CHAPTER 5 - NEOGENE TECTONIC EVOLUTION OF THE IBERIAN PENINSULA AND WESTERN MEDITERRANEAN

In this chapter the geological evolution of the study area from the Neogene up to present is presented in the same way as the Paleogene evolution has been described in the previous chapter, in maps for every 3Ma. The major tectonic events during the Neogene in the region were, after an initial period of tectonic quiescence, the opening of the Western Mediterranean basin and the collision of Africa and Eurasia (figures can be found in the color section, pages 99-113).

21 Ma, E. Miocene (L. Aquitanian - E. Burdigalian), Figure 5.1

General

Iberia is in a tectonically quiet epoch and based on the available data, it is impossible to reconstruct the stress field. Tectonic activity is concentrated around the onset of sea-floor spreading in the Provençal basin (lasting until about 16.5 Ma), and the onset of opening of the Algerian basin. The first limited compressional deformation of the Iberian foreland related to the collision with the Betics coincides with the first signs of major collision of Africa with the Alboran block. Contemporaneous with the outward thrusting of the Alboran block, its internal parts are under extension.

Detail

Western margin

Along the western margin the Sado Basin is stable and subjected to erosion, in the Lisboan area Miocene sedimentation starts [Pimentel & Azevêdo, 1994] by a transgressive series entering the Lower Tajus basin [Azevêdo, 1991].

Northern margin

Although major deformation offshore Cantabria is ending during the Aquitanian, minor compressional deformation is affecting up to Lower Miocene sediments [Ziegler, 1988]. The Danois Bank is very shallow; the “inner Basin” is deeper [Boillot *et al*., 1979]. Deformation onshore Galicia is inferred from sedimentation in the As Pontes Basin, but this is the last episode of tectonics affecting the basin [Huerta *et al*., 1996]. Within the tectonic setting it seems very likely that the inferred N-S compression [Santanach Prat, 1994] has been active until the Late Oligocene. Alluvial gravels and limestone in the Bierzo Basin indicate a source area far away to W [Martín Serrano *et al*., 1996], which might be the same source area as for the sediments in the As Pontes basin.

Central Iberia

In the Duero Basin E-W extension is inferred from its westward sinking favored by N-S trending normal faults [Santisteban *et al*., 1996b]. But still in the western and southwestern basin no E. Miocene sediments are preserved [Portero Garcia *et al*., 1983], due to an increasing part of the basin that drains towards the W through Portugal [Santisteban *et al*., 1996a]. Along the SSW-Duero (Penaranda-Alba) E. Miocene conglomerate and sandstone, proceeding from the SW, suggest ongoing uplift of the southeastern basin border [Corrochano & Carballeira, 1983b]. The Rioja area is relatively quiet [Muñoz Jiménez & Casas Sainz, 1997]. A folding phase is occurring in the Loranca Basin and a westward prograding sequence of detritical sediments enters the Loranca basin from the Iberian Range [Diaz Molina & Lopez Martinez, 1979].

S. Pyrenees and Ebro

Apart from the active uplift of the Aragonese Pyrenees (Jaca) [Arenas & Pardo, 1996], the only prominent feature is the inferred start of uplift of the entire Pyrenean region due to isostatic re-equilibration [Roure *et al*., 1989].

SE Iberia and Betic realm

Fold development related to N-S to NNW-SSE compression in the Eastern Prebetics [Beets & De Ruig, 1992] is the first sign of the collision of the Betics with the southern Iberian margin. In the same domain, Aquitanian- E. Burdigalian sediments consist of algal limestone, calcarenite and to the east conglomerate [HNPC, 1992] under ~N060^{o} compression [Montenat *et al*., 1996]. The Middle Burdigalian is discordant on top of the former serie, which is another indication of active tectonics [Fontboté & Vera, 1983]. A transgression over the Internal Prebetics might be related to the onset of foreland basin development with typical first stage marine deposits: limestone, sandstone and marl, to the south less detritic, more limestone [Fontboté & Vera, 1983]. In the Subbetics (dispersed outcrops of) bioclastic shallow marine limestone and sandstone are observed, the eastern part of the Subbetics starts its clockwise rotation (up to 130 degrees presently) [Lonergan & White, 1997]. The collision of the Internal and External zones (Subbetics and Malaguide) is revealed by the sedimentary evolution in the Espejos Basin. First, the Aquitanian Solana formation, which contains submarine fans, is in close connection with the Malaguide (where major thrusting occurs) but still far removed from the Subbetics [Geel, 1996]. Whereas, in the E. Burdigalian Espejos basin (a deep basin on the suture) detritus from Subbetics, Malaguide AND Alpujarride shows the start of collision of Internal and External zones [Geel, 1996]. The Intermediate Units, the units in between the Internal and External zones, show a foreland basin setting with deposition of sandy limestone. Bathymetry is deepest in these Intermediate Units and in the southernmost part of Internal Prebetics [Fontboté & Vera, 1983].

The internal Alboran experiences a first rifting episode [Platt & Whitehouse, 1999], associated subsidence led to a westward transgression over emerged lands, depositing the first marine sediments [Comas *et al.*, 1992]. This rifting is parallel to the regional axis of shortening (WSW) [Martínez-Martínez & Azañón, 1997], further proven by the intrusion of a basaltic dike swarm at 23-22 Ma [Priem *et al.*, 1979] suggesting E-W trending rift (back arc spreading) [Torres-Roldan *et al.*, 1986]. The subduction stopped shortly after this intrusion [Zeck *et al.*, 1992]. The start of rapid cooling of the Alpujarride [Lonergan & Johnson, 1998] and the surrection of relieves in the Malaguide and related syntectonic deposits (Alazoina, Ciudad Granada formations) [Fontboté & Vera, 1983]. Compression in the Ghomaride is ceasing [Maate, 1996].

The Dorsalian is emerged and forms a relative narrow and probably discontinuous ridge, separating the new Mediterranean from a southern basin [Durand Delga & Olivier, 1988]. The "brechas de Nava", discordant polygene continental breccias deposited in the External Dorsal indicate an earlier phase of deformation [Fontboté & Vera, 1983] that led to the development of this ridge. During the E. Burdigalian marly pelite with silex is dominant in the Predorsalian [Fontboté & Vera, 1983].

Catalan-Sardinian margin

While in the CCR synrift stage sedimentation in Valles Penedes [Roca *et al.*, 1999], and in the Valencia Trough foreland limited lower Miocene continental sedimentation indicate an extensional setting [Martínez del Olmo, 1996], compressional deformation is active in the Baleares [Bakker, 1988]. On Mallorca northwestward thrusting results in unstable platform deposits [Ramos-Guerrero *et al.*, 1989], littoral sediments and conglomeratic wedges on Mallorca. The Mallorca/Menorca block rotates 20 degrees clockwise since the timing of magnetization (prior to Oligo-Miocene) but before upper Miocene. This rotation might be related to the thrusting on Mallorca [Freeman *et al.*, 1989] or the opening of the Liguro-Provencal Basin. Burdigalian marine deposits cover a paleorelief [Pomar Goma, 1983].

The rotation Corso-Sardinian Block occurs in a short time span between 20.7 and 18.6 Ma [Hippolyte *et al.*, 1993] or 21 and 16.5 Ma [Roca, 2001]. Calc-alkaline volcanism related to the retreating northwestward subduction, enabling the rotation of Corsica/Sardinia, is observed in the Valencia Trough [De Ruig, 1991] and along the edges of the Sardinian extensional basin [Bois, 1993]. In between the subduction front and counterclockwise rotating Sardinia, the Sardinia/Maghrebian Chain develops to the southeast of Sardinia. Progressive foreland basin sediments are being deposited in front of an E-SEward advancing chain, from time to time overriding its own marine foreland sediments [Catalano *et al.*, 1995]. On Corsica/Sardinia the last transpressive (??) tectonics (up to Aquitanian sediments in pull apart basins) are observed [Carmignani *et al.*, 1995] but in Alpine Corsica mesoscopic normal faults lead to formation of clastic sedimentary basins [Egal, 1992]. A new active rifting phase is documented for the Sardinian rift basin [Monaghan, 2001].

N. Pyrenees and SW France

In southern France, the Late Oligocene active rifting induced subsidence is diminishing, but late stage subsidence lowers many of the littoral basins to below sea level. The southernmost structures still show limited active extension: the graben of Rosselo is still developing along Tet and Tec faults, filled by continental and small marine fluxes [HNPC, 1992] and in the Narbonne basin extensional reactivation of St Chinian frontal thrust is still active [Roure *et al.*, 1994]. For the rest of the basins, however, post-rift marine sediments are being deposited over the synrift sequences. In the Herault basin slight erosion is probable: Burdigalian marine sediments unconformable rest on top of the synrift deposits [Sérrane *et al.*, 1995]. In the Valréas Basin marine infill is related to post-rift thermal subsidence as well [Roure & Coletta, 1996]. In the Nimes/Camarque Basin an erosion surface is formed between synrift Aquitanian and onlapped by post-rift Burdigalian marine sediments [Sérrane *et al.*, 1995] and a little more distal: in the Valensole plateau and Manosque the last episode of sedimentation occurs (extension ~stopped) [Roure & Coletta, 1996]. In the German part of the northern Alpine foreland basin, continental molasse deposition or even erosion occurs [Andeweg & Cloetingh, 1998].

S. Alps - Adriatic domain

In the Gonfolite basin an Early-Middle Burdigalian erosional hiatus is observed [Bersezio *et al.*, 1993], related to active thrusting [Ziegler *et al.*, 1996].

N. Africa

The Kabylian units are seperating from the Baleares and approaching the African margin and even obducted as nappes onto the Tellian Margin [Wildi, 1983], [Ziegler, 1988]. This emplacement results in the start of the development of foreland type basin, in which more than 1500m of Neogene deposits will accumulate. The entire Northern African Flysch Trough experiences south directed contraction [Martínez-Martínez & Azañón, 1997]. The Rif of Morocco starts to develop as a paleohigh, depositing the Acilah sandstone with southern provenance to north of it. Compressional tectonic activity is reported for the S. C. High Atlas as well. The Zoumi sandstone unit is deposited to the north [Morley, 1987] and southward overthrusting of the chain results in uplift with associated subsidence of the Ouarzazate (foreland) basin (becoming less open marine) [Görler *et al.*, 1988]. Uplift of the Subrif chain is evidenced by AFT data [Azdimousa *et al.*, 1998].

18 Ma, E. Miocene (L. Burdigalian), Figure 5.2

General

Extension in the Ligurian and Algerian basins is coming to an end, but is still active along the basin borders in the Valencia Trough area and near the margins of Corsica and Sardinia. In the Alboran region contemporaneous internal extension and frontal compression are active. Along the western margin of Iberia inversion structures are common, which indicate plate boundary activity near Gorringe Bank. The North African foreland basin, formed by the emplacement of Kabylian units onto the northern margin, is incorporated rapidly in the evolving Tellian fold-and-thrust belt in the Langhian.

Detail

Western margin

The western margin of Iberia is under compression. Indirect evidence comes from a marine transgression that is ending in the Sado/Lusitanian Basin, which might be related to tectonic uplift [Pimentel & Azevêdo, 1994]. More direct evidence comes from the same Lusitanian Basin, where inversion of the basin under NW-SE compression [Lepvrier & Mougenot, 1984] eroded ~1000m Tertiary sediments [Wilson *et al.*, 1989]. The northern border fault of the Lower Tajus Basin (Cercal fault) is activated under ~NS compression [Curtis, 1999]. The timing of this inversion is offshore well dated by relatively undisturbed Langhian sediments unconformable over a Burdigalian sequence with clear NS-compression [Rasmussen *et al.*, 1998]. Along the southern part of the margin, Arrabida is partly active causing significant erosion of the Mesozoic sequence [Ribeiro *et al.*, 1990] related to the NW-SE compression [Lepvrier & Mougenot, 1984]. Offshore, Gorringe Ridge is popping up, overriding to the south the subsiding W Horse Shoe plain [Torelli *et al.*, 1997]. In the entire Atlantic offshore SW Iberia, first Tertiary deformation starts during latest Oligocene-E. Miocene [Torelli *et al.*, 1997].

Northern margin

In Kings Trough extensional subsidence and rifting occurs between about 20 and 16 Ma [Srivastava *et al.*, 1990]. During Miocene (not dated more precisely) the Inner Basin develops on the Asturian Margin, isolating and deepening the Danois Bank [Boillot *et al.*, 1979]. Onshore, an end comes to the strike-slip activity in Galicia: in the As Pontes Basin sedimentation continues until ~E. Miocene related to N-S compression [Santanach Prat, 1994].

Central Iberia

In the Duero Basin E-W extension and westward sinking continues, favored by N-S trending normal faults [Santisteban *et al.*, 1996b]. The absence of E. Miocene sediments in the W/SW Duero suggests further retraction of basin edge [Portero Garcia *et al.*, 1983]. In front of the Cameros thrust, a blind thrust is activated [Molinero Huguet & Colombo Piñol, 1996]. Subsidence in the Almazan basin progresses along ENE trending normal faults [Bond, 1996] and in the Loranca Basin alluvial fans enter from the SE and west, where the Sr. Altomira is actively thrusting westward [Muñoz Martín, 1997]. The first Miocene sediments are being deposited in the southern part of the Madrid Basin [Sanz Montero *et al.*, 1992].

SE Iberia and Betic realm

A general transgression affects the Prebetic related to foreland subsidence in front of the Betic thrust sheets, while other parts within the Subbetics/Prebetics emerge due to folding. This creates NE-SW trending highs and lows with pronounced relief. The basins are up to 100-200m deep [Kenter *et al.*, 1990]. In the central part of the Prebetic of Alicante sudden subsidence occurs in a trough between two emerged areas, of which southern one is being uplifted, as attested by a southern provenance of detritus and angular unconformities [Geel & Roep, 1998]. The foreland basin is deepening from the External Prebetics, where Burdigalian-Langhian marl and calcarenite and to the east sandstone intervals are being deposited [HNPC, 1992] on the Internal Prebetics. Here marl with levels of turbiditic sandstone fill in a marine basin of up to ~1000m deep [Fontboté & Vera, 1983]. In the Intermediate Units sandy limestone deposition is the result of active deformation in the Subbetics [Fontboté & Vera, 1983], thrusted southward over the Espejos Basin (suture external-internal zones) [Geel, 1996]. Both the Subbetics and the Internal zones were located at a position offshore Alicante, 100km more eastward than their present-day location [Geel & Roep, 1998]. The western foreland basin (incipient Guadalquivir Basin) is witness of active tectonics in the approaching Internal Zones by the deposition of collapse deposits like the "Arcillas con Bloques" (clay with olistostromes) and (Campo de Gibraltar area) the "Areniscas de Aljibe" (1000m sandstone of the middle part of deep marine fans) [Fontboté & Vera, 1983]. The Internal zones in the western Alboran are actively thrusting westward [Durand Delga & Olivier, 1988], having incorporated the Dorsalian. The transgressive Las Millanas serie is sealing the frontal thrust of the Malaguide/Alpujarride complex over the Dorsal Units [Fontboté & Vera, 1983].

Active NNW-SSE (perpendicular to axis) extension [Martínez-Martínez & Azañón, 1997] in the Internal Betics is ceasing at 19-18Ma, but a last stage of cooling is inferred for 18-16Ma [Andriessen & Zeck, 1996]. Uplift is continuing, but the rapid stage comes to an end [Zeck *et al.*, 1992]. Exhumation of the Internal Betics [Lonergan & White, 1997] and the western Alpujarride under uniform fast cooling at 19-20Ma [Monié *et al.*, 1994] are related to tectonic unroofing [Lonergan & Johnson, 1998]. Synchronous olistostrome/ marine conglomerate deposition occurs over the basement of the Western Betics [Comas *et al.*, 1992].

Catalan-Sardinian margin

The elevation of the CCR is reduced considerably by normal faulting; most of these normal faults become inactive in the Burdigalian although subsidence continues (post-rift) [Roca *et al.*, 1999]. Marine conditions spread over the present-day coast; the first marine influence in the Valles Penedes is documented by transitional sedimentation [Batrina *et al.*, 1992]. All along the northwestern margin of the Valencia Trough marine environments are spreading progressively over the trough margins [Roca *et al.*, 1999]. Active opening of the Valencia Trough is waning, so the subsidence of the northwestern margin might be flexural, related to the contemporaneous northwestward thrusting at the Baleares [Gueguen *et al.*, 1998]. This thrusting of the most frontal Betic related deformation stopped short of the axis of the Valencia Trough during the early Langhian [Geel & Roep, 1998]. The same is observed at Mallorca, where the last NW-wards thrusting and major folding of the Sierra de Tramuntana occurs in latest Burdigalian-Langhian [Fontboté *et al.*, 1983]. Syntectonic turbidites with paleocurrents towards the N-NNE into the Valencia Trough are shed from the emerging Baleares. Locally olistostromes occur as precursors of these turbidites, indicating very active tectonics [Ramos-Guerrero *et al.*, 1989], which is finished at L. Burdigalian - E. Langhian [Bois, 1993]. In the Langhian, a maximum transgression submerges part of the Baleares; Ibiza is submerged [Pomar Goma, 1983]. The southern parts of Mallorca stay emerged due to the former thrusting [Fontboté *et al.*, 1983] while in Menorca marine sedimentation is combined with syntectonic conglomerate fans [Pomar Goma, 1983], indicating tectonic activity as well [HNPC, 1992].

Throughout the entire Miocene, the Sardinia Rift is filled with shallow marine sediments, with reefs on paleohighs, indicating depths of several hundreds of meters [Carmignani *et al.*, 1989]. At this stage active extension is ending and post-rift sediments accumulate in the basin [Monaghan, 2001]. On Corsica Miocene sedimentation starts, reaching full marine conditions in the Langhian [Sartori & Capozzi, 1998]. Southeast of Sardinia, in the Sardinia Channel emplacement of the Kabilo-Calabrian units along the Drepano Thrust onto the Sicilian-Maghrebian predate the end of the Langhian [Catalano *et al.*, 1995], while the Calabrian and Peloritan blocks are being separated from Sardinia (start of opening of the Tyrrhenian) [Gueguen *et al.*, 1998]. Deep-sea arcosic turbidites are being deposited in the Sardinia Channel, in front of the thrust stacks [Carmignani *et al.*, 1989].

N. Pyrenees and SW France

Active rifting has ceased completely in southern France, but a period of strong post-rift subsidence follows. The basinward part of the Gulf of Lions margin, during the late Burdigalian still a continental basin, is rapidly passing into marine series, implying strong post-rift subsidence [Sérrane *et al.*, 1995]. In the Herault Basin post-rift marine sediments (unconformable over synrift) are onlapping the pre-rift basement [Sérrane *et al.*, 1995], but the marine environment does not reach the Alès basin. A transgression affected the Nimes Basin as well during a tectonic pause [Villeger & Andrieux, 1987], the marine sequence was onlapping an erosional unconformity [Sérrane *et al.*, 1995]. To the east, the Manosque Basin is being incorporated in the Valensole Basin [Roure & Coletta, 1996]. The Northern Alpine thrust nappes reach their present-day position, in the German foreland the Upper Marine Molasse is deposited, connection to the sea is located towards the east [Andeweg & Cloetingh, 1998].

S. Alps - Adriatic domain

In the Southern Alpine domain the foreland thrust wedge starts to be deformed [Schmid *et al.*, 1996]. Massive sandstone and conglomerate (Como Formation) is deposited, related to renewed uplift of the N. Alps or development of the Southern Alps [Bernoulli *et al.*, 1989].

N. Africa

A marine transgression enters the Tellian margin, due to foreland basin development. In the Central Constantinois (NE-Algeria) the first documented internal deformation occurs under 'Alpine' NNW-SSE compression [Aris *et al.*, 1998]. The emplaced Kabylian blocks are still submerged: olistostromes are being deposited onto them, indicating high tectonic activity [Wildi & Huggenberger, 1993]. In both the Algerian and Tunisian foreland calc-alkaline volcanic activity is increased [Dewey *et al.*, 1989]. The uplift of the S.C. High Atlas is accompanied by the associated Ouarzazate basin subsidence [Görler *et al.*, 1988] and uplift of the Subrif is documented by AFT data [Azdimousa *et al.*, 1998].

15 Ma, M. Miocene (L. Langhian - E. Serravallian), Figure 5.3

General

A decrease in convergence rate between Africa and Eurasia [Lips, 1998] results in a tectonically relative quiet period in the western Mediterranean. Extension in the developing Alboran Basin and radial thrusting outward of the Rif/Gibraltar/Betics are active contemporaneously. From 18-15Ma Iberia and Africa are connected, Kabylia is colliding with Africa [Frizon de Lamotte *et al.*, 2001]. African mammals spread over the Peninsula [Calvo *et al.*, 1993] and this connection did not occur through France and the Eastern Mediterranean [Geraads, 1998]. Extension in the Valencia Trough area and near Corsica/Sardinia is waning.

Detail

Western margin

The Sado basin is emerged, stable and a transgressive series enter in between the Lisboan and Sado areas [Pimentel & Azevêdo, 1994].

Central Iberia

In the Duero basin, the E-W extension with related westward sinking favored by N-S trending normal faults [Santisteban *et al.*, 1996b] is waning. In the central part of the basin the first dated Miocene deposits (Duenas facies) [Portero Garcia *et al.*, 1983] occur as distal occasional alluvial canals coming from the NW. In the northern part small amounts of more proximal alluvial fan sequences are being deposited [Portero Garcia *et al.*, 1983]. The short-lived Sierra de Altomira becomes inactive, attested by Langhian sediments onlapping the structure. In contrary, the SCS starts to pop-up [Muñoz Martín, 1997]. Deposition of the first sediments in the western Tajo, which have northern provenance [Junco Aguado, 1983], indicate the onset of this activity of the SCS.

SE Iberia and Betic realm

In the Eastern Internal Prebetic wrench related pull-apart basins develop with abnormal high sedimentation and subsidence rates and asymmetric infill [Geel, 1996], related to NNW-SSE compression [Montenat *et al.*, 1996]. Deposition in the basins is dominated by marl with turbiditic sand passing into marl with marine fauna in the Intermediate Units [Fontboté & Vera, 1983]. Further southeast, in the Subbetics olistostromes are being shed of the advancing Internal Zones, especially in the western part of the 'mobile belt' of North Gibraltar Strait [Sanz de Galdeano & Vera, 1992]. At the border between the External and the Internal zones new basins form during the L. Burdigalian-Langhian, the onset of strike-slip deformation causes shoaling and uplift [Geel, 1996].

The Internal Betics display no important relief apart from several places near active faults [Sanz de Galdeano & Vera, 1992]. In the Sierra Alhamilla area during the Upper Langhian continental or shallow marine sandstone and conglomerate rich in Alpujarride detritus are deposited, while during the Early to Middle Serravallian marl to turbiditic open marine to pelagic environments prevail [Martínez-Martínez & Azañón, 1997]. The internal parts of the Alboran experience the first main episode of extension from 17-15Ma [Comas *et al.*, 1999], but the direction of this extension is far from uniform. Ranging from N-S in the eastern sector [García-Dueñas *et al.*, 1992], NNW-SSE (perpendicular to axis) in the Alboran Domain [Martínez-Martínez & Azañón, 1997] to NW-SE extension in the western Betics and in the eastern Alboran (E of 3.2W). In the latter area extensive mud-diapirism and volcanics occur [Comas *et al.*, 1992]. No sedimentation at this time is observed at ODP967: paleohigh until at least Serravallian [Comas *et al.*, 1999].

Catalan-Sardinian margin

The marine influences spread further onto the margin of the CCR, related to thermal post-rift subsidence [Torné *et al.*,]. Major onshore marine influences are documented in the Valles Penedes, where major fan-deltas and coralgal platforms on highs develop. Towards the Serravallian the setting becomes more regressive [Batrina *et al.*, 1992] resulting in an increasing restriction of carbonate sedimentation and the development of a shelf talus progradational system [Roca *et al.*, 1999]. Along the northwestern margin of the Valencia Trough the same is observed from Late Langhian to present-day. Erosional breakdown of the CCR and progradation of the Castellon delta into the Valencia Trough starts in Serravallian [Ziegler, 2000]. Off shore in the Valencia Trough rifting of the W-NW margin is leading to volcanics, uplift of the Baleares and onlapping of the margin with the first open marine sediments (in combination with a sea level rise) [Martínez del Olmo, 1996]. Following this open marine stage, a platform-talus-basin system derived from a siliciclastic coastal belt develops [Martínez del Olmo, 1996]. On Mallorca, the youngest thrust movements occur in the Sr. Tramuntana [Ramos-Guerrero *et al.*, 1989]. A sequence of turbidites with possibly the start of a regressive serie towards top has been observed on northern Mallorca [Ramos-Guerrero *et al.*, 1989], contemporaneous, in the central part lacustrine and evaporitic sediments are being deposited in actively subsiding basins [Pomar Goma, 1983]. On Ibiza, the last Neogene sediments (marine) are being deposited [Pomar Goma, 1983]. Sea floor spreading has come to an end in the Provençal basin. Alkaline dikes intruded eastern Corsica [Carmignani *et al.*, 1995], indicating extensional setting. To the north and east of Sardinia, areas of subsidence and sedimentation point at the onset of Tyrrhenian extension as well [Sartori & Capozzi, 1998]. To the southeast of the island, isolated calc-alkaline magmatic intrusions (until ~Tortonian age) occur in the Sardinia Channel, related to Nwards subduction of African lithosphere [Tricart, 1994].

N. Pyrenees and SW France

Infill of the Rosselo Graben is shallow marine [HNPC, 1992]. The first compressional deformation after the Oligocene rifting in observed in SE France in both the Ardeche (~ENE-WSW compression [Bonijoly *et al.*, 1996]) and the Nimes Basin. In the latter, marine sand shows indicators of tectonic activity under N080^{o} compression [Villeger & Andrieux, 1987]. This compression is related to the emplacement of the Western Alps accommodated by lithospheric strike-slip along the line Nice-Corsica-Tyrrhenian [Stampfli *et al.*, 1998]. The Vercors experiences minor uplift [Butler, 1987].

In the German Alpine Foreland the Upper Freshwater molasse is deposited, with sediment sourcing from the east [Andeweg & Cloetingh, 1998].

S. Alps - Adriatic domain

The foreland thrust wedge of the Southern Alps is building up [Schmid *et al.*, 1996].

N. Africa

In the Tellian foreland, gravitational nappes are being emplaced in the foreland basin [Vially *et al.*, 1994], with contemporaneous alkaline volcanism in the Kabylian. This type of volcanism becomes active in the Middle Atlas as well from ~15-6Ma in a SW trending zone [Giese & Jacobshagen, 1992]. At the junction of the Middle and High Atlas, start of sedimentation in the Moulouya region is inferred [Morel *et al.*, 1993]. The southern border of the High Atlas is deformed under N-S compression creating progressive unconformities [Fraissinet *et al.*, 1988], gravity sliding and folding of the Southern Atlas marginal zone, closing the Ouarzazate basin from marine environments. From now on uplift of more than 1000m is shown by marine Miocene that is exposed at 1000m at present-day [Görler *et al.*, 1988]. Uplift of the Subrif Chain is coming to an end at ~13.9Ma, as is inferred from AFT data [Azdimousa *et al.*, 1998].

12 Ma, M. Miocene (L. Serravallian), Figure 5.4

General

A period of major intraplate activity in the Iberian Peninsula. The southern margin of Iberia collides with the Internal Betics. Deformation related to this Alpine collision is not restricted to the nearby foreland, but major inversion is recognized throughout the entire Iberian Peninsula and even as distant as the western part of France, south England and in the Atlantic [Ziegler, 1988]. Collision is reactivated along the Northern African Margin as well, in particular in the Rif. Extension starts to develop in the Tyrrhenian region.

Detail

Western margin

Inversion is documented in the Algarve Basin, forming anticlines with a structural relief of over 1000m [Ribeiro *et al.*, 1990] and southward thrusting of the Ponsul fault over the Castelo Branco basin, creating accommodation space for sedimentation [Dias & Cabral, 1989]. Paleocurrents in the developing Guadiana basin are towards the west (Lusitanian)[Moya Palomares, 1999]. The structural depression of the Eastern Horse Shoe Plain develops [Torelli *et al.*, 1997].

Northern margin

Limited information is available that the collision at the Betic side of the Peninsula even affected the northern margin. Offshore Cantabria, the Asturian Basin is being eroded [Riaza Molina, 1996] and limited deformation is affecting up to L. Miocene sediments [Ziegler, 1988]. The Cantabrian front is actively thrusting southward, tilting the earlier Tertiary strata along the northern edge of the Duero basin and depositing small amounts of proximal facies of alluvial fans [Portero Garcia *et al.*, 1983]. Deposition of proximal (SW) to distal (NE) sediments in the Bierzo basin is followed by a fracturing phase [IGME, 1982c]. This fracturing is coinciding with the inferred reactivation of the western border of the Duero Basin and the individualization of the Bierzo basin [Corrochano & Carballeira, 1983a].

Central Iberia

In the Duero Basin a maximum of lacustrine environments occurs, but alluvial fans are fringing the basin from the edges. Distal alluvial sediments and alluvial plains with provenance from S/SE, NW and NE are recognized [Portero Garcia *et al.*, 1983]. The torrential alluvial deposits in the Penaranda-Alba (SSW Duero) attest activity of the southern basin border, the SCS [Corrochano & Carballeira, 1983b]. This is confirmed by active thrusting of the SCS over both its northern (Duero) and southern (Tajo) foreland basins [De Vicente *et al.*, 1996b]. AFT data for the Guadarrama suggest uplift from 12-10 Ma at a cooling rate of ~6-7 degrees/Ma [Sell *et al.*,]. Basin subsidence in the southwestern Duero [Santisteban *et al.*, 1996b] can be related to this thrusting stage. Subsidence in the Almazan Basin and activity of the Cameros thrust, shedding a coarsening up sequence of sandstone to conglomerate [Muñoz Jiménez & Casas Sainz, 1997] show that the compression related to the Betic collision is transmitted to these regions as well. This compression with a ~N140-155 directed Sh_{max} remains dominant from now until recent day [De Vicente *et al.*, 1996b].

SE Iberia and Betic realm

The western part of the External Prebetics is submerged, while in the eastern part (Alcoi) marine sedimentation persists until Early Tortonian [HNPC, 1992]. Marl with marine fauna in the Intermediate Units [Fontboté & Vera, 1983] show a southward deepening in front of the approaching Betics. The northern Subbetics are incorporated in the active belt recorded by a phase of folding and fracturing [Fontboté & Vera, 1983]. In the eastern sector, the Subbetics are thrusted in N/NW ward direction over the Prebetics from the Middle Serravallian, while in the western Subbetics olistostromes are being deposited in the broad Proto-Guadalquivir (North Betic Strait), especially in western and central part [Sanz de Galdeano & Vera, 1992]. This different behavior between east and west is most likely related to difference in crustal strength between the eastern (weak) and western (strong) Iberian foreland. The strong western sector forms a broad foreland basin, while in the east the foreland basin is extremely narrow and incorporated in the advancing thrust fronts [Andeweg & Cloetingh, 2001]. During the Late Serravallian the Subbetic thrust slices break up due to dextral strike-slip faulting [Geel & Roep, 1998].

While the frontal parts of the Internal Betics are thrusting over the Iberian and African foreland, extension invaded the contractional areas. The Gibraltar thrust is being inverted, generating SSE directed low angle normal faults in the western part of the Betics, in the Rif these faults are NE directed [Martínez-Martínez & Azañón, 1997]. Extension directions therefore, are varying from one place to the other. In the western Betics NW-SE dominates [Comas *et al.*, 1992], in the eastern Betics a NE-SW direction is prominent [García-Dueñas *et al.*, 1992] and in the Alboran domain the extension is WSW, parallel to the former orogen [Martínez-Martínez & Azañón, 1997]. But even within the Alboran domain, differences exist between west and east. In the first small deep faulted depressions bounded by paleohighs without sedimentation [Comas *et al.*, 1993] occur while regional subsidence starts [Campillo *et al.*, 1992], in the latter subsidence is localized in small E-NE/W-SW rift grabens [Comas *et al.*, 1992]. This generalized extension is leading to the absence of important relief in the Internal Betics apart from near active faults [Sanz de Galdeano & Vera, 1992]. For example backthrusting in the Betic stack occurs, being thrusted over the External zones [Fontboté & Vera, 1983]. Rotation of the Sierra Espuña ceased [Allerton *et al.*, 1993]. Deposition in the Neogene basins occurs in shallow marine environments [Martínez-Martínez & Azañón, 1997]. Through time, these basin have developed from open marine to pelagic during the Serravallian, to very shallow (end synrift?) towards the end of the Serravallian [Martínez-Martínez & Azañón, 1997].

Catalan-Sardinian margin

The oceanic crust in the Algerian and Alboran Basin has been formed completely [Lonergan & White, 1997]. Development of progradational terrigenous shelf-slope complex with an outbuilding fan delta continuous in the CCR region [Roca *et al.*, 1999], filling up progressively the former active rifts and onlapping paleohighs [Batrina *et al.*, 1992]. Water depths in the Valencia are shallower than present-day [Roca & Deselgaulx, 1992]. In the Trough, accommodation space created by the waning active extension is filled by large amounts of sediments from the continent [Martínez del Olmo, 1996]. Uplift of the

Baleares [Martínez del Olmo, 1996] can be related to active listric normal faults on Mallorca [Gelabert Ferrer, 1997]. Extension occurs to the east and southeast of Sardinia as well [Tricart, 1994].

S. Alps - Adriatic domain

Growth and uplift of the foreland thrust wedge of the Southern Alps continues [Schmid *et al.*, 1996]. N050^o directed compression is observed in the central and external belts of the Northern Apennines [Boccaletti & Sani, 1998]. To the back of the Northern Apennines, 3000-3500m Premessinian sediments in Carnaglia basin (E. of Sardinia) indicate an important contemporaneous tensile event [Catalano *et al.*, 1989]. Western Sicily is a foreland of the Maghrebian/Sardinian belt during the E. Langhian-Tortonian [Catalano *et al.*, 1989].

N. Pyrenees and SW France

Limited folding in the Aquitanian basin [Dercourt *et al.*, 1986] indicates that NW-SE compression [Rocher *et al.*, 2000] is still active at Iberia-Eurasia boundary and can be related to the major collision of the Betics in the south of Iberia. More eastward, the first N-S directed compression in the region after the Oligocene rifting is documented by a N170 directed compressional event in the Nimes Basin [Villeger & Andrieux, 1987]. In areas closer to the Western Alpine front, the compressional direction is rotating towards perpendicular to the Alpine front, e.g. ENE-WSW compression in the Ardeche [Bonijoly *et al.*, 1996]. This is resulting in inversion of the Valensole/Manosque basins due to activity of the Durance fault and molasse sedimentation in the Valensole area [Roure & Coletta, 1996]. In the German part of the Northern Alpine Foreland Basin the Upper Freshwater Molasse is filling the basin from the east and forms the last stage of molasse sedimentation [Andeweg & Cloetingh, 1998]. Major fans enter the basin in the Swiss part [Sissingh, 1997].

N. Africa

Along the Tunisian shelf the Numidian Flysch nappes are being emplaced as gravitational nappes [Vially *et al.*, 1994] or are thrusting to the south, onto the margin [Tricart, 1994]. In the Algerian Margin, the same thrust sheets are emerged [Aris *et al.*, 1998]. In the Moroccan foreland of the Middle Atlas, N040^o-060^o oriented strike-slip faults are being reactivated due to emplacement of the Rif. Related alkaline volcanism is active [Brede *et al.*, 1992] and migrated rapidly from the Valencia Trough area to northern Kabylia [Vérges & Sàbat, 1999]. N160^o compression leads to N070^o trending thrusts and sinistral motions along the N040^o/060^o oriented border faults of the Middle Atlas [Jacobshagen, 1992]. On the internal side of the Rif, extension is active and resulting in growth faults and bathyal claystone [Chalouan *et al.*, 1997].

9 Ma, L. Miocene (Tortonian), Figure 5.5

General

A change in direction of African-Eurasian plate kinematics is inferred and a NW direction for the convergence between both is documented for at least the central Mediterranean [Mazzoli & Helman, 1994]. Intraplate deformation in Iberia continues under similar tectonic conditions as in the Serravallian but in lesser magnitude. Changes in morphology of the seafloor in the North Atlantic are related to the Alpine orogeny [Tucholke & McCoy, 1986]. In the Betic/Rif tectonic uplift of massifs is common, limiting the connection between the Mediterranean and Atlantic progressively.

Detail

Western margin

The compressional deformation is waning, but still present in the SW corner of Iberia. In the Algarve, basin inversion and active southward thrusting of the Arrabida belt are observed [Ribeiro *et al.*, 1990], related to renewed NW-SE compression [Lepvrier & Mougenot, 1984]. The northern borders of both the Lower Tajo Basin [Curtis, 1999] (Extremadura thrust) [Lepvrier & Mougenot, 1984] and the Castelo Branco Basin (Ponsul fault) [Dias & Cabral, 1989] are thrusting southward over the basins.

Northern margin

In the Cantabrian Range, the most recent thrusting movements of the Sierras de los Obarenes have been dated Tortonian [Jurado & Riba, 1996], although compressional deformation even extends into at least the Pliocene [Cortes Gracia & Casas Sainz, 1997]. Similarly, compressional deformation is recognized offshore affecting up to L. Miocene sediments [Ziegler, 1988].

Central Iberia

The borders of the Duero Basin seem to be active still, or witness the importance of the Middle Miocene compressional event. Towards the east, in both the Almazan and the Rioja area, ongoing compressional deformation is documented. In the first, small alluvial fans continue to build out with paleocurrents from the NNE, only forming a basin margin until ~early Pliocene [Bond, 1996]. The borders of the Rioja Basin (Cameros and SW Pyrenean thrust fronts) reach their present-day position [Muñoz Jiménez & Casas Sainz, 1997]. Taking into account the active thrusting of the Sierras Obarenes and the occurrence of large proximal alluvial fans along the northern edge of the Duero Basin [Portero Garcia *et al.*, 1983], it is most likely that the Cantabrian Range is actively deforming as well. Along the southern edge, large proximal alluvial fan sediments [Portero Garcia *et al.*, 1983] and in the SSW (Penaranda-Alba) even torrential alluvial deposits [Corrochano & Carballeira, 1983b] indicate activity of the southern border (SCS) as well. This is confirmed by AFT-data of the SCS that show a renewed cooling episode from ~10Ma at 6-7C/ma [Sell *et al.*,]. For the central parts of the Duero basin a lacustrine salt lake basin is restricted to the Eastern sector and the Almazan basin [Corrochano & Armenteros, 1989]. Large parts of the Duero basin becomes exoreic, related to a sinking towards the west by near radial extension [Santisteban *et al.*, 1996b] and capture by the head ward eroding Duero river. The Iberian Range reaches its topographic maximum (1800m) [Guimerà & González, 1998] and within the Chain, the Teruel Basins start to development along N-S normal faults [Alvarado, 1978]. The Cabriel Basin (to the south of the Iberian Range) is filled with up to 400m alluvial and lacustrine sediments, and related to a large listric basement fault [Anadon & Moissenet, 1996]. The Southern Tajo Basin is filled with Tortonian sediments, evolving from conglomerate into alluvial fan deposits [Adrover *et al.*, 1983].

SE Iberia and Betic realm

From about 11Ma, the Eastern Prebetics (Alicante) are emerged [Geel, 1996]. A major unconformity documents an orogenic phase that created a paleorelief that mirrors present-day topography. Around arising belts, coarse conglomerates accumulate in basins up to 200m deep [Kenter *et al.*, 1990]. The compression direction in this region changes to N-S towards the Messinian [Montenat *et al.*, 1996; Jonk & Biermann, 2001], leading to a new suite of strike-slip related basins in the Subbetics (e.g. Lorca) [Geel, 1996]. The North Betic Strait connection from the Atlantic with the Mediterranean is being interrupted, the last olistostromes are being deposited in its western sector at around ~E. Tortonian [Sanz de Galdeano & Vera, 1992]. The Internal Betics show an irregular topography with rising anticlinal mountain ranges, e.g. the Sierra Alhamilla [Weijermars *et al.*, 1985], surrounded by complex basins capturing the erosional products. In the Eastern Internal Betics during the early Tortonian continental conglomerate basins occur [Martínez-Martínez & Azañón, 1997], in the area of the future Sierra Alhamilla a basal layer of red conglomerates (continental and marine) rich in Nevado-Filabride detritus is deposited. This layer forms the first post-rift sediments and is covered by a transgressive serie with turbidites [Martínez-Martínez & Azañón, 1997]. Parts of the Nevado-Filabride must have experienced spectacular uplift [Sanz de Galdeano & Vera, 1992] and the first Nevado-Filabride clasts are recognized in sediments. AFT data for the Sierra Nevada show a first phase of cooling related to tectonic denudation [Johnson, 1997], south of the Sierra Nevada N070^{o} trending strike-slip faults are very active [Sanz de Galdeano *et al.*, 1985]. In the eastern Betics, E-W trending fault systems are activated under a NW-SE oriented maximum principal axis of stress [Huibregtse *et al.*, 1998]. In the southern Betics, the coastline extended north of the present-day coastline, as witnessed by interconnected basins [Soria *et al.*, 1999] in which shallow marine deposits accumulate [Sanz de Galdeano & Rodriguez Fernandez, 1996]. Tortonian marine sediments are the first to be deposited in the Granada/Guadix Basin [Fernandez *et al.*, 1996]. Marine influences are found in transgressive deposits in the entire western Alboran. Normal faulting is still active along the eastern and western borders of the western Alboran Basin [Campillo *et al.*, 1992] but active rifting is ceasing [Comas *et al.*, 1999]. At least the eastern Alboran basin shows an interruption of rifting [Comas *et al.*, 1992]: the base of the Tortonian sediments forms a generally unfaulted or only poorly faulted horizon and is onlapping previous structured basement highs [Comas *et al.*, 1992]. Tectonics in the western Alboran basin is still active. In the southwestern Alboran active extension along normal faults ceased during Tortonian, somewhat later than in the northern and eastern Alboran, leading to deposition of bathyal claystone and coarse turbiditic sandstone [Chalouan *et al.*, 1997]. On the west side of the Gibraltar arc, the Horse Shoe structural low is being formed in the middle-late Miocene and filled with giant endo-olistostromes during late Miocene from the structural highs surrounding the area [Torelli *et al.*, 1997].

S. Pyrenees and Ebro

The Cerdanya Basin and Conflent Basin develop along E-W normal faults related to dextral transtensional activity of the NE-ENE trending Tet Fault [HNPC, 1992]. The infill of the Emporda Basin with littoral sediments [HNPC, 1992] suggests tectonic activity as well. Renewed exhumation of the Pyrenees starts [Fitzgerald *et al.*, 1999], related to this, excavation of the Ebro Basin leads to increased sediment supply in the Valencia Trough (Castellon delta).

N. Pyrenees and SW France

Along the Alpine Chain, the last molasse sedimentation occurs in the Valensole plateau [Roure & Coletta, 1996], and generally, in the Northern Alpine Foreland Basin, where 8 Ma dates the end of foreland sedimentation [Schmid *et al.*, 1996]. In the German foreland basin (until Tortonian, freshwater molasse), uplift after the Upper Marine molasse amounts as much as 700m [Andeweg & Cloetingh, 1998]. In the front of these molasse basins, compressional deformation of the foreland continues inversion of the Manosque basin [Roure & Coletta, 1996] and development of the Jura Mountains [Bois, 1993]. Folding of the Jura commenced at ~11Ma and continues at least to the Pliocene [Ziegler *et al.*, 1996] and is synchronous with active thrusting in the Vercors (10-6Ma) [Butler, 1987]. Uplift occurs in the foreland of the Molasse basin and Massif Central and major volcanic activity in the latter [Bois, 1993]. The Alps become evidently a climatic divide [Jelen *et al.*, 1997].

Catalan-Sardinian margin

Offshore CCR minor compressional inversion of normal faults has been observed, that could be related to the Betic compression [*Roca, pers.*]. Even although limited extension is active, rapid progradation of the Ebro Delta occurs in the Valencia Trough that is the locus of high sediment supply. This high sediment influx is related to erosion of the Ebro Basin. The first deep-water facies are being deposited on the Spanish margin [Martínez del Olmo, 1996]. Mallorca/Menorca experience an additional 025 (+-15) clockwise, propably local rotation since the upper Miocene [Freeman *et al.*, 1989] and are affected from the Serravallian by an extensive phase, creating listric normal faults [Gelabert Ferrer, 1997].

S. Alps - Adriatic domain

Extension is active in the area east of Sardinia. The initiation of extension in the N. Apennines is dated at 8-12Ma [Mazzoli & Helman, 1994] and at the Baronie Ridge (east off shore Sardinia), the start of extension at ODP 654 causes sub-aerial deposition [Sartori & Staff, 1989]. In the N. Apennines in the internal belt sedimentation is ending before a large unconformity develops, in the central and external belt, a L. Miocene unconformity is present [Boccaletti & Sani, 1998]. The Sardinia Basin that has been a depth of some hundreds meters throughout the entire Miocene, now is shoaling to evaporitic and lagoon environments close to sea level [Carmignani *et al.*, 1989]. This indicates uplift, as is documented for Corsica and Sardinia [Bois, 1993]. Exposure of the N. Apennines and the Corsica/Sardinian block suggests rift shoulder uplift on both sides of the incipient rifting of the Tyrrhenian. In the Sardinia Channel en-echelon NW-SE dextral strike-slip accommodates this limited southeastward opening [Catalano *et al.*, 1989].

N. Africa

The northern margin of Africa is very active during the latest Miocene. In the east (Atlas Range of Central Tunisia), the first major contraction corresponding to a major post-nappe shortening event of the Tell Mountains [Tricart, 1994], does not yet cause compressional uplift in the southern Tunisian foreland. In Algeria the final emplacement of the Flysch nappes occurs under *N-S* compression [Aris *et al.*, 1998]. The pattern of maximum horizontal compression is trending NNW-SSE in Algeria towards N-S in the Oriental Rif [Ait Brahim & Chotin, 1989] and a general NE-SW trend in the Moroccan foreland [Galindo-Zaldívar *et al.*, 1993] is more or less perpendicular to the Riffian thrust front. The Rif is thrusting over the Mesorif foreland basin, and the accretionary wedge in the Prerif experiences rapid extensional collapse and deepening. Deep-water sediments are being deposited over shallow water sediments [Flinch, 1996] and a transgression inundates the Guercif foreland Basin [Zizi, 1996]. In the Subrif marl and marine conglomerate sedimentation [Ait Brahim & Chotin, 1989] is happening in a WNW-ESE extensional setting [Ait Brahim & Chotin, 1989]. The Moroccan foreland is being deformed. The emplacement of the Rif is reactivating the N040^{o}-060^{o} trending border faults of the Middle Atlas. Related to the sinistral movement along northern border faults [Herbig, 1988], alkaline volcanism is active and N070^{o} trending thrusts develop. At the junction of high and Middle Atlas, sedimentation continues in the Moulouya Basin [Morel *et al.*, 1993]. Even more distal the south central High Atlas experiences a slow to vanishing uplift, lakes and swamps develop in a closed basin between the High and Anti Atlas [Görler *et al.*, 1988].

6 Ma, L. Miocene - E. Pliocene (Messinian - Zanclean), Figure 5.6

General

Northward thrusting of the Betics blocked the North-Betic connection with the Atlantic Ocean, while in the Rif the southern connection was closed as well. The Mediterranean Basin was closed completely from marine waters and started evaporating, leaving an accumulation of salt at the basin floor (the so-called Messinian Salinity Crisis). The severe base level lowering caused strong incision of rivers in the margins. Within the course of only a few million years, strike-slip deformation in the Gibraltar Arc reopened the connection with sea, flooding the basin in short time.

Detail

Western margin

The marine environments that entered the Sado Basin towards the end of the Miocene return to terrigenous in the Pliocene [Pimentel & Azevêdo, 1994], in the Castelo Branco basin tectonic stability and continued erosion is documented [Dias & Cabral, 1989].

Central Iberia

In the Duero Basin, a last system of lacustrine sedimentation (Paramo 2) occurs along a central axis (Valladolid/Palencia/Burgos). In the connection between the Ebro and Duero basins no sedimentation is occurring [Pineda Velasco, 1996]. In large parts of central Iberia 'Raña' is being deposited throughout the lower areas. In the northeastern Madrid Basin NNE and NNW basement discontinuities are being reactivated extensionally and control the distribution of L. Miocene alluvial systems. In the basins in the Iberian Range, the Teruel basin infill finishes and the Jiloca basin starts to develop [Guimerà, 1997]. The Cabriel Basin develops in relation to extensional subsidence enhanced by Triassic floored basement, and is filled in with alluvial deposits, predominantly coming from the NE [Anadon & Moissenet, 1996]. The western Valencia area is developed in the same sequence of deformation.

SE Iberia and Betic realm

Thrusting of the Prebetic onto the southeastern Iberian foreland blocks the North Betic Strait [Sanz de Galdeano & Rodriguez Fernandez, 1996]. The coastline in the Guadalquivir Basin is shifted westward and is relocated near Cordoba [Sierro *et al.*, 1996]. In the Gulf of Cadiz active basin subsidence is ceasing [Sanz de Galdeano & Vera, 1992]. In the Gibraltar area, the Rif-Betic arc blocks the strait [Weijermars *et al.*, 1985]. Within the eastern Betics several anticlinal ranges develop rapidly in relation to N020°-N040° trending strike-slip zones, possibly related with the rotation of the stress field to a N-S direction [Jonk & Biermann, 2001]. Rapid uplift of the Sierra Nevada is being revealed by AFT data related to a second phase of cooling by folding and accompanied by differential erosive denudation [Johnson, 1997]. Thermal activity and deep fractures in the area [Sanz de Galdeano *et al.*, 1985] imply that caution should be taken when interpreting these data. However, independent data show similar features: Tortonian marine sediments in the Sierra de Carrascoy (eastern Betics) are presently elevated to ~1000m [Sanz de Galdeano *et al.*, 1998], and in the Sierra Nevada these can be found at elevations of over 1850m [Sanz de Galdeano & López-Garrido, 1999]. Southeast of the Sierra Nevada, the Sierra Alhamilla rises up as well. These ranges can be explained by large scale folding in restraining bends of N020°-040° trending sinistral strike-slip faults [Andeweg & Cloetingh, 2001]. But, not only the mountain ranges are being uplifted, the whole Betics experience an important stage of uplift. Most of the numerous basins in the area change from basins with reefs to lakes in the L. Tortonian and progressively shallow further during the Messinian [Sanz de Galdeano & Vera, 1992]. Except for the basins close to the present-day coast, this uplift caused withdrawal of the sea and disconnection from marine Mediterranean or Atlantic waters [Soria *et al.*, 1999]. Bisection and uplift of Guadix/Granada basins after L. Tortonian is related to the indentation of the Sierra Nevada [Andeweg & Cloetingh, 2001]. The general pattern of Messinian to present-day progressive shallowness in Betic basins is only interrupted by an E. Pliocene transgression. A distensive phase occurring in the Eastern Betics is associated with calc-alkaline volcanics [Goy & Zazo, 1986b]. In the eastern and central part of the Alboran basin, Messinian deposits record compressional tectonics, particularly along margins and structural highs. Active N-S contraction from the L. Tortonian causes folding, strike-slip faulting and inversion of previous faults [Comas *et al.*, 1992]. Towards the end of the Messinian transcurrent movements occur along ENE faults in E-W to ESE-WNW extension [Campillo *et al.*, 1992].

Catalan-Sardinian margin

Paleo water depth in the northern Valencia Trough is approximately equal to today, in the southern part slightly shallower (~800m maximum)[Roca & Deselgaulx, 1992]. The Ebro delta is continuing to build out after the Messinian lowstand [Roca, 2001]. Volcanism is active in the Olot area, the Columbretes and southeastern Iberia. Corsica and Sardinia are uplifted [Bois, 1993], the Sardinia Basin finally shoals to continental environments from the Middle Pliocene [Yilmaz *et al.*, 1996] leading to the first continental deposits since L.Oligocene. Regional extension invades the Sardinia Channel and the Tunisian shelf experiences (rift shoulder?) uplift [Tricart, 1994].

N. Pyrenees and SW France

Folding of the Jura continues at least to Pliocene [Ziegler *et al.*, 1996], the Jura allochton overrides the Bresse Rift partly [Roure & Coletta, 1996]. The West-Alpine external massifs are rapidly rising due to strong mechanical coupling of the orogenic wedge and its foreland. Related to this, the Bresse Rift experiences several hundreds of meters of late subsidence as the flexural depression in front of the advancing Jura. Uplift of the Massif Central [Bois, 1993] is in relation to significant volcanic activity. With the Nimes Basin NNE-NE (020) compression continues [Villeger & Andrieux, 1987].

S. Alps - Adriatic domain

The Southern Alpine thrust wedge is inactive demonstrated by a sealing Messinian unconformity [Schmid *et al.*, 1996], but compressional deformation is still active in the N Apennines. ~N020^{o} directed compression is active in both the internal and external belts [Boccaletti & Sani, 1998]. Contemporaneous extension along the Sardinian margin shifted southeastward [Spadini, 1996], leading to a water depth of about 1000m in the N. Carnaglia basin (E. Mess.) [Sartori *et al.*, 1989].

N. Africa

During the latest Miocene, a minor compressional event deforms the Tunisian shelf, corresponding to a second post-nappe shortening in the Tell mountains [Tricart, 1994]. In the Central Constantinois (NE Algeria) extensional Pliocene troughs develop, Mesozoic faults are being reactivated under NW-SE extension, forming fault bounded continental basins [Aris *et al.*, 1998]. Extension is present in the Oriental Rif and Rif foreland as well, directed ~N030^{o} [Groupe, 1977] approximately perpendicular to the regional compression. Inversion of Subrif basins due this NNE-SSW compression [Ait Brahim & Chotin, 1989], results in accentuation of border relieves and closes the connection between the Atlantic and Mediterranean in N. Africa [Ait Brahim & Chotin, 1989]. Just as in the eastern Betics Guadix/Granada basin, renewed uplift in the S.C. High Atlas related to strike-slip activity results in separation of the Ouarzazate (east) and the Ait Kardoula region (west) [Görler *et al.*, 1988].

3 Ma, L. Pliocene, Figure 5.7

General

During the E. Pliocene, vast plains of carbonate cemented conglomerate caps (raña) developed in central Iberia. A L. Pliocene general uplift of Iberia results in uplifted beach sediments along many of the Iberian margins and the start of erosion of the vast raña deposits. The western Alboran basin is being deformed.

Detail

Western margin

Deformation off shore Galicia [Murillas *et al.*, 1990] during the Pliocene is inferred. Sedimentation of fan conglomerate in the Castelo Branco [Dias & Cabral, 1989] is another clue for tectonic activity. In the southwestern corner of Iberia, compressional deformation is active. In the Sado basin paleocurrents towards NW [Pimentel & Azevêdo, 1994] suggest renewed uplift of the hinterland of the basin [Pimentel & Brum da Silveira, 1991]. The River Guadiana, that demonstrated paleocurrents towards the Sado basin during the Late Miocene and now drains for the first time towards the south Moya-Palomares, proves uplift of this region [*Roca, pers.*]. A Pliocene abrasion plateau in SW Iberia is now elevated at ~500-700m. Along the southwestern Iberian margin NW-SE compression and perpendicular NE-SW extension is observed. During the Quaternary local extension forms NW-SE trending normal faults in the region [Flores Hurtado, 1994].

S. Pyrenees and Ebro

Apart from the margins and Central Iberia, a generalized uplift affects the entire Pyrenean mountain range [Muñoz *et al.*, 1983]. In Navarra (S. border of Sierra de Cantabria) compressional structures extend to at least the Pliocene [Cortes Gracia & Casas Sainz, 1997] and in the Ebro Basin generalized fracturing and normal faulting are resulting from N-S to NNE-SSW compression with perpendicular extension [Arlegui Crespo, 1996].

Catalan-Sardinian margin

In many of the littoral basins along the eastern margin of Iberia evidence for N-S compression and E-W extension has been documented [Santanach *et al.*, 1980]. In general, the present-day emerged zones of the CCR are under non-marine conditions by now [Batrina *et al.*, 1992]. The small basins more to the north, like the Emporda Basin still are under marine influences [HNPC, 1992]. Littoral sediments are being deposited in central Mallorca as well [HNPC, 1992]. Continued elevated sediment supply into the Valencia Trough is evident by rapid progradation [Martínez del Olmo, 1996]. Extension in Tyrrhenian shifted further southeast: the oceanic crust of the Vasilov Basin developed before 3.5 Ma [Spadini, 1996].

Central Iberia

Within the Iberian Range, alluvial sediments fill the Jiloca basin [Guimerà, 1997]. The extensive Pliocene continental deposits high in mountain ranges (up to 1100m in the SCS) are being eroded during the Quaternary. A change of sedimentation to erosion occurs in the Duero, Ebro and Tajo Basins. Raña deposits (lime-cemented caps) are limited by N-S normal faults, indicating NS-compression [Martin Escorza, 1977]. An important NE-SW fluvial network developed in the eastern Madrid Basin [IGME, 1976], which indicates an active uplift of tilt of this part of the Madrid Basin.

SE Iberia and Betic realm

Ongoing compressive strike-slip activity of the N020°-040° trending faults in the eastern Betics [Andeweg and Cloetingh, 2001], e.g. the Serrata fault [Boorsma, 1993] and the Alhama de Murcia fault [Martínez Díaz & Hernandez Enrile, 1992]. The latter is causing continued uplift of the anticlinal sierras as the Sierra de Carrascoy [Sanz de Galdeano *et al.*, 1998]. In general, an uplift of 125-700m is inferred for the Eastern Betics and the Prebetics [Janssen *et al.*, 1993]. After uplift of the Central Betics (radial?) extension reorganized many older basins and maybe opened the Strait of Gibraltar [Sanz de Galdeano & Vera, 1992]. Small pull-apart basins in the western Alboran however, point to strike-slip along the Strait of Gibraltar as the governing mechanism of opening [Campillo *et al.*, 1992]. But in the E. Pliocene in the western Alboran Basin dip-slip to oblique High Angle Normal Faults are active as well [Comas *et al.*, 1992]. In the central to eastern Alboran basin, compressional deformation is abundant. The anticlinal structure of the Alboran Ridge is formed [Mauffret *et al.*, 1987], along the SE bordered by a NW dipping reverse fault that lines up with the Jebha fault located to the SE [Meghraoui *et al.*, 1996]. Along both edges of the Alboran Ridge positive flower structures develop [Campillo *et al.*, 1992], pointing to an important strike-slip component in the deformation. Between the Alboran Ridge and mainland Algeria, the Al Hoceima pull-apart basin is created (a N070° trending synclinorium with north dipping axial planes) [Chalouan *et al.*, 1997] by dextral motion along two E-W faults that form the prolongation of the Yussuf Ridge [Meghraoui *et al.*, 1996].

N. Pyrenees and SW France

A climax of alkaline volcanic activity in the Massif Central is associated with (after L. Pliocene) regional basement uplift [Bois, 1993]. The Rosello Graben in Southern France is still in marine environments [HNPC, 1992].

N. Africa

In the Tunisian Atlas E. Pleistocene synsedimentary reverse faults indicate that the deformation front has reached the northern boundary of the stable Saharan Platform [Tricart, 1994]. In the northeastern Algerian foreland a NW-SE extensional phase [Aris *et al.*, 1998] is documented. In the Tellian belt, near N-S compression is active contemporaneously, especially east of Algiers. This combination of facts suggests a reactivation of the Saharan flexure [Vially *et al.*, 1994]. Moving westward, in both the Oriental Rif and (Guercif) foreland (NNW-SSE) and the Western Rif (ENE-WSW) compression dominates [Groupe, 1977]. The Rharb and the Cheliff flexural basins in front of the Rif wedge are strongly subsiding and filled with up to 3000m marine Plio-Quaternary sediments [Meghraoui *et al.*, 1996]. Active emplacement of the Rif is related to sinistral strike-slip movement along the southern border fault of the Middle Atlas [Herbig, 1988]. At the junction of the High and Middle Atlas, NW compression is deforming all sediments older than Pliocene in the Moulouya region [Morel *et al.*, 1993]. The entire High Atlas region is being uplifted rapidly, the basins as well. A second phase of folding indicates that this uplift is most likely related to compressional deformation [Görler *et al.*, 1988].

0 Ma, Holocene, Figure 5.8

General

Intraplate deformation is still very active and accommodates the internal deformation of the Iberian Peninsula, which is squeezed between approaching Africa (convergence rates between Africa and Iberia based on NUVEL-1 [Argus *et al.*, 1989]), Eurasia and the opening Atlantic. A generalized uplift affects Iberia and NW Africa. The stress trajectories in Iberia are according to SIGMA [1998].

Detail

Western margin

Tectonic activity is abundant along the Portuguese coast. Uplift and normal faulting (N-S and E-W faults), possibly related to NNW-SSE trending strike-slip fault is observed [Granja, 1999]. In the Sado Basin NNE/SSW faults are being reactivated under NW-SE compression, offsetting and tilting raña's [Pimentel & Azevêdo, 1994]. Uplift of the Grandola basement block (west of Sado) separates the Sado basin from littoral environments and causes renewed subsidence [Pimentel & Brum da Silveira, 1991]. In the Castelo Branco: renewed SE-thrusting Ponsul fault is observed [Dias & Cabral, 1989]. GPS data show uplift of the northern border and subsidence of the Lower Tajus Basin. In the Algarve uplift is even dated since 1755 [Hindson *et al.*, 1999]. NE-SW compression with perpendicular extension [Flores Hurtado, 1994] resulted along the Huelva coast in E-W trending normal faults and NNW-SSE and NW-SE faults that conditioned the deposition Holocene sediments [Zazo *et al.*, 1999]. Off shore southwestern Iberia dextral slip occurs along an ENE-WSW directed basement fault along S. Gorringe Bank and Faro to the Guadalquivir Basin [Maestro *et al.*, 1998]. Deformation of quaternary sediments in the area is observed [Tortella *et al.*, 1997].

Northern margin

Uplift is evident in Galicia as well: marine quaternary sediments are now up to 55-60m above sea level [Vidal Romaní, 1989] and the rivers in the Cantabrian Range are erosional, no sedimentation [ITGME, 1990c]. Helium isotopic ratios reveal important seismic activity in Galicia [Pérez *et al.*, 1996], NS-trending normal faults cause significant seismicity [SIGMA, 1998] and recent movement of faults in the Bierzo basin affect Plio-quaternary sediments [IGME, 1982a].

Central Iberia

In the Tajo Basin the last 'basin' sediments are of about 2-2,5Ma, sedimentation afterwards only occurs in river terraces. A large amount of terraces exists along the rivers, even up to 20 along the Henares. A tectonic control for their development is evident [Capote & De Vicente, 1989]: 1) the terraces are all located at one side of the river, while it is eroding the other side [Pérez González *et al.*, 1989], and 2) paleoseismites have been dated at ~300.000 years in the area of River Jarama This fits with the observation that the area was struck in the Middle to Lower Pleistocene by increased tectonic activity [Giner Robles, 1996].

SE Iberia and Betic realm

In the eastern Betics, left lateral activity along NNE-SSW faults (Carboneras, Palomares, Alhama de Murcia [Martínez Díaz & Hernandez Enrile, 1992]) indicates the activity of compressional tectonics [Bousquet, 1979]. Vertical motions observed by leveling demonstrate tectonic activity of several fault zones in the eastern Betics [Giménez *et al.*, 2000]. In the Eastern Prebetic (Alicante) E-W folds are observed in Lower Pleistocene deposits. Even younger normal faulting along N-S faults is documented. Marine quaternary sediments are now at 45m [Goy & Zazo, 1986a]. In the west-central Betics continental subduction of Iberia under Alboran could have accommodated up to 150 km of convergence from the Middle-Late Miocene [Morales *et al.*, 1999]. Uplift of the Alboran Ridge [Comas *et al.*, 1999] is suggested by a basinward shift of the depot centers at a higher rate than the lowering of the sea level could produce [Campos *et al.*, 1992]. In the central Alboran structural inversions in the Alboran Ridge and formerly formed pull-apart basins in the Strait of Gibraltar occurs with a dextral component along NNW trending border faults in the W. Alboran Basin [Campillo *et al.*, 1992]. The Yussuf Ridge in the central Alboran shows the development of a tilted block bounded to the south by a normal fault with up to ~400m throw [Mauffret *et al.*, 1987]. This deformation pattern in the Alboran and Betics can be correlated to activity in the Atlas and be related to a large sinistral shear zone [Andeweg & Cloetingh, 2001].

S. Pyrenees and Ebro

Southern margin Pyrenees: recent activity of anticline Barbasto-Balaguer resulting in seismicity and deformed quaternary sediments, indicates N-S compression, still activity of southernmost Pyrenean feature. Ebro Basin: general fracturing predominantly N-S trending develops under E-W distension [Arlegui Crespo, 1996]. Normal faulting causes uplift in the Emporda Basin [Vergés *et al.*, 1996] and alkaline volcanism migrated to this region [Vergés & Sàbat, 1999]

Catalan-Sardinian margin

Along the eastern margin of Iberia, N-S compression and E-W extension is observed in many littoral basins [Santanach *et al.*, 1980]. NS-normal faults are still active in the Valencia Trough [Maillard *et al.*, 1992]. In northeast Iberia recent uplift along buried frontal thrust of CCR and La Selva Basin has been detected by high precision leveling [Giménez *et al.*, 1996]. Bisection of the Valles basin is related to neotectonic movements as well [de Mas Canals, 1984] and an extensive tectonic event is derived from seismicity [Masana Closa, 1996]. The Baleares are being uplifted as well: Pliocene marine sediments on Mallorca are now at 150-200m [Roca & Deselgaulx, 1992].

N. Pyrenees and SW France

The stress directions derived from focal mechanism solutions in the Pyrenean domain remain unresolved [Delouis, 1993], due to difficulty of defining the stress field in a highly deformed collision zone. In the west, the North Pyrenean Fault is still active, while in the central and eastern part of the Pyrenees activity is related to the Tet fault and volcanic activity [Souriau & Pauchet, 1998]. The Massif Central is uplifted and affected by transtensional deformation, leading to ENE trending blocks [Ziegler, 1994]. The Jura foreland is still deforming, inferred by leveling [Jouanne *et al.*, 1995]. Stress patterns in mainland France according to [Rebaï *et al.*, 1992].

S. Alps - Adriatic domain

N Apennines: stress data according to Montone *et al.* [1999]

N. Africa

N. Tunisia: stress data from *WSM.* Northeastern Algeria is under ~N130-150 compression [Aris *et al.*, 1998], resulting in N060^{o} folds, inverse faults trending N050^{o}-070^{o} and conjugate strike-slip faults deforming the Plio-Quaternary basins in the Tellian Atlas [Meghraoui *et al.*, 1996]. Alkaline magmatism migrated into the Tell region [Vérges & Sàbat, 1999]. The mean state of stress in northeastern Morocco

is NNW-SSE directed compressional strike-slip, derived from shallow seismicity (up to ~17km) [Medina, 1995]. This direction is in good agreement with the patterns of stress directions inferred from fault slip data compilations [Galindo-Zaldívar *et al.*, 1993]. All along the northern African Margin (from Tanger to Algiers) marine terraces are being uplifted at rates of 0.2mm/yr [Meghraoui *et al.*, 1996].
Both structural indicators & recent earthquakes document sinistral motion along the Transalboran fault (TAF) in Morocco [Jacobshagen, 1992]. Compressive strike-slip as is shown along the southern border of the Middle Atlas, which is thrusting southeastward over Pleistocene conglomerates [Giese & Jacobshagen, 1992]. This tectonic activity is accompanied by a phase of alkaline volcanics [Giese & Jacobshagen, 1992]. Between the High and Middle Atlas, the Moulouya Basin is under N-S compression [Morel *et al.*, 1993]. Within the High Atlas no present-day tectonic movements are being observed along the Southern High Atlas Fault (SHAF) east of the Tizi n'Test fault. To the west of this junction, the SHAF lines up with the TAF [Jacobshagen, 1992]. The southern High Atlas is being uplifted and eroded under NNW-SSE compression [Fraissinet *et al.*, 1988], just as the Anti Atlas [Görler *et al.*, 1988]. The Ouarzazate basin is subsiding slowly [Fraissinet *et al.*, 1988].