering deltaic fans along the Alpine thrust front (Appendix 7). The generally thick and conglomeratic, thrust-wedge-fringing fans were characterised by steep proximal areas dominated by braided rivers. Downstream, they gave way to relatively low-gradient floodplains with meandering rivers. Farther away from the rising mountain belt, lakes and swamps occurred. During this Chattian episode of molasse deposition, a predominantly radial drainage system existed west of the Puchkirchen Turbidite Basin. Rapid uplift and enhanced northward propagation of the Alpine orogenic wedge (i.e., forward thrusting and elevation of the Helvetic nappe system) in response to stepwise underplating of the External Massifs onto the Alpine thrust belt combined with imbrication and elastic downflexing of the European foreland crust and strong mechanical coupling of the orogenic wedge with the foreland plate (Sinclair et al., 1991) gave rise to increased clastic input. This caused the river system to shift to the east and to evolve into a largely longitudinally, eastward-directed drainage system (Appendix 7; Büchi & Schlanke, 1977; Berger, 1996; Sissingh, 1997). The topographic relief of the Alps and, as a consequence, the erosional unroofing of the mountains and the supply of clastics to alluvial fans along the proximal margin of the North Alpine Molasse Basin increased (Appendices 6 and 7). The younger, essentially Aquitanian system of meandering rivers was the first to cut a significant pattern of longitudinal valleys in the peri-alpine region. During the Chattian-Aquitanian, the Central Alps and western Eastern Alps were mountainous. The eastern part of the North Alpine orogenic wedge formed the hilly pre-Eastern Alps that were flanked in the north by the lowlands of the Augenstein Platform (Appendix 7; Frisch et al., 1998). Thus the Rupelian-Aquitanian sequences represent a first-order upwards-shallowing and coarsening cycle that started with a widespread phase of marine transgression and basin deepening and ended with a non-forced regression giving rise to predominantly continental sedimentation. Flexural subsidence decreased during this shoaling and coarsening upwards cycle, and syn-thrust erosion and sedimentation increased.

Westwards, the North Alpine Molasse Basin was continuous with the West Alpine Molasse Basin, which was more or less curved around the western Alpine thrust front (Sissingh, 2001). The latter remained a marine depocentre till the end of the Rupelian, when the basin became fully continental (Appendices 6 and 7; Sissingh, 2001). The closure of the marine basin corresponded in time to a glacio-eustatic fall in sea level and the simultaneous eastward-progressing continentalisation of the North Alpine Molasse Basin. In the West Alpine Molasse Basin, the Mid-Oligocene Unconformity is tectonic as well (Evans & Mange-Rajetzky, 1991), apparently in relationship to progressing Alpine thrust-wedge tectonics. Marine conditions did not return. Instead, alluvial facies such as fans and ephemeral channels accumulated in a number of tectonically controlled (sub)basins. Oligocene tectonism, which uplifted and destroyed the marine West Alpine Molasse Basin, resulted ultimately in the development of an erosional continental palaeomorphology with substantial palaeorelief. The main direction of clastic supply was towards the (south)west and away from the Alpine fold-and-thrust belt (Appendix 7; Sissingh, 2001). Prior to the permanent closure of the basin during the Aquitanian, a northward-directed fluvio-marine current system, that drained the continental region bordering the Alpine orogenic wedge, most probably existed.

In the eastern Aquitaine Basin deposition of continental molasse including lacustrine limestones and fluvial clastics continued throughout the Oligocene. As for the older Palassou Conglomerates, the bounding hiatuses rather than the piemont conglomerates were controlled by N-S trending compressional tectonic activity. However, the breaks in sedimentation and the time-equivalent and widespread changes in lithology in the tropical fluvial-plain and lagoonal-marine parts of the basin farther to the north and the west (Cahuzac et al., 1995; Gayet, 1985) are also correlative with prominent eustatic changes in sea level (Fig. 7; Muratet & Cavelier, 1992). During the Oligocene, thick, Palassou-type sequences of conglomerates did not accumulate anymore, apparently in response to restricted Pyrenean orogenic activity since the paroxysmal end of the Eocene. However, N-S trending compressional overthrust tectonics continued to affect deposition in the Aquitaine Basin episodically until the earliest Miocene, as evidenced by the sedimentary sequences (Fig. 7; Muratet & Cavelier, 1992), and the Chattian development of the Narbonne piggy-back basin within the northeastern bend of the Pyrenean overthrust (Appendix 7; Szulc et al., 1991).

Within the European Cenozoic Rift System evaporitic circumstances of deposition continued to prevail under a regime of extensional syn-sedimentary tectonics through both of its major rift segments from the Priabonian into the early Rupelian (Sissingh, 2003b). In the Upper Rhine Graben the severely restricted, largely continental environmental conditions simultaneously came to an end on a graben-wide scale and were succeeded by a transgressive, initially open (offshore) marine environment of deposition during the later part of the Rupelian (Derer et al., 2003). In succession, the transgressive marine Foraminiferal Marls and anoxic Fish Shale and the variably transgressive and regressive, marine-brackish to brackish-lacustrine Meletta and Cyrena beds were deposited. In the Mainz Basin and in de adjacent northernmost extension of the Upper Rhine Graben proper, significant sequences of fossiliferous coastal-marine sands also accumulated. Deposition of these strata occurred as E-W trending rifting continued following the main phase of rifting (Rothausen & Sonne, 1984; Sissingh, 1998, 2003a,b).

Within the Rhenish Massif, deposition in the small Neuwied Basin may have begun later than in the Upper Rhine Graben, i.e., during the Priabonian (Meyer, 1994; Meyer & Stets, 1996; Sissingh, 2003a,b). Rift propagation from the northern Upper Rhine Graben towards the post-Eocene Lower Rhine Embayment may have caused diachronous, northwestward-progressing subsidence and deposition in the northwestern branch of the Rhenish Triple Junction that was related to SW-NE trending extension. In the newly developed Neuwied Basin, lignite-bearing clays and conglomerates accumulated from the Priabonian into the early Rupelian, whereas in the Lower Rhine Embayment marine clays and sands initially accumulated in an overall southeastward-directed transgressive regime during the early Rupelian (Appendix 6; Hager & Prüfert, 1988; Schäfer et al., 1997). In the latter basin, this kind of deposition continued during the late Rupelian after a brief interruption. Contemporaneously, accumulation of brackish-water, lagoonal deposits was initiated in the region of the Neuwied Basin (Kadolsky, 1975; Meyer & Stets, 1996). A saline passage does not seem to have existed between the basins. Most probably, marine transgression of the southern Rhenish Massif occurred from the Mainz Basin area in the south, as well as from the Paris and Luxembourg basins in the west (Appendix 6). However, continued rifting led to a late Rupelian marine connection between the North Sea Basin and the Upper Rhine Graben via the Hessen Depression. Since the marine Upper Rhine Graben was also connected to the marine North Alpine Molasse Basin (Berger, 1996; Sissingh, 1997, 1998, 2003a,b), a long marine corridor was established between the North Sea and the peri-alpine basin during the later part of the Rupelian (Appendix 6). Within this corridor, a southward- and a northward-directed current system occurred during respectively the early part and the middle to late part of the later Rupelian (Appendix 6; Martini, 1990). This marine corridor disappeared at the very end of the Rupelian.

The Chattian of the Upper Rhine Graben consists of the limnic Freshwater Beds and the brackish Cerithium Beds (Sissingh, 2003a,b). The latter sequence is composed of calcareous sediments, which were deposited under increasingly saline conditions. During the early Chattian accumulation of the Freshwater Beds, communication with the external marine realm was temporarily terminated at both ends of the Upper Rhine Graben. Deposition of the overlying Cerithium Beds continued until the early Aquitanian, when deposition of a final series of comparable saline formations of Early Miocene age started. In the Neuwied Basin, Chattian deposits were laid down in freshwater environments (Meyer & Stets, 1996). Only from the nearby Westerwald Basin are some remnant lagoonal deposits of Aquitanian age known.

The presence of brackish-water and more normal-marine deposits in the Upper Rhine Graben from the late Chattian onwards, implies a connection with an external marine realm. Until recently, the identification of saline passages was relatively uncertain and conceptual due to controversial age interpretations (Meulenkamp & Sissingh, 2000a,b; Sissingh, 2003a). However, improved biostratigraphic dating and micro-palaeontological analyses recently indicated (see Reichenbacher (2000) for details) that close to the onset of the Chattian the northward-directed current system in the saline passage way that connected the North Sea Basin, via the Hessen Depression and the Upper Rhine Graben, with the North Alpine Molasse Basin, (Figs 8 and 9; Encl. 5; Appendices 6 and 7) ceased to exist. Its disappearance coincides with the mid-Oligocene eustatic fall of sea level. This event also caused continentalisation of the North Alpine Molasse Basin in the south. In the north, communication between the Upper Rhine Graben and the North Sea Basin ended with the development of a barring high in the Hessen Depression (Meiburg & Kaever, 1986; Sissingh, 2003a,b). During early deposition of the Cerithium Beds on top of the Freshwater Beds, saline communication with the North Alpine Molasse Basin was briefly re-established (Figs 8 and 9; Encl. 5). Somewhat later, the saline Linz Passage, that connects the Mainz Basin and the Lower Rhine Embayment across the Rhenish Massif, developed during the late Chattian-earliest Aquitanian and again in the latest Aquitanian (Figs 8 and 9; Encl. 5).

In the Rhône Graben, clastics and carbonates together with evaporites accumulated during two discrete depositional phases during the early and late Rupelian, (Sissingh, 2001). Continental to lagoonal deposition also occurred in the graben system of the Massif Central (Bodergat et al., 1999). The occasional Rupelian marine influences in the Rhône Graben and the Massif Central basins are assumed to have their origin in the West Alpine Molasse Basin (Appendix 6), as was the case during the Priabonian (Fig. 10; Appendix 5). Marine influxes detected in the Marseille Basin, however, came from the palaeo-Mediterranean (Tethyan) realm and indicate the presence of a N-S trending saline passageway in between the Iberian and Corsica-Sardinia blocks (Appendix 6; Nury & Schreiber, 1997). Variably evaporitic deposits continued to accumulate in the Rhône Graben during the early Chattian (Sissingh, 2001). Following an intra-Chattian break in deposition, sedimentation resumed in the Bresse Graben with deposition of transgressive sands containing *Miogypsina*. Upwards, these shallow marine deposits graded into brackish strata, which are overlain by lacustrine limestones and marls. The fossiliferous basal sands indicate a sudden, short-lived marine incursion from the south which connected the West Alpine Foreland Basin with the Bresse Graben via the Coligny Passage (Fig. 10; Appendix 7). In general, the Chattian of the Rhône Graben area was deposited in lakes and lagoons, which were barred from the open marine realm.

Subsequent to a brief tectonic phase of erosion/non-deposition and affected by the development of another angular unconformity in the earliest Rupelian, Oligocene deposition in the Paris Basin resumed basin-wide in a transgressive lagoonal-marine facies with the exception of the southeast where lacustrine conditions prevailed (i.e., the deposition of the Brie Limestones) (Fig. 7; Gély & Lorenz, 1991). The transgression peaked in mid-early Rupelian time. The following regression culminated with a mid-Rupelian episode of erosion/non-deposition induced by an eustatic fall in sea level. In the late Rupelian, (intertidal) lagoonal-marine and fluvio-lacustrine environments predominated (e.g. deposition of the Fontainebleau Sands). These events reflect a trend towards continentalisation of the Paris Basin. Marine communication with the Atlantic domain persisted intermittently throughout the Rupelian and Chattian. The Paris Basin and its connections to the Atlantic were stepwise reduced in size until saline influxes ceased completely and permanently, and deposition was confined to a large freshwater lake (i.e. the deposition of the Étampes and Beauce Limestones) in the late Chattian-Aquitanian (Fig. 7; Appendices 6 and 7; Mégnien & Mégnien, 1980; Gély & Lorenz, 1991).

Miocene

During the Aquitanian, non-marine deposition prevailed in the North Alpine Molasse Basin. However, the basin was probably crossed in mid-Aquitanian time by a saline corridor connecting the Mediterranean realm with the Upper Rhine Graben (Fig. 9; Encls 5 and 6; Appendix 7; Reichenbacher, 2000). At the beginning of the Burdigalian, which north of the Alps was a period characterised by a warm to subtropical climate, a widespread and rapid eustatic marine transgression established a wave- and tide-controlled seaway in the North Alpine Molasse Basin (Appendix 8; Allen et al., 1985, Allen & Bass, 1993; Berger, 1996, Sissingh, 1997). The marine ingression entered the basin both from the south and the east (Figs 8 to 10; Appendix 8). The sea, coming from the south, covered a considerable portion of the future Jura Mountains, onlapped the Black Forest Massif and transgressed the Upper Rhine Graben to an unknown extent during the mid-Burdigalian (Figs 8 and 9). The early Burdigalian peri-alpine seaway connected the Mediterranean Basin with the Carpathian Foredeep, initially through a corridor in the region of the West Alpine Molasse Basin and later on through the Rhône Graben (Appendix 8; Sissingh, 2003b). The inference of a strongly tide-influenced depositional realm with at least mesotidal regimes implies that this major seaway was connected to the open ocean. Distally, water depths reached some 100 m (Berger, 1985) and within the basin tidal banks, shoals and islands occurred. Along the northern front of the Alpine thrust-wedge, conglomeratic fan deltas continued to grow at the mouths of northward-discharging intra-Alpine streams (Appendix 8). After a brief, tectonics-related regression represented by a palaeosol horizon, the late Burdigalian was characterised by a rise in relative sea level, increased clayey deposition, and encroaching depositional cycles of fan-deltas and other proximal deposits. Between the fluvial distributary systems, which are characterised by conglomeratic and sandy channel fills and sheet-flow deposits, tidally-influenced coastal facies including beaches, tidal sand waves and channels as well as intertidal sand flats dominated. These facies are bordered by a near-shore facies belt, which includes subtidal shoals with mega-ripples and intershoal swales, which are replaced further offshore by glauconitic and pebbly coquina banks. At the northern margin of the North Alpine Molasse Basin sandy beaches and channelised tidal flats were established along rocky coasts in the region of the present-day Jura (Homewood et al., 1989). To the east, the northern basin margin was bordered by shoreline cliffs, which were cut into Upper Jurassic limestones during the early part of the late Burdigalian. In the eastern part of the North Alpine Molasse Basin itself, a mainly westward-directed transgression first claimed the area closest to the Alpine nappes in earliest Burdigalian time. Later, it onlapped an elevated region farther northwards that existed throughout the early Burdigalian

(Sissingh, 1997). Thrust-wedge induced subsidence that accompanied in- and out-of-sequence thrusting caused a general, basin-wide shift of the depocentre to the north, as far as the present-day basin axis. Around the Eggerburgian-Ottnangian transition (mid-Burdigalian), the entire eastern basin was inundated by a tide-influenced 'epicontinental sea' while the orogenic wedge was again episodically thrusted to the north. Subsequent Burdigalian sedimentation occurred in marine to brackish and continental facies. During Chattian to mid-Burdigalian times sediment transport along the basin axis was towards the east, but it reversed direction towards the end of the Burdigalian (Appendices 7 and 8). Thus in the east, a southwestward-directed fluvial system which discharged in a marine basin towards the west was ultimately established (Appendices 8 and 9; Büchi & Schlanke, 1977; Unger, 1989; Doppler, 1989; Reichenbacher, 1993). The contemporaneous westward tilting of the basin coincided with a westward increase in flexure of the foreland plate (Pfiffner et al., 2002), in line with the general syn-collision motion of the Apulian Microplate (Appendix 3; Sissingh, 2006).

In the Eastern Alps the replacement of NW-SE trending rotational compression by N-S trending strike-slip compression (Peresson & Decker, 1997) and the large-scale onset of concomitant lateral extrusion of orogenic crustal blocks to the east, resulted by mid-Burdigalian time in the opening of the Styrian Basin and some small intramontane (pull-apart) basins near important strike-slip faults (Appendix 8; Ebner & Sachsenhofer, 1995; Frisch et al., 1998). By the beginning of the Langhian, the continentalisation of the North Alpine Molasse Basin, as first occurred in its eastern part during the late Burdigalian, was abruptly completed in all parts along the Eastern and Central Alps. This was probably caused by the end of underplating of the External Massifs and an increase of the Alpine thrust advance rate (Sinclair et al., 1991). Marine depositional conditions persisted only at the western extremity of the foreland basin, near the Valence Basin. The earlier established, generally westward-directed axial drainage pattern persisted (Berger 1996; Sissingh, 1997, 2001). Uplift of the southern spur of the Bohemian Massif led to a palaeogeographic disconnection with the Paratethys in the east. Along the southern border of the basin, the Alpine thrust front continued to be active and alluvial fans continued to be fed with large quantities of gravel from the rising Alps (Bachmann et al., 1982). Adjacent alluvial plains were incised by meandering rivers and channels. A composite and repeatedly changing 'mega-Rhône' river system, originating in the Eastern Alps, received water from rivers flowing towards the basin from both the Franconian Platform in the north and the Alpine orogenic wedge in the south (Appendix 9). It discharged into the narrow sea which extended northwards through the Rhône Graben from the western Mediterranean Basin (Demarcq & Perriaux, 1984; Sissingh, 2001). Floral assemblages recovered from the Langhian to early Tortonian molasse sequence indicate subtropical to temperate climatic conditions. Alluvial fan and plain facies continued to predominate in the North Alpine Molasse Basin until the Tortonian. Since its youngest known deposits are of early Tortonian age, the Late Miocene to Pliocene history of the North Alpine Molasse Basin is poorly known.

At the westernmost end of the basin, Serravallian and Langhian fan-delta sands and conglomerates ultimately occluded the western, tide-influenced entrance of the basin. Wholesale uplifting and tilting, causing westward-increasing regional erosion in the northern foreland basin (Lemcke, 1974) and increased relief of the Alps (Andeweg & Cloetingh, 1998), started subsequently during the Tortonian. It induced the termination of molasse deposition and the transformation of the North Alpine Molasse Basin into an area of sediment cannabalisation and bypassing. Post-depositional tectonics related to Apulia-Europe plate convergence eventually detached the basin in the west as foreland deformation propagated towards the Jura. The décollement surface, above which the present-day western part of the remnant pro-wedge foreland basin was riding northwards (possibly until the Early Pliocene) in piggy-back fashion, is along the low-friction series of Triassic evaporites in the subsurface (Laubscher, 1992; Ziegler et al., 1996; Becker, 2000). Initially, the fluvial transport of the clastic erosion products from the rising Alps was directed to the west, as in the preceding period. However, basin uplift was strongest in the west. In response to this tilting of the basin, various rivers draining the proximal Alpine foreland started to flow eastwards from late in the Miocene onwards. The basinal uplifting may be related to isostatic adjustment of the lithosphere in response to unflexing of the overthrusted European plate in association with gradually waning thrust movements and foreland loading by the Apulian plate (Andeweg & Cloetingh, 1998).

Miocene deposition in the Aquitaine Basin was characterised by the accumulation of shallow marine 'faluns' (sandy lumachelles) in the westerly platform domain, whereas continental molasse-type sequences characterise the eastern part of the basin (Fig. 7; Appendices 7 to 9). Contemporaneous with the last episode of reef growth and a major eustatic rise in sea level, sandy fluvial deposits derived from the Pyrenean orogen and the southwestern Massif Central characterise the continental domain, following the Burdigalian uplift of the Massif Central (Simon-Coinçon, 1993; Sissingh, 2001). Simultaneous with westward propagation of shelf deposits, the sea retreated from the basin after final transgressions into the central part of the basin during the Langhian and Serravallian (Cahuzac et al., 1995). Since the Tortonian, the Aquitaine Basin is fully covered by a dense drainage system with rivers which (over)filled the basin with detritus from the south, east and northeast as the Massif Central continued to rise (Dubreuihl et al., 1995). These rivers incised and eroded the basin fill as well, especially so during the regressive Messinian, when sedimentary bypassing also prevailed (Appendix 10).

During the intra-Aquitanian accumulation of the Corbicula Beds, the Upper Rhine Graben was a shallow-water, low-energy lagoon with at times a poor water circulation and anoxic bottom conditions. In the vicinity of the Heidelberg subbasin, salt and anhydrite were laid down. The Corbicula Beds are overlain by calcareous and saline formations such as the Lower and Upper Hydrobia Beds (Sissingh, 2003a,b). This indicates that the supply of the Upper Rhine Graben with saline water (and fauna) from the outside continued intermittently until the Langhian (Figs 8 and 9; Encl. 5). During the mid-Aquitanian, the Mediterranean Basin was connected with the Upper Rhine Graben via the West Alpine Foreland Basin, the Coligny Passage and the Bresse Graben (Figs 9 and 10; Appendix 7; Reichenbacher, 2000). When widespread marine conditions returned to the North Alpine Foreland Basin, a marine Raurachian Passage developed between this basin and the Rhine Graben during the mid-Burdigalian (Figs 8 to 10; Encl. 5; Appendix 8). While marine influences still episodically reached the graben from the south, communication between the Lower Rhine Embayment and the Upper Rhine Graben was re-established by mid-Burdigalian time through the Linz Passage (Figs 8 and 9; Encl. 5; Appendix 8). These marine incursions and their accompanying faunal immigrations were controlled by an interplay of eustacy and tectonics. In the Upper Rhine Graben, the brackish-lacustrine upper Lower and Upper Hydrobia and Landschnecken beds conclude the Burdigalian depositional record, whereas the Langhian is represented by the Prososthenia Beds (Reichenbacher, 2000) in this basin. Both the Burdiglian and the Langhian sequences formed under brackish to marine conditions of deposition. The youngest strata of the Burdigalian, however, are more or less limnic, signifying regressive depositional conditions.

In the (southern) Lower Rhine Embayment and Hessen Depression continental deposition prevailed (Hager & Prüfert, 1988; Schäfer et al., 1997, 2004; Sissingh, 2003a,b). In the Lower Rhine Embayment, lignite-bearing coastal-lowland deposits were laid down sequentially from the early Chattian to the Tortonian (Hager & Prüfert, 1988; Zagwijn, 1989; Schäfer et al, 1997, 2004). Given that the Upper Rhine Graben was connected to the marine realm, it is assumed that marine incursions have occurred in the swampy coastal lowlands of the southern Lower Rhine Embayment until the Langhian (Figs 8 and 9). However, correlative horizons of marine or brackish-water deposits are not conclusively known from the southern part of the basin (Sissingh, 2003a). From the Rupelian-Chattian transition onward, swampy coastal lowlands occurred in this basin. The first major glacio-eustatic fall in sea-level event resulted in widespread erosion that was associated with a cooling of the climate (Sissingh, 2003a). The subsequent global amelioration of the climate coincided with a major eustatic sea level rise and widespread transgressive deposition. The contemporaneous swamps were generally confined to the southern part of the basin until the beginning of the Burdigalian, when the shoreline suddenly regressed in a north(west)ern direction and the bordering coastal swamps prograded in the same general direction (Sissingh, 2003a). At the end of the Burdigalian, eustatic lowering of the sea level induced a particularly pronounced and brief progradation of the coastal plain. Contemporaneously with this rapid and major seaward shift of the coastline and the adjoining coastal marshes (i.e., 'forced regression'), an extensive brown-coal deposit, the Morken Seam, was deposited (Sissingh, 2003a). Following major eustatic marine flooding of this short-lived coastal-lowland, the terminal Langhian Frimmersdorf Seam developed under similar, regressive environmental circumstances.

Marine communication between the Hessen Depression and the Upper Rhine Graben ceased from the early Chattian onwards (Appendix 7). From this time onwards, the eastern branch of the Rhenish Triple Junction became increasingly continental (Meiburg & Kaever, 1986). Swamps re-appeared in the Hessen Depression at the end of the Chattian, as indicated by lignites (Appendix 7). During the Aquitanian-Burdigalian, fluvial sands were laid down in most parts of the Hessen Depression (Appendices 7 and 8). It seems that the sea returned into the basin for the last time during the Langhian (Figs 8 and 9; Encl.s 5; Appendix 9; Sissingh, 2003a).

During the Serravallian, deposition in the Upper Rhine Graben proceeded in exclusively non-calcareous, largely lacustrine facies. Minor streams draining bounding highs seem to have supplied the sandy clastics to the graben. Following a period of non-deposition/erosion during the early Tortonian, fluvial clastic sedimentation resumed during the Tortonian to Messinian. The deposits were for the main part supplied by the river Rhine, which by then flowed northwards from the Vosges across the Rhenish Massif to the Lower Rhine Embayment and North Sea Basin. The predominance of fluviatile deposition after a period of regional uplift and erosion is attributed to continuing widespread tectonic activity during the early Tortonian (Sissingh, 1998, 2003a).

At the very beginning of the Miocene, deposition in the Rhône Graben was characterised by the accumulation of lacustrine limestones (Sissingh, 2001). Together with relatively marly deposits, they represent a land-locked palaeogeographic system that included some very large lakes. In the south, marine depositional conditions prevailed in the gradually northward-prograding Gulf of Lions, an embayment which was bordered in the east by the southeastward-rotating Corsica-Sardinia block. From the Aquitanian-Burdigalian transition onwards, the Rhône Graben was again palaeogeographically strongly modified under influence of regional tectonics and a rapidly progressing eustatic transgression from the south (Sissingh, 2001, 2003b). The southern part of the Rhône Graben subsided and became part of a Lower Rhône Archipelago (Demarcq, 1984). Concurrently, the Cucuron-Valensole Basin developed east of the Durance Fault. The northern and central parts of the Rhône Graben as well as the Massif Central were tectonically uplifted. In this adjacent region, it initiated strong erosion and accompanying deposition of sands by an intra-graben system of northward-flowing rivers (Sissingh, 2001). As a consequence of this tectonic activity, the initial Burdigalian ingression of the sea from the Gulf of Lions did not reach the central and northern parts of the Rhône Graben. Within the structural confines of the graben, the marine incursion proceeded during the early Burdigalian only till some distance south of Valence. Contemporaneously, however, a northward-directed transgression seems to have established a marine corridor between the Gulf of Digne and the North Alpine Molasse Basin, close to the western front of the Alpine orogenic wedge. During the late Burdigalian, a seaway with tidal currents eventually developed from the Gulf of Lions across the Valence Basin towards the North Alpine Molasse Basin. *Avicennia* mangroves, which had existed since the late Aquitanian, occurred along the newly defined shorelines of the Gulf of Lions. In the east, the evolving seaway was connected with the marine Paratethys, from which basin the North Alpine Molasse Basin was also transgressed during the early and late Burdigalian. Langhian to Serravallian deposition was controlled by a northward-directed marine incursion into the terrestrial central and northern parts of the rift (Sissingh, 2001). Tides occurred in this time-transgressively enlarged area of marine sedimentation, like in the preceding Burdigalian seaway. Littoral sands and conglomerates were the most common deposits. Deltaic fans of conglomeratic material predominated deposition in the Valence Basin and near the Alpine thrust front, farther to the (north)east. In the contemporaneous Gulf of Lions *Avicennia* mangroves still occurred during the Langhian, in association with offshore coral reefs. In the Massif Central intra-graben rivers continued to carry sandy erosional products northwards (Appendices 8 and 9).

In the Rhône Graben, the sea regressed eustatically around the Serravallian-Tortonian transition. As a result, brackish-water and fluvio-lacustrine, mainly clastic sediments were deposited in the northern section of the graben, with conglomerates more common in the central graben segment where littoral marine conditions continued until the early Tortonian. Depositional conditions became increasingly continental during the Tortonian. The accompanying southward retreat of the sea is evidenced by the accumulation of prograding conglomerates and lignite-bearing strata. These sedimentary changes may be related to a general uplift of the Rhône Graben area rather than to a persistent drop in global sea level (Sissingh, 2001). The regional uplift may have included the Massif Central, where a large fluvial system continued to drain the old high towards to north (Appendix 9). The Valensole Basin became more discrete and continental during the late Tortonian, in association with tectonic uplift of the Vaucluse High in the west and advancement of Alpine thrust sheets in the east (Ford et al., 1999). The continentalisation of the Rhône Graben and other, surrounding basins climaxed in the Messinian, when erosion and non-deposition became suddenly dominant over sedimentation due to the terminal Miocene drying out of the Mediterranean Basin. A widespread and intensely erosive palaeohydrographic system of overall southward-discharging rivers and minor steams was established in response to the Mediterranean salinity crisis during the late Messinian. It resulted, amongst others, in definitively establishing the Rhône as the major river draining the region of the western North Alpine Molasse Basin and the adjacent Alps, as well as the West Alpine Foreland area as far as it comprised the central and southern Rhône Graben segments. These major changes in palaeogeography coincided with a terminal Miocene phase of enhanced tectonics, which basically affected all of peri-orogenic eastern France (Sissingh, 2001). Tectonic activity during the Late Miocene is especially represented by the westward-directed thrusting of the crescent-shaped Jura and the Vercors over the eastern margins of respectively the Bresse Graben and the Royans Basin, in conjunction with a general re-emplacement of the Subalpine Chains (Encl. 2; Laubscher, 1992; Becker, 2000). At the same time, the Valensole Basin became an important land-locked locus of detrital deposition (Ford et al., 1999).

In the southern part of the former Paris Basin, the Beauce Lake desiccated in response to cessation of thermal subsidence and Middle Euralpine intra-plate compression and tectonic uplift that also affected the Massif Central at the Aquitanian-Burdigalian transition (Sissingh, 2006). After the deposition of shallow-water lacustrine limestone and marl in the Aquitanian (Wattinne et al., 2003), and the development of a base-level unconformity and the establishment of a regime of fluvial sediment bypassing in the domain of the closed Paris Basin at the beginning of the Burdigalian, the massif became the source of 'Bourbonnais s.l.' clastics (Sissingh, 2001) which were transported towards the Loire and Ligerian basins by the Cher and Loire rivers until the end of the Late Miocene (Fig. 7; Appendices 8 to 10; Mégnien & Mégnien, 1980; Tourenq & Pomerol, 1995).

Pliocene

All along the Upper Rhine Graben tectonics were strongly re-activated during the Early Pliocene. Coeval sediments are (mostly) absent as a consequence of uplift and erosion/non-deposition. Overlying the corresponding unconformity, deposition of fluvial and limnic facies resumed during the mid-Pliocene in response to a new phase of rifting of the Upper Rhine Graben. In the south, conglomerates were deposited by a palaeo-Aare-Doubs river system which extended from the Alps to the Bresse Graben (Villinger, 1998). At about the same time, the modern Rhine river was established in association with a tectonic modification of the palaeohydrography of the North Alpine Foreland (Petit et al., 1996).

In the Rhône Graben, a similar Early Pliocene phase of tectonic uplift and erosion was followed by renewed rifting (Rat, 1984). The Bresse Graben became a fluvio-lacustrine complex with swamps, in which deltaic sands and conglomerates, as well as lignite-bearing marls, accumulated (Sénac, 1981; Bonvalot et al., 1984). The coarser-grained clastics mostly originated from the Alps and were laid down by the palaeo-Aare-Doubs and Rhône rivers. Fluvial conglomerates occurring along the western margin of the Bresse Graben were derived from the adjacent part of the Massif Central. Marine and brackish environments of deposition were totally absent in this part of the Rhône Graben. However, a short distance south of Lyon, marine clastics were deposited in a S-N orientated ria system that stretched all the way from the Gulf of Lions (Ballesio, 1972). This ria system developed in the incised Rhône valley in response to the opening of the Gibraltar Strait at the Miocene-Pliocene transition and the subsequent marine flooding by the Atlantic Ocean of the dried-out Mediterranean Basin.

Post-Miocene uplift of highs, continuing development of volcanic build-ups and progressing erosive effects of rivers further enhanced the palaeomorphology of the Massif Central (Sissingh, 2001). The pre-existing river system with northward-directed discharges of clastics was maintained. North of the massif, it included the Pre-Seine and the Cher, as the most important rivers draining the massif (Tourenq & Pomerol, 1995; Larue & Étienne, 1998). The Lot, Aveyron, Viaur and Tarn continued to flow westwards across the Aquitaine Basin, depositing an extensive alluvial fan near to the Atlantic coast at the final Tertiary stage of the westward propagation of the Aquitaine continental-shelf and -slope deposition (Simon-Coinçon, 1993; Dubreuihl et al., 1995). Meanwhile, the Ardeche continued to drain the rising high towards the east as it had done since the late Miocene (Appendix 11).

Concluding palaeogeographic remarks

The syn-kinematic palaeogeographic evolution of the West European Platform encompasses many rapid changes in the depositional environments of the sedimentary basins, as evidenced by their very varied stratigraphic records. Small changes in the tectonic setting and restricted fluctuations of the relative sea level induced widespread changes in the generally filled to overfilled, shallow-water basins. Time and again, narrow saline passages between basins were established and successively disrupted in response to such events (Figs 8 to 10). These passages formed frequently during the Early Oligocene and Early Miocene and disappeared permanently during the later Miocene (Fig. 11), with the notable exception of the Pliocene flooding of the Rhône Graben. The resultant late Cenozoic continentalisation (Appendices 9 to 11) may reflect a tectonomagmatic emergence process that was a consequence of platform-wide underplating (magmatic thickening of the lithosphere). The igneous underplating would have been induced by widespread mantle upwellings, possibly subsequent to Late Cretaceous-Paleogene sub-lithospheric plume channelling that propagated from the eastern Central Atlantic Ocean to Central Europe (Hoernle et al., 1995; Oyarzun et al, 1997; Goes et al. 1999). The subsequent uplift of the platform was associated with Miocene volcanism in the Hegau, Urach and Kaiserstuhl regions and with increasing mantle plume-type volcanism in the Massif Central, Rhenish Massif and Hessen Depression (Sissingh, 1997, 2001, 2003a, 2006). However, a comparable increase in volcanic activity is not evident in the Bohemian Massif (Kasiński, 1991). The accompanying thermal expansion of the lithosphere contributed to the tectonomagmatic elevation of the platform. In addition, the epeirogenic rise and the concurrent exhumation and fluvial denudation of the platform was enhanced by a long-term lowering of the global sea level (Haq et al., 1988). The temporally and spatially differentiated uplift (underplating) that ultimately shaped continental Western and Central Europe was presumably also positively affected by flexural fore-bulge deformation (Laubscher, 1992) or compressional folding (Ziegler et al., 2002). In addition, the 'post-compressional' unflexing of the subducted European Plate that has been postulated to explain the post-molasse uplift of the North Alpine Foreland Basin and the Alps (Andeweg & Cloetingh, 1998) was also of importance. In the latter case, mantle upwelling seems to have terminated mantle downwelling beneath the Alpine orogen. As another conjecture of this paper, it is suggested that the Late Tertiary continentalisation of Western and Central Europe, including the progressive updoming of the Armorican Massif, Massif Central, Burgundy Swell, Vosges, Back Forest and the Rhenish and Bohemian massifs (Ziegler, 1994), is ultimately linked to the Late Cretaceous onset of seafloor spreading and mantle upwelling in the Central Atlantic domain. Post-Early Eocene crustal extension and weakening of the West European Platform facilitated NNE-migration of the mantle upwelling and igneous underplating of the European lithosphere until their completion in the Miocene. Decreasing compression and shortening of the platform in response to diminished Middle to Late Euralpine collision forces (accompanied by reduced convergence of the Apulian and European plates) may until the Plio-Pleistocene have contributed to the uplift. By then, interaction of Apulian-European collision forces and North Atlantic ridge-push forces resulted in the increased subsidence of North Atlantic, Mediterranean and European basins – inducing in part re-activation of rifting (Sissingh, 2003b, 2006). This very wides-pread event was also accompanied by stress-induced lithospheric deflections that induced localised inversion of basins and enhancement of palaeoreliefs in the general area (Cloetingh & Kooi, 1992). Alkaline volcanism peaked again during this period in the Eifel and Westerwald regions, Hessen Depression, Cheb Graben and Massif Central (Sissingh, 2001, 2003a, 2006). Thus, diminishing Middle to

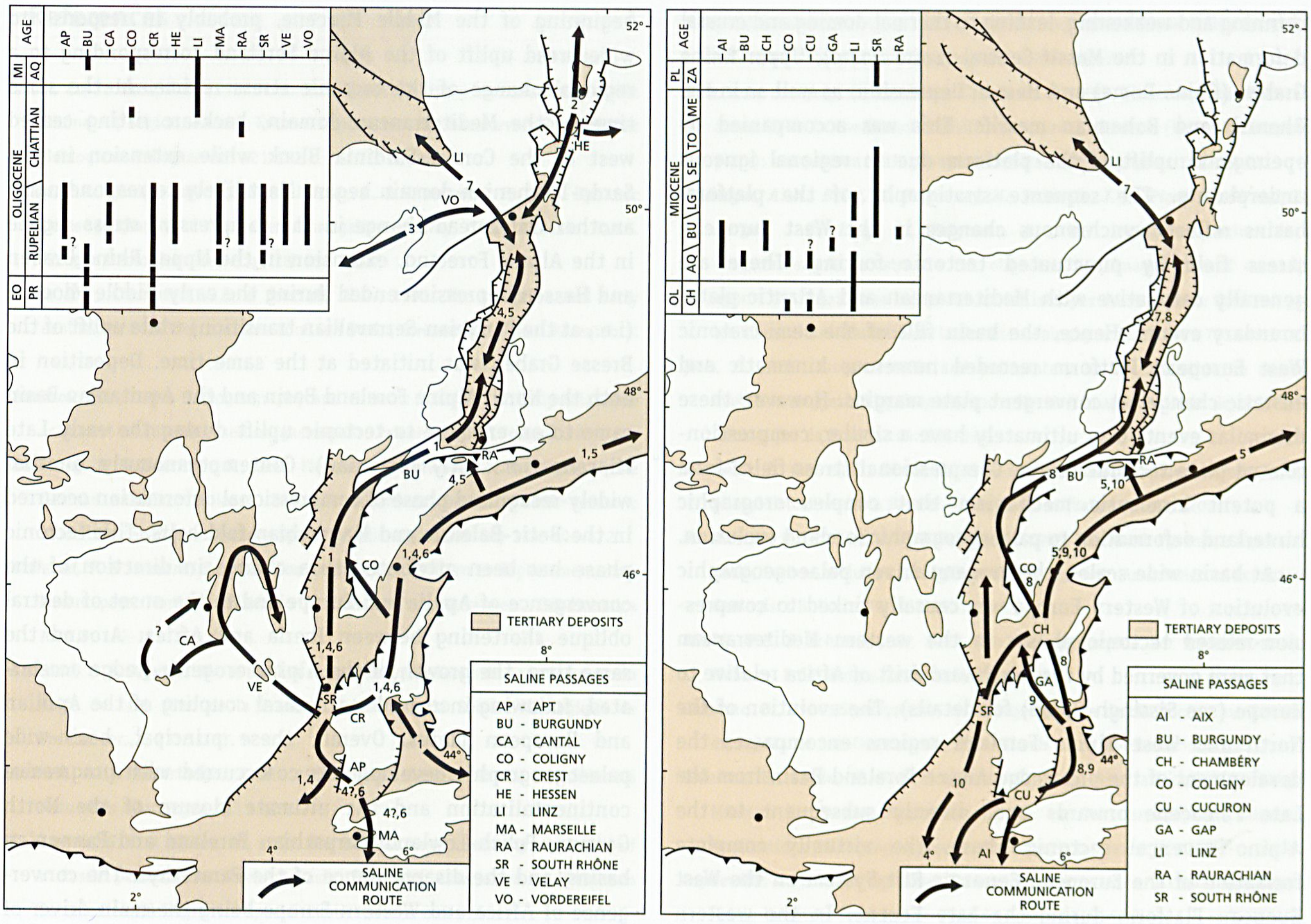

Fig. 11. Schematic map of saline passages and communication routes of the North and West Alpine Foreland domains during the Late Eocene-Early Pliocene (also see Fig. 9 for legend).

Late Euralpine orogenic events in the Alps correlate with increasing epeirogenic movements in the West European Platform. Though the overall importance of the plate-kinematic and tectonomagmatic events as key controls on the evolution of the platform are considered to be well established, many details remain to be resolved.

General conclusions

The changes of the kinematic stress fields that were caused by plate-tectonic re-organisations at the contacts of the African, Apulian, Iberian and European plates had far-reaching impacts on the tectonic evolution, basin stratigraphy and palaeogeography of the West European Platform. A sequence of first-order formative stages in the structural, palaeotopographic and palaeohydrographic development of the platform can be distinguished from the Paleocene initiation of the Alpine Foreland Basin onwards. These stages are closely linked to the plate-boundary events that drove the development of the Pyrenean and the Alpine orogens. In conjunction with changes in relative sea level, episodic block movements along crustal fractures were an important control on the development of the platform basins. The flexurally-controlled isostatic subsidence of the peripheral North Alpine, West Alpine and North Pyrenean foredeeps was not until the Early Oligocene compensated for by large-scale supply of sediments. Only when compression-controlled thrust-wedge mass accretion, propagation and erosion achieved, in combination with eustatic sea-level changes, a balance between tectonic subsidence and sediment supply could the Alpine and Pyrenean molasse basins be filled to overfilled. In contrast, the European Cenozoic Rift System was filled to overfilled with sediments from its Middle Eocene inception to the present-day, albeit with sizable periods of non-deposition. The rift evolved structurally by syn-kinematic subsidence along normal and strike-slip faults. As for the foreland basins, their subsidence was enhanced by sediment loading. Overall, the external shape of the individual, generally asymmetric grabens (i.e., the geometry of their bounding master faults) reflects the externally imposed tectonics (i.e., the main direction of extensional plate stresses). Palaeogeographically, the evolution of the basins was also strongly influenced by relative changes in sea level. Pre-existing basement structures such as trans-lithospheric shear zones were important controls on the location of the volcanic centres within the West European Platform. Upwelling of the hot asthenosphere at such zones of weakness may have caused progressive lithospheric thinning and weakening, leading to thermal doming and crustal deformation in the Massif Central (Loire Dome), Upper Rhine Graben (Rhine Dome) and Hessen Depression, as well as in the Rhenish and Bohemian massifs. This was accompanied by epeirogenic uplift of the platform due to regional igneous underplating. The sequence stratigraphy of the platform basins reflects synchronous changes in the West European stress field by punctuated tectonic forcing. These are generally correlative with Mediterranean and Atlantic plate-boundary events. Hence, the basin fills of the semi-cratonic West European Platform recorded numerous kinematic and eustatic changes at convergent plate margins. However, these dissimilar events may ultimately have a similar, compression-related plate tectonic origin. Compressional stress fields form a potent kinematic mechanism that couples orographic hinterland deformation to palaeogeographic foreland evolution.

At basin-wide scales, the orogeny-driven palaeogeographic evolution of Western Europe was causally linked to compression-related tectonic phases in the western Mediterranean that were governed by the northward drift of Africa relative to Europe (see Sissingh (2006) for details). The evolution of the North and West Alpine Foreland regions encompasses the development of the pro-wedge Alpine Foreland Basin from the Late Paleocene onwards and, directly subsequent to the Alpino-Provençal tectonic phase, the virtually complete formation of the European Cenozoic Rift System on the West Euopean Platform during the Late Eocene. In the western Mediterranean the episode of major rifting coincided with the closure of the Piemonte-Ligurian-Alboran Ocean during a collision climax induced by the north-south convergence of Apulia and Iberia with Europe. This was a period of intensified compression, thrusting and crustal shortening along the southern margin of the Alboran-Kabylia Block. The western part of the Alpine Foreland Basin was first closed during the earliest Miocene (i.e., at the Aquitanian-Burdigalian transition), contemporaneous with the end of extension in the Rhône Graben and the closure of the Paris Basin. In the western Mediterranean simultaneous major thrusting in the Betic Cordilleras and Balearic Islands began in tandem with the onset of oceanic spreading in the Liguro-Provençal Basin. These events marked the climactic end of the Pyrenean tectonic phase that was typified by north-south compression of the West European Platform in response to ongoing convergence of Iberia with Europe. They occurred shortly after the mechanical coupling of the Iberian and European plates and the resultant extinction of the Iberia-Europe plate boundary (i.e., during the Aquitanian), causing Iberia to become a part of Europe. This major change in plate-tectonic configuration and plate-kinematic setting resulted in the coeval initial development of the Betic Cordilleras in response to north-south striking compression at the extant Africa-Iberia plate-boundary zone. Final continentalisation of the North Alpine Foreland Basin and the Upper Rhine Graben started at the beginning of the Middle Miocene, probably in response to widespread uplift of the Alpine Foreland corresponding to a regional change of the tectonic stress regime. At the same time in the Mediterranean domain, back-arc rifting ceased west of the Corsica-Sardinia Block while extension in the Sardo-Tyrrhenian domain began. Most likely corresponding to another widespread change in the compressive stress regime in the Alpine Foreland, extension in the Upper Rhine Graben and Hessen Depression ended during the early Middle Miocene (i.e., at the Langhian-Serravallian transition) while uplift of the Bresse Graben was initiated at the same time. Deposition in both the North Alpine Foreland Basin and the Aquitanian Basin came to an end due to tectonic uplift during the early Late Miocene (i.e., early Tortonian). Contemporaneously, another widely-recognised phase of compressional deformation occurred in the Betic-Balearic and Magrhebian fold belts. This tectonic phase has been attributed to a change in direction of the convergence of Apulia and Europe and to the onset of dextral oblique shortening between Iberia and Africa. Around the same time, the growth of the Alpine orogenic wedge accelerated, following increased mechanical coupling of the Apulian and European plates. Overall, these principal, basin-wide palaeogeographic developments co-occurred with progressive continentalisation and the ultimate closure of the North German, Polish Lowland, Carpathian Foreland and Pannonian basins, and the disappearance of the Paratethys. The convergence of Africa and Western Europe being the main driver of all these palaeogeographic changes (Appendix 12).

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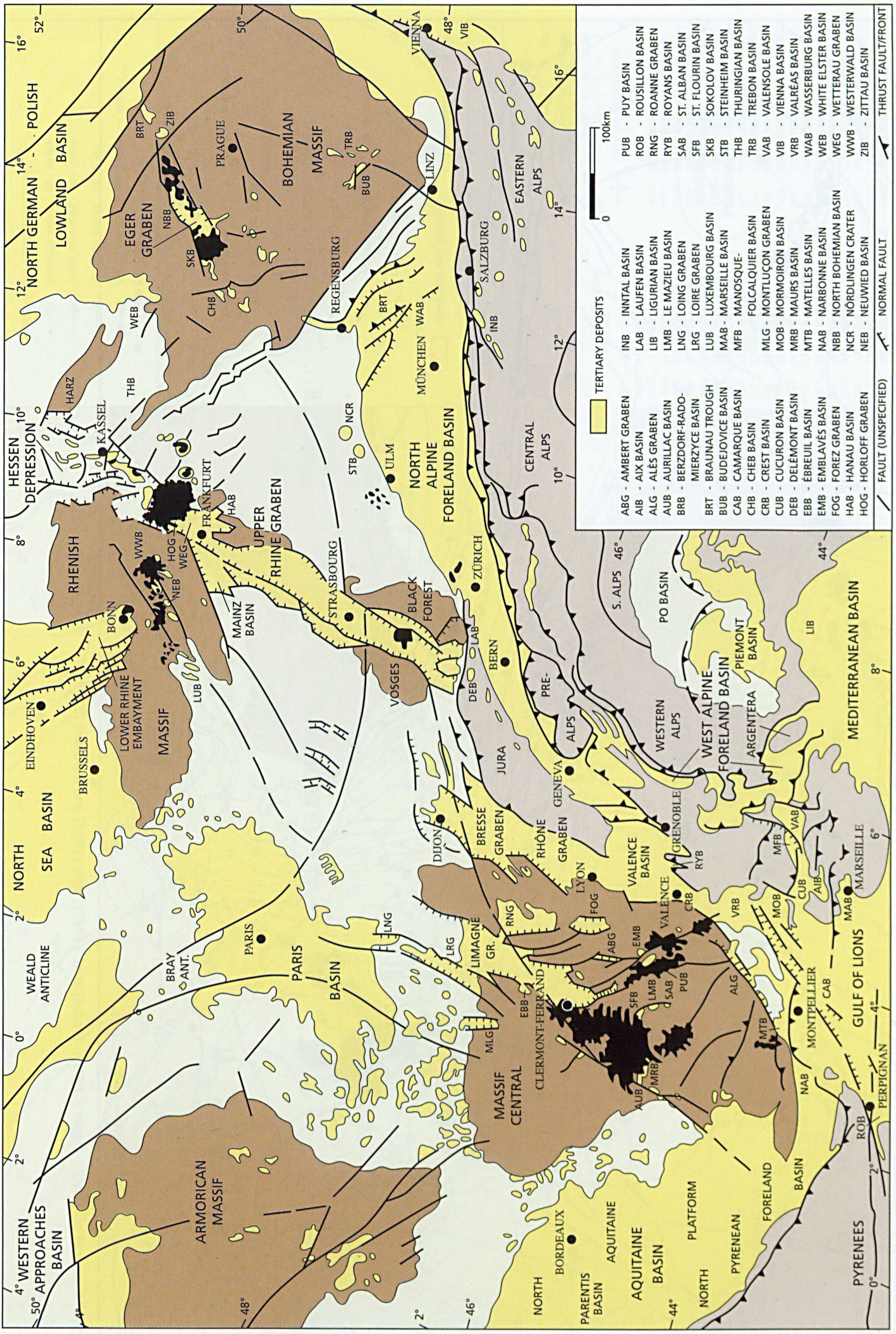
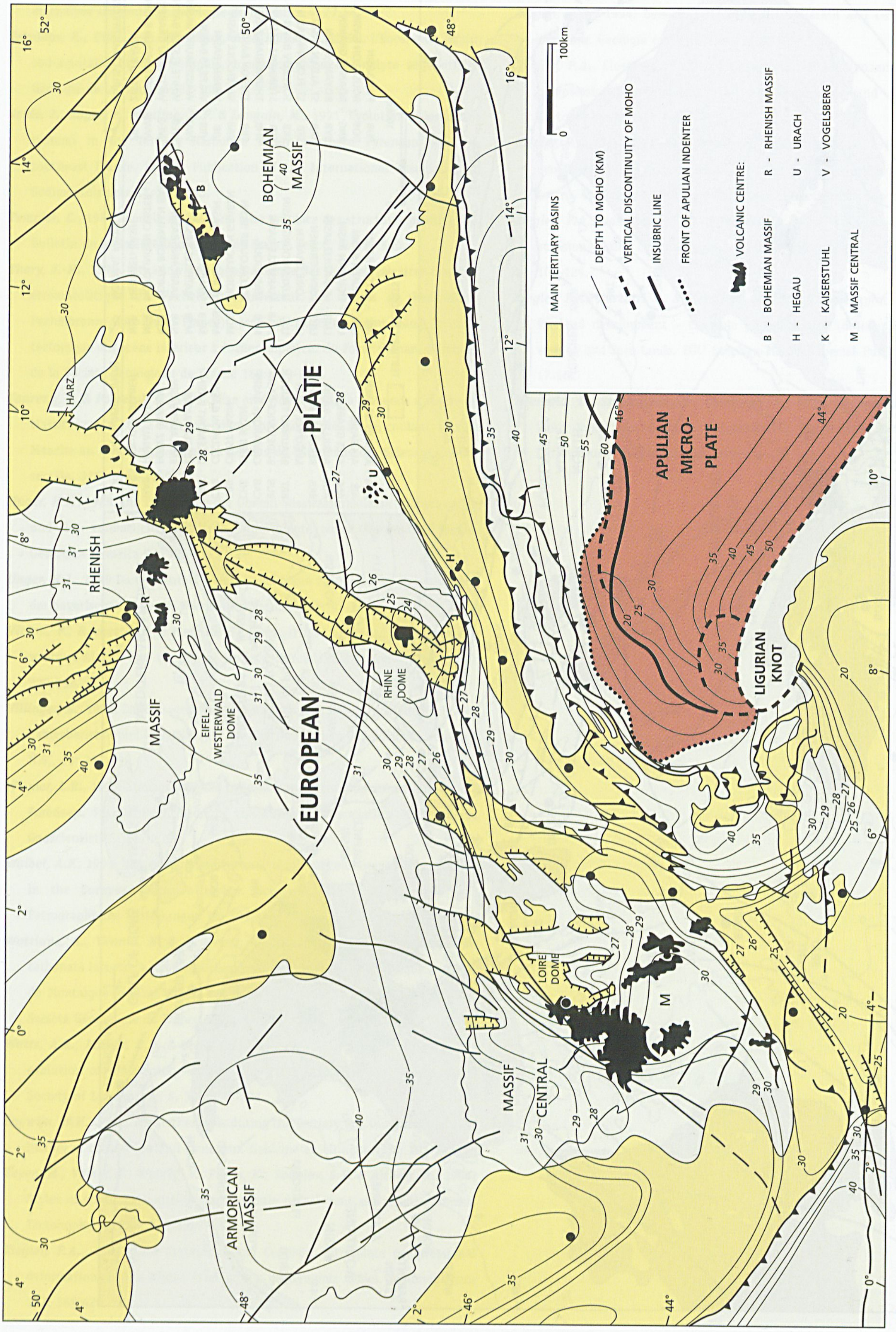
Appendix 1. Tertiary tectonic features and basins of the West European Platform

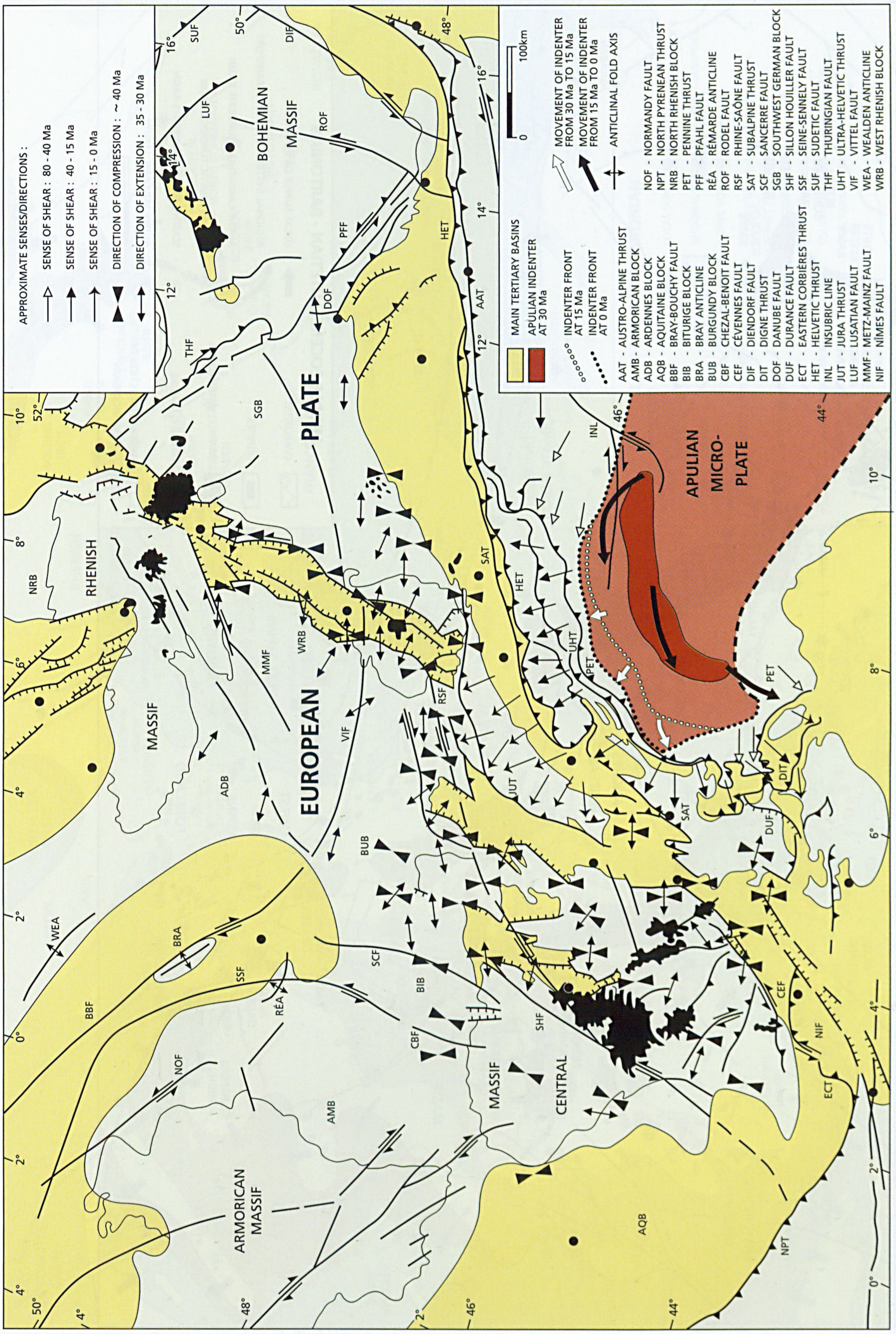


Appendix 2. Tectonomagmatic map of the West European Platform



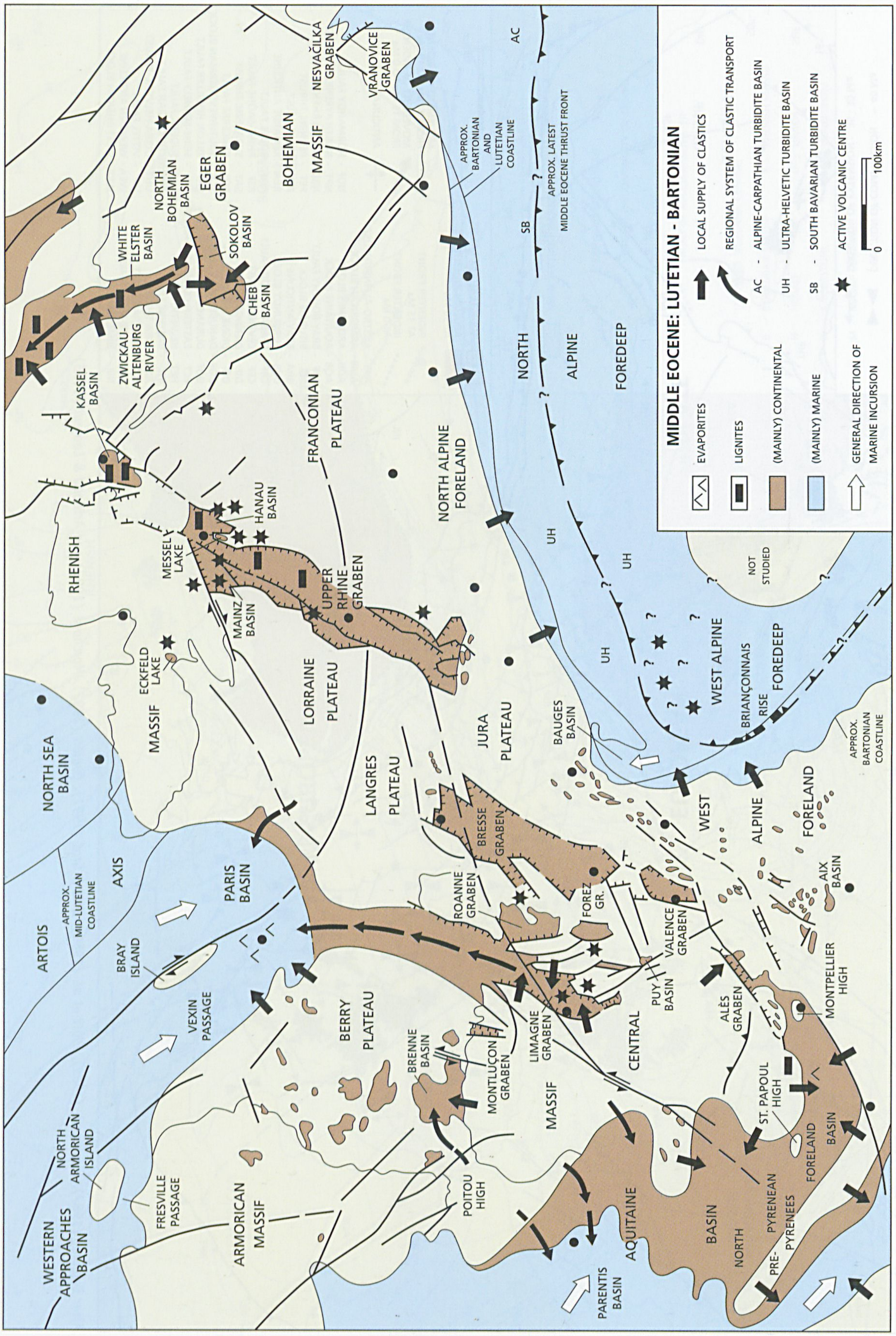
After Meissner et al. (1987), Ziegler (1990), Prodehl et al. (1992), Bois (1993) and Marchant (1993)

Appendix 3. Tectonic stress map of the West European Platform

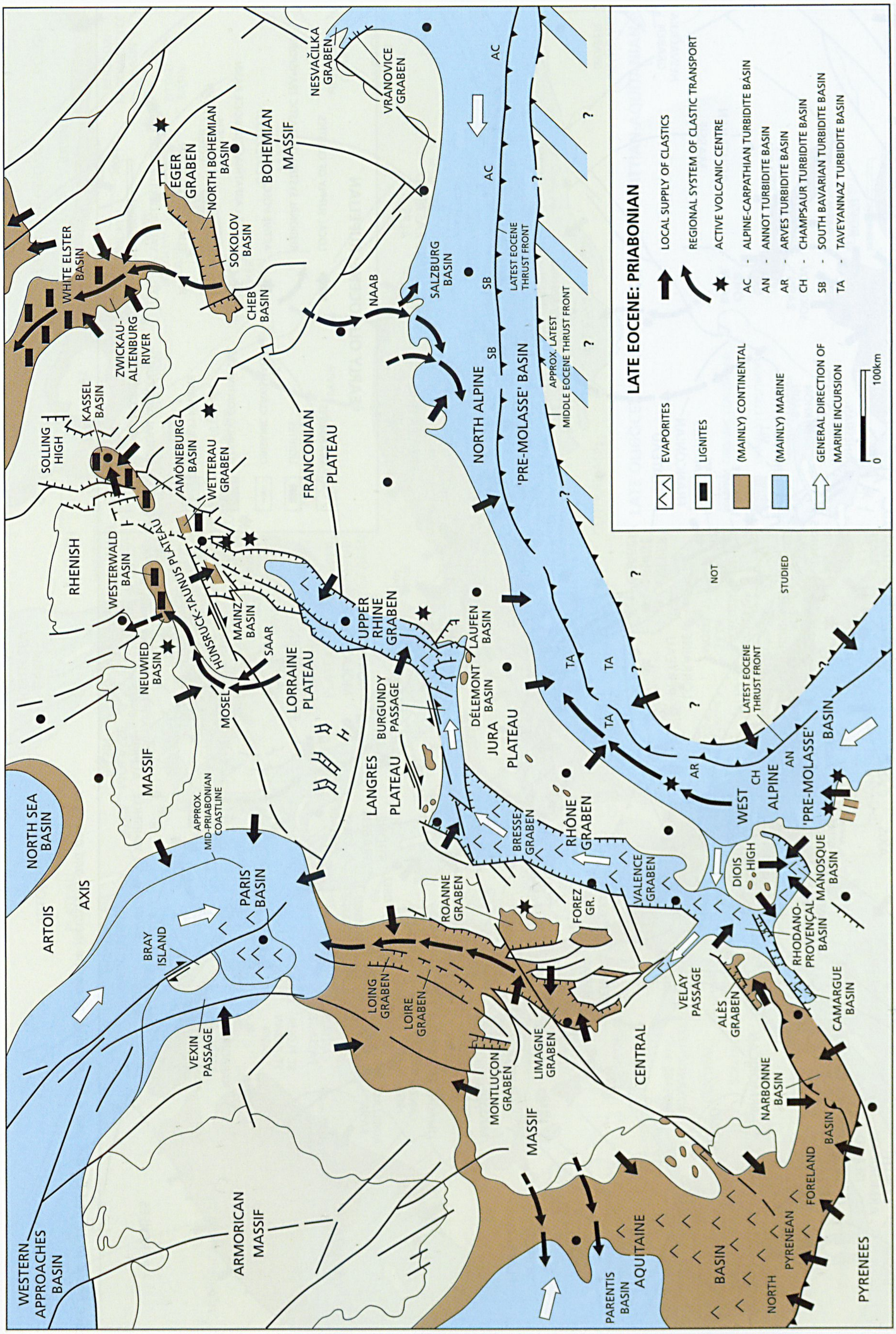


After Bergerat (1987), Blès et al. (1989), Platt et al. (1989), Blès & Gros (1991), Coulon (1992), Marchant (1993) and Arthaud & Laurent (1995)

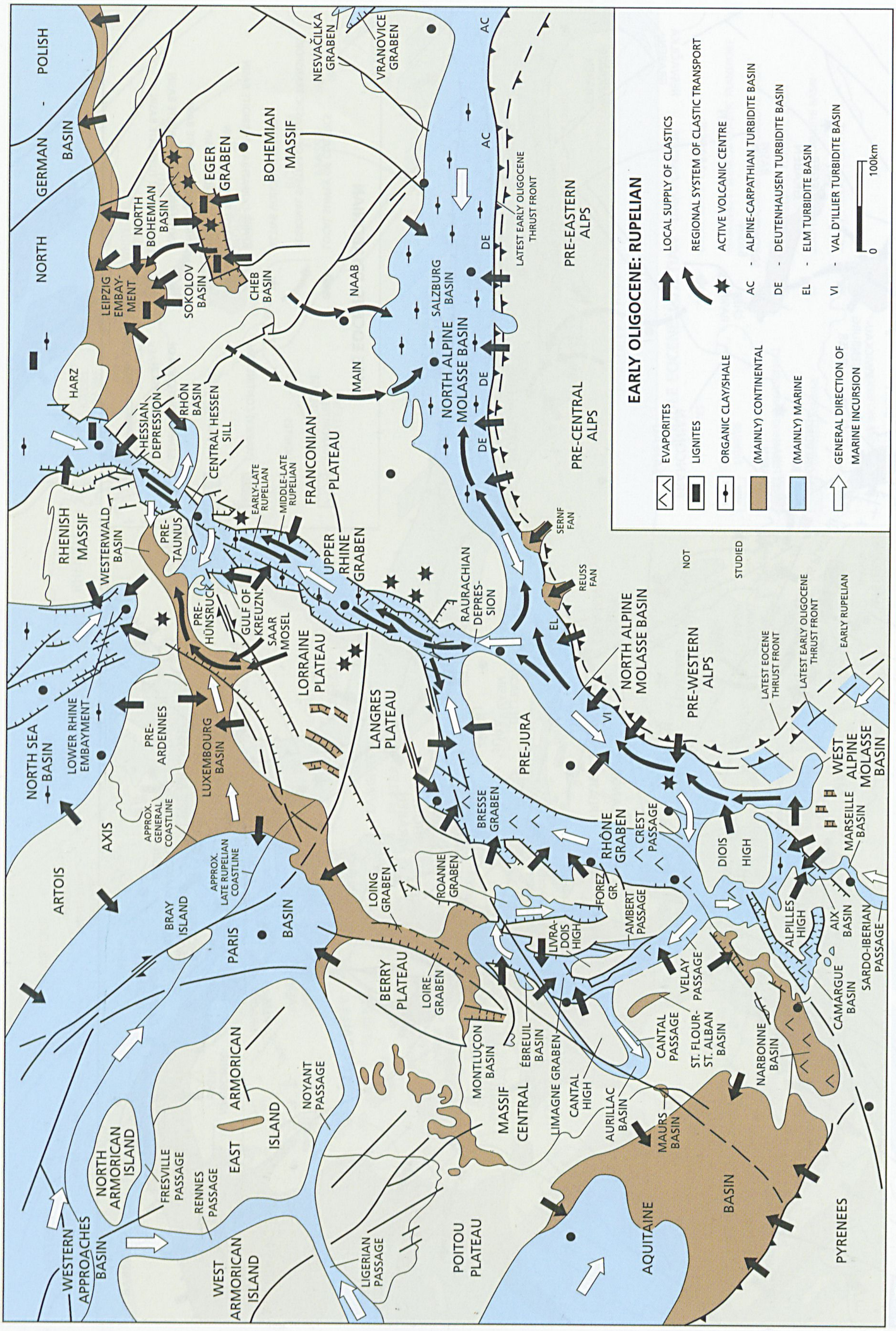
Appendix 4. Lutetian to Bartonian palaeogeography of the West European Platform



Appendix 5. Priabonian palaeogeography of the West European Platform

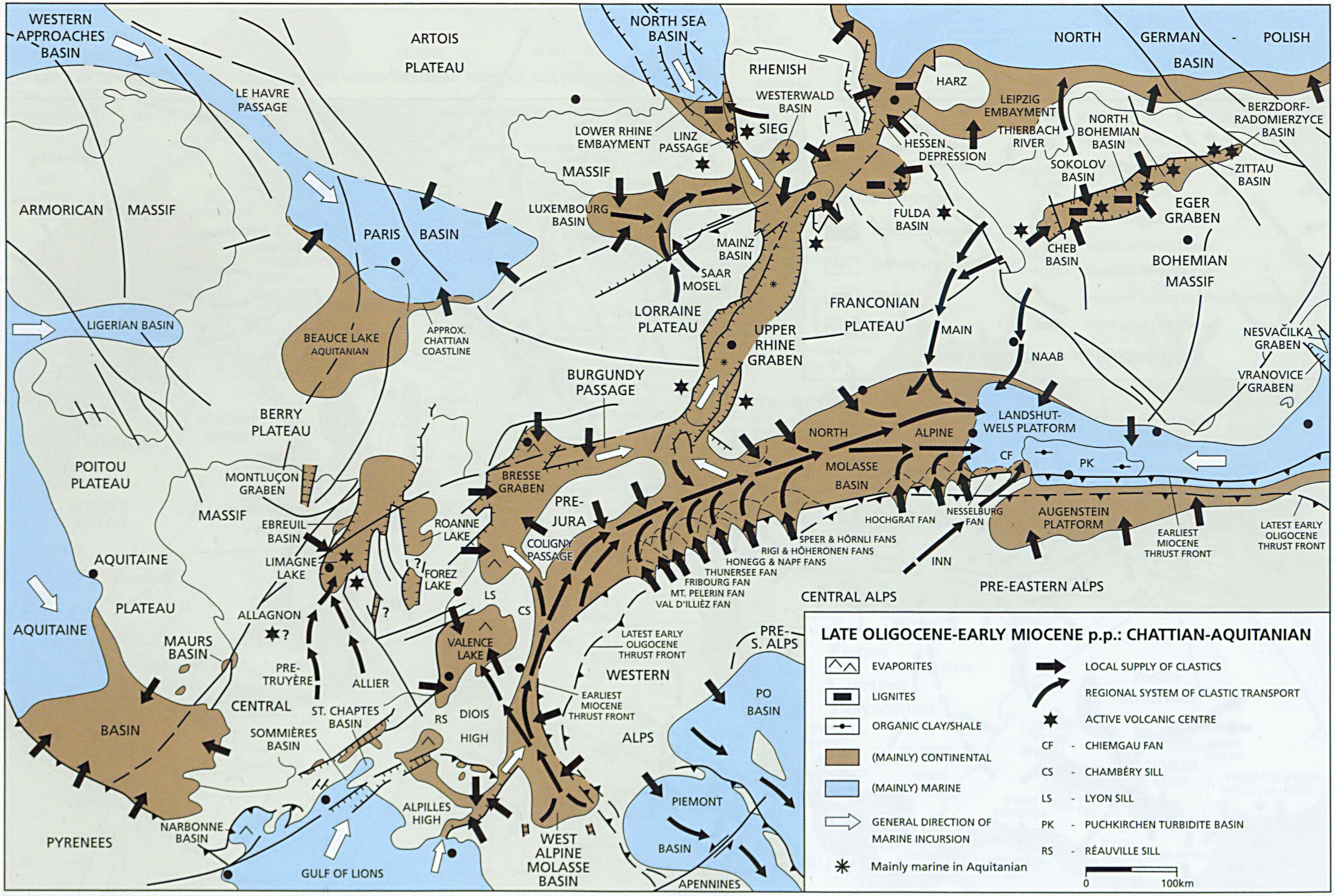


Appendix 6. Rupelian palaeogeography of the West European Platform



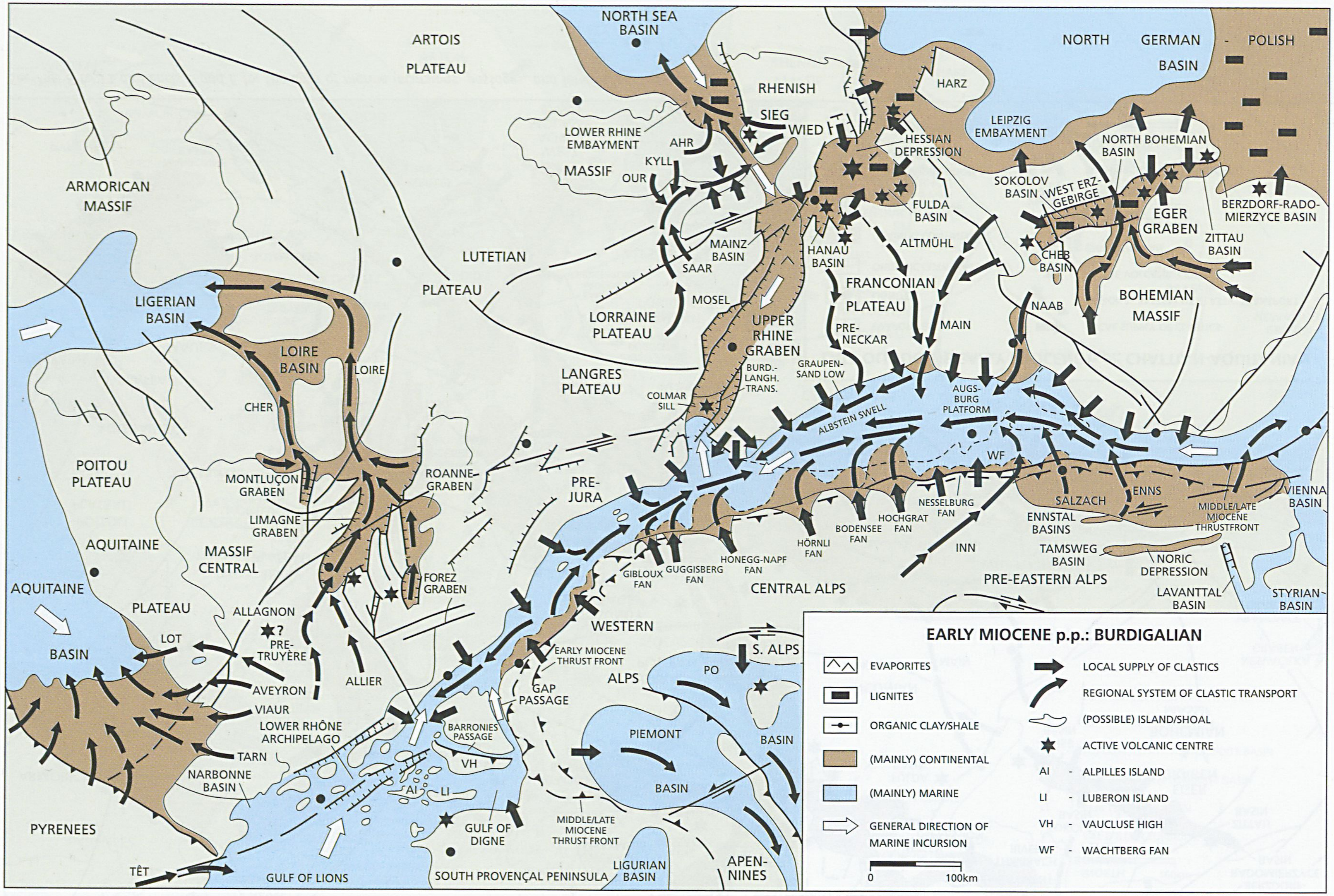
See Figs 8 to 11 and Encls 5 and 6 for the ages of marine incursions and passages

Appendix 7. Chattian to Aquitanian palaeogeography of the West European Platform



See Figs 8 to 11 and Encls 5 and 6 for the ages of marine incursions, passages, and land-locked basins

Appendix 8. Burdigalian palaeogeography of the West European Platform



See Figs 8 to 11 and Encls 5 and 6 for the ages of marine incursions, passages, and land-locked basins

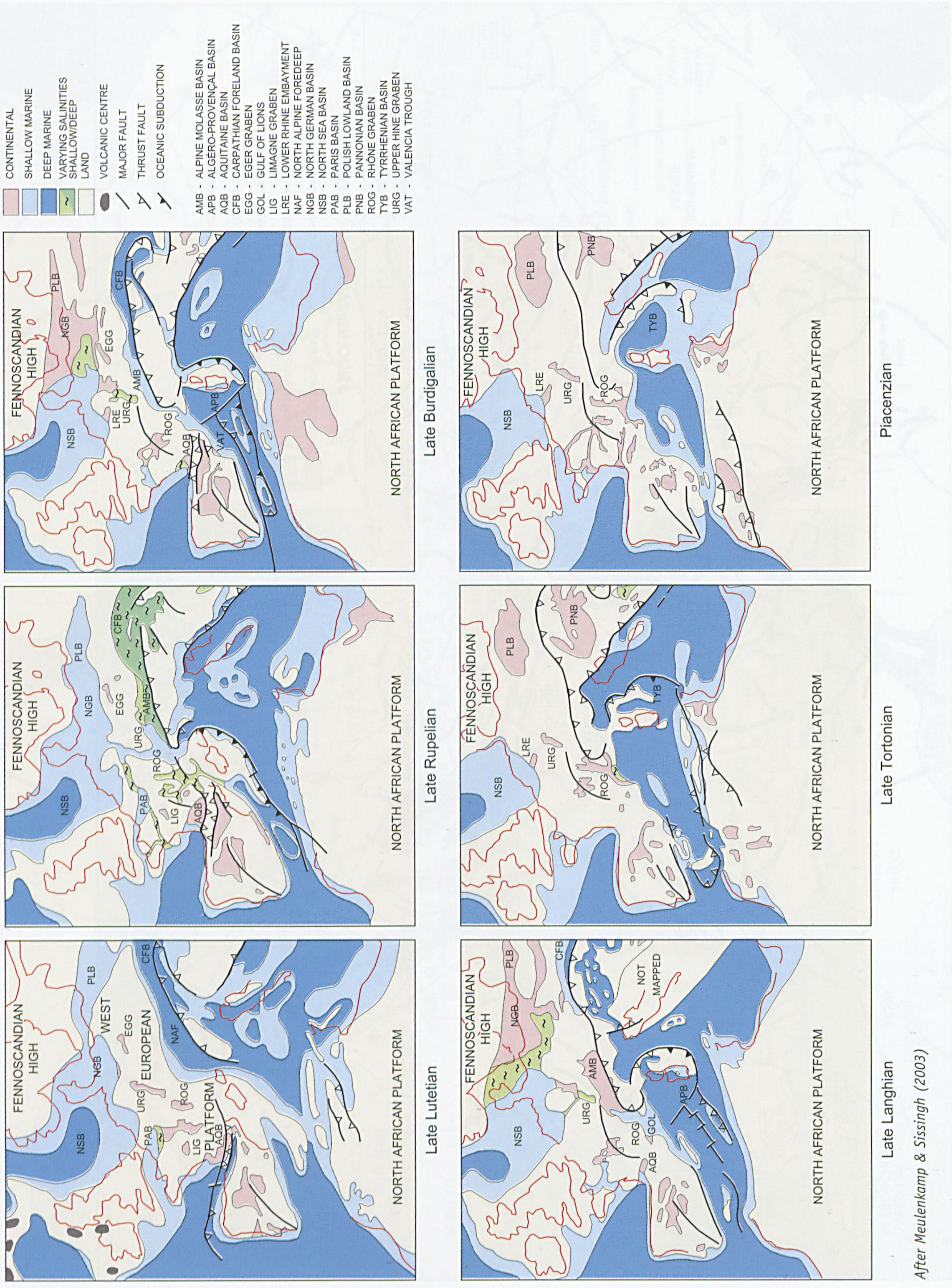
Appendix 9. Langhian to Tortonian palaeogeography of the West European Platform

See Figs 8 to 11 and Encls 5 and 6 for the ages of marine incursions, passages, and land-locked basins

Appendix 10. Late Messinian palaeogeography of the West European Platform

Appendix 11. Zanclean to Piacenzian palaeogeography of the West European Platform

Appendix 12. Schematic maps illustrating the late Lutetian to Piacenzian palaeogeographic evolution of Western Europe and its surrounding areas



After Meulenkamp & Sissingh (2003)