CHAPTER 3 - NEW STRUCTURAL DATA FROM FIELD STUDIES IN NORTHWESTERN AND CENTRAL IBERIA

Based on the results of an extended literature study (presented in Chapter 4 and 5), several areas and time intervals were identified as lacking good data on the (paleo)stress field. However, in many of these areas or time intervals, additional constraints cannot be obtained, due to absence of sediments of the time interval considered.

Within the framework of the SIGMA project [SIGMA, 1998], which focused on determination of the recent stress field, the northwestern part of Iberia was investigated for kinematic indicators and structural data. The NWO "Iberia" project the focus was on the NE-part of the Madrid Basin, along the southeastern border of the Spanish Central System. In the Paleogene deposits of this area growth strata were recognized during an initial survey and a combined study of sedimentology, structural geology and geothermochronology (fission tracks) was carried out in order to unravel the Paleogene tectonic history of the area and to investigate potential constraints this could yield on the tectonic evolution of central Iberia.

This chapter is subdivided in two sections. The first section deals with new (paleo)stress data from northwestern Iberia and discusses the results in a more general framework. The second section is devoted to the Paleogene evolution of the northeastern Spanish Central System.

3.1 New structural and kinematic indicator data for NW Iberia

The elevated basement ranges of the Cantabrian Cordillera and the NW of Iberia traditionally have been studied for the Hercynian deformation of the region (e.g. Lefort [1979]; Matte [1986] and Pérez Estaún *et al.* [1988] and references therein). Before opening of the Bay of Biscay, Iberia was part of the Ibero-Armorican arc, the arcuate Hercynian deformation front in Iberia, S. England, Armorica (N. France), the Ardennes (Belgium), and Newfoundland. The Hercynian structure can still be observed very well and has a strong influence on present-day topography. The Cantabrian Cordillera, however, shows marked differences in elevation and physiography with respect to the rest of western Iberia and other belts of Hercynian age (e.g. the Ardennes). Younger tectonic processes must have been active in the region in order to explain the present-day geomorphologic expression of the high (2500m) and the steep mountains towering above the flat Duero basin and at small distance from the Gulf of Biscay. Alpine deformation in the region resulted from southward subduction of the European plate under the Iberian plate during the Paleocene-Eocene [Boillot *et al.,* 1979; Alvarez Marrón *et al.*, 1995; Gallart *et al.*, 1995]. Undoubtedly, stresses related to this subduction were transmitted into the nearby Iberian continent and have led to deformation. Recently, more Alpine structures were being recognized within the Cordillera e.g. [Marín, *et al.*, 1995], offshore (Middle Miocene folding, unpublished Shell data), and along its southern border [Alonso *et al.*, 1996]. Direct observations of Alpine deformation, however, remain limited due to scarceness of Mesozoic and Cenozoic sediments that could yield age-constraints on observed tectonic activity. Tertiary sediments do occur in the Duero Basin and several small, scattered and isolated intramontaine Tertiary basins (see Figure 3.1.1). These sediments are only dated in the Duero Basin and in the lignite-bearing As Pontes Basin. In the latter case, both Late Oligocene to Early Miocene and Middle to Late Miocene ages have been suggested, based on fossil dating and palynology. Recently, magnetostratigraphic dating [Huerta *et al.*, 1996] has constrained the tectonic activity in the As Pontes basin to have lasted from 28.7Ma until ~21Ma. Dating of terrigenous sediments in the other small intramontaine basins was carried out by correlation to similar sediments in basins in which age constraints have been obtained (the Duero and As Pontes). This relative dating should be considered with great caution only [Martín Serrano *et al.*, 1996], as should conclusions on timing of deformation observed in these basins based on this type of dating.

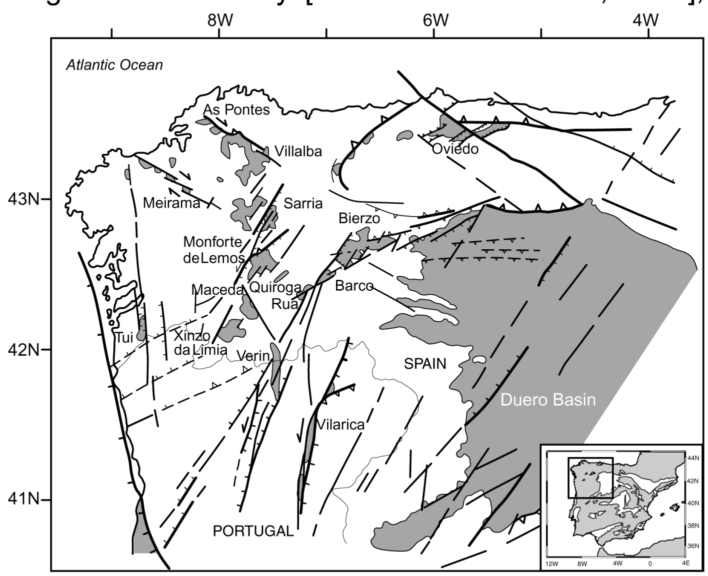


Figure 3.1.1
Overview of the Northwestern Iberian Peninsula, the major Alpine faults and the local Cenozoic basins.

Traditionally, all the basins of NW Iberia were interpreted as remnants of one larger basin ([Delmaire Bray, 1977; Sluiter and Pannekoek, 1964]) that was dominated by normal faulting and subsequently partly eroded. Within the lignite-bearing As Pontes Basin, however, compression structures were discovered and the basin evolution was linked to compressive strike-slip deformation ([Garcia Aguilar, 1987; Bacelar *et al.*, 1988; Cabrera *et al.*, 1996; Huerta *et al.*, 1996]). Evidence for compression has been put forward for several of the other basins as well (e.g. Santanach Prat [1994]).

With regard to the tectonic regimes that have been proposed to form and subsequently deform the basins, marked differences occur between the numerous small basins. The basins in the northwestern extreme of the region are situated along two ~NW-SE trending strike-slip faults. They are part of a regional set of faults with the same trend. This set of faults deformed the accretionary wedge that formed during the Early Tertiary subduction in a late stage of the Pyrenean compression [Cabrera *et al.*, 1996]. Basins (Meirama, As Pontes) along these faults have been interpreted as pull-apart basins [Ferrus Piñol, 1994] related to non-linearity in the fault traces. The Vilariça basin in NE-Portugal [Cabral, 1989] is related to strike-slip motion as well, but situated along the NNE-trending Ponsul fault. The Monforte de Lemos, Maceda and Quiroga basins are most likely related to strike-slip faulting along NNE trending faults as well [Del Olmo Sanz, 1985] but observations of the border contacts are rare. The Tui basin, however, has been interpreted to have an extensional origin [Santanach Prat, 1994].

On the other hand, the Oviedo Basin is interpreted as a thrust-related basin resulting from strike-slip along the NW-SE trending Ventaniella-fault [Alonso *et al.*, 1996] in a clear N-S compressional setting. The same tectonic regime (NS compression) is proposed for the northern edge of the Duero Basin where Tertiary sediments are inclined to vertical [Alonso *et al.*, 1996] by southward thrusted Paleozoic basement of the Cantabrian Cordillera. The origin of the Bierzo Basin has been related to a combination of N-S compression and strike-slip tectonics based on its geographical position in between the northern Duero (NS compression) and the Vilariça (strike-slip) basin [Santanach Prat, 1994].

Because of the limited amount of data and the inferred differences in origin and tectonic style of the basins, it is hard to present a general tectonic model explaining the evolution of all of them. Santanach Prat [1994] argued that the structure of Tertiary basins in NW Spain is in agreement with NS-shortening. This author relates development of these basins with the Pyrenean orogeny, solely. In this region, this Pyrenean activity only lasted till the late Oligocene-Early Miocene. Present tectonic activity is suggested by increased seismic activity in northwestern Iberia, with earthquakes of magnitude (Mb) up to 5.4 [SIGMA, 1998]. This shows that compression related to the Pyrenean collision was not the last tectonic event that deformed the region. The present-day stress field inferred from focal mechanism solutions indicates approximately NNW-SSE compression (N140^{o} -N160^{o}), with a relatively large perpendicular extensional component [SIGMA, 1998].
As yet, paleostress data in the region were absent. This type of data was required to discriminate between the effects of the Pyrenean collision and younger deformation effects. Therefore, structural geological data were gathered in cooperation with the SIGMA project [SIGMA, 1998] and will be presented in the next sections. Based on the limited occurrence of Tertiary sediments and previous observations within the SIGMA framework, two specific areas were selected to complete the database of kinematic indicator data. The first is the Bierzo basin and its sub-basins, and the second is the Asturian/Cantabrian coast. The general geology and structural outline and data for both will be described in the next section. Finally, the observations will be discussed in the regional context of northwest Iberia.

Bierzo Basin

The Bierzo basin (see Figure 3.1.2) is the largest and most impressive intramontaine basin of NW Iberia (50 by 15 to 30 km). Topography surrounding the basin is still controlled by the trends of Hercynian structures and related lithologic boundaries. The basin forms a pronounced contrast with this trend, intersecting the trend of the older structures, as is visible in the shaded topography in Figure 3.1.5a. Mountains are as high as 2200m at small distances from the basin borders are and elevated over 1700m above the base of the flat basin floor (average elevation at 420m). The basin can be subdivided into two bigger sub-basins (Ponferrada & Bembibre/Noceda) and several smaller basins (Vega de Espinareda, Ribón). Towards the southwest, the narrow WSW trending O'Barco Basin has been studied as well because it basically is the southwestern extension of the Bierzo Basin. The sedimentary infill of the Bierzo Basin consists of a complex detritic assembly of conglomerates, sand, silt, clay, and carbonate strata up to 700 meters in thickness. No fossils have been found within the sediments; so indirect dating is generally done by correlation to sediments in the nearby Duero Basin. Sluiter and Pannekoek [1964] considered all the different facies to be local variations of one single sedimentary sequence. Later studies, IGME [1982a], IGME [1982b] and Herail [1982], distinguish two complex units separated by an unconformity that was associated with an important pulse of fracturing, resulting in the individualisation of the Bierzo Basin (s.l.) and the Duero Basin.

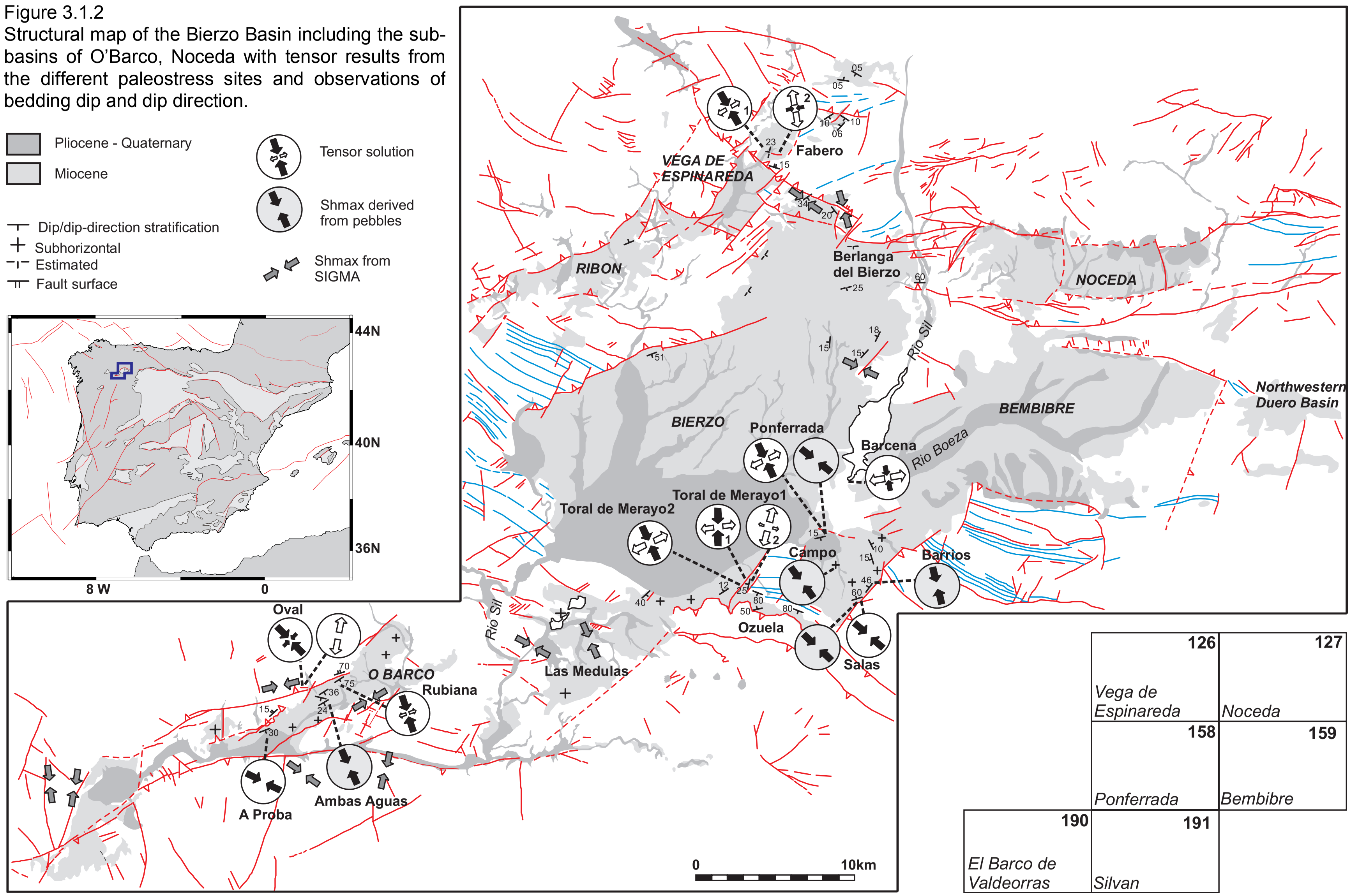
The lower unit (T1 in this study, or the Toral Formation of Herail [1982]) is attributed to the Miocene (Vindoboniense), although Delmaire Bray [1977] suggests Paleogene ages for part of the sequence. Generally the unit is composed of fine detritic sediment. At the base a coarse gravel base covers a thin layer of red clay. This coarse gravel fines upward into lime and clay with occasional carbonate material. The unit is interpreted as an alluvial fan changing from proximal setting to flood plain, deposited over gentle paleotopography. Based on distribution patterns of proximal and more distal facies in regional context, a sediment source located to the SW of the basin has been inferred [IGME, 1982b]. The upper sequence (T2, the Medulas and Santalla Formations of Herail [1982]) consists of red detritic sediments, generally coarser than the lower unit, and has been attributed to the Late Miocene to Pliocene.

The basement beneath the basin sediments is composed of multi-phase deformed Precambrian to Paleozoic (up to Lower Devonian) metasediments and igneous bodies with a discordant, folded and fractured uppermost Carboniferous (Stephanian) basin. The Hercynian structures still form an arc running N-S near the Asturian coast, turning ~SSW in the area around the Bierzo Basin. The sutures and sedimentary provinces that can be observed in the uplifted basement in the Cantabrian range can be traced into the western Duero Basin and are supposedly present under the Bierzo and the Duero Basin. The Carboniferous strata are folded in N-S direction, approximately. Because Mesozoic and Paleogene sediments are absent in the region, it is not possible to constrain this deformation more accurately than post-Carboniferous. More to the NW (in the Magdalena Basin) Cretaceous sediments have been folded together with the Carboniferous strata [IGME, 1982a]. This suggests an Alpine age for the deformation in the area around the Bierzo Basin.

The dominant structural trends in the entire basin are NNE-SSW and EW, and in the northeast and southwest an additional ENE-WSW trend is present (see Figure 3.1.2). Due to scarce outcrops, the contact between basement and Tertiary sediments can often only be observed indirectly in the field (change in color, vegetation, slope and/or lithology of clasts). Therefore, the origin of this contact remains unclear along most borders. Based on these limited observations [Sluiter and Pannekoek, 1964] present the basin borders as normal faults in their sections. Nevertheless, the authors tend to an interpretation of inverse movements along some basin border faults in their text. From this tectonic setting for the Bierzo Basin a model was derived explaining the various basins in NW Iberia to be remnants of a disected former larger basin.

More recent, a limited number of direct observations of the contact indicate that both the northern and the southern borders actually are thrusts, placing Paleozoic basement over the Neogene sediments. Geophysical methods have revealed an initial offset of faults on both sides of the Noceda sub-basin of more than 700m [IGME, 1982a]. A few outcrops reveal a ~N360^{o}/35^{o} dipping thrust along the northern border of this sub-basin, placing Stephanian metasediments over Tertiary sediments. Based on some of these outcrops and the trace of the border contact on geological maps, the tectonic origin of the basin borders has been deduced by Santanach Prat [1994]. A set of E-W trending thrusts is interpreted as forming several branches that join up towards the east to form the frontal thrust of the Cantabrian Cordillera. The (de)formation of the Bierzo Basin has, according to Santanach Prat [1994], taken place under an intermediate state of stress between strike-slip (governing the development of most of the basins in Galicia and northern Portugal), and pure compression (responsible for the development of the Cantabrian Cordillera and the Duero Basin). In this way, this author relates the development of the Bierzo Basin mainly to the Pyrenean collision. Multiple reactivations of the border faults, even after deposition of the Tertiary sediments has been inferred, based on the distribution of the sediments and recent activity (faults are active even during Quaternary [IGME, 1982a]), has altered the shape of the basin anew. In order to constrain the amount and type of deformation that affected the basin after its initial development, structural data were gathered along the basin edges.

Figure 3.1.2
Structural map of the Bierzo Basin including the sub-basins of O'Barco, Noceda with tensor results from the different paleostress sites and observations of bedding dip and dip direction.



New structural and kinematic indicator data from the Bierzo Basin

During a field campaign in May 1996, partly together with Dr. Jose Manuel Gonzalez-Casado (Universidad Autonoma de Madrid), kinematic indicator data have been gathered in the basin. Deformation of the basin sediments is observed mainly close to the borders of the basins. Along the southern border the basin fill consists mainly of conglomerates of the upper sequence (T2). Due to the nature of the sediments, kinematic indicators are hard to find but larger scale structures have been observed more often. Along the northern edge of the basin, outcrops of the lower unit (T1) occur, offering good paleostress sites in the carbonate levels intercalated in red clay. As suggested by the complex outline of the basin, a first examination of the observed kinematic indicator data does not provide a clear pattern of deformation. The observed fault planes in sediments along the borders of the basin do not group in clear families in many cases. A few outcrops will be discussed in more detail, and the general results of the paleostress observations are presented in Table 3.1.1 and discussed at the end of this section.

Fabero (Figure 3.1.3a)

Just southwest of Fabero a fresh outcrop was studied at a site for a future commercial zone. In a south-facing outcrop, 23 kinematic indicator data were observed in red clay and silt with intercalations of coarser beds containing pebbles and calcreted levels. These sediments can be attributed to the upper part of the lower unit (T1) and dated at around early Miocene. Therefore, the structural data observed in the outcrop demonstrate middle Miocene or younger tectonics. Two tensors have been deduced from fault slip data: ~NS compression and ~NNW-SSE extension. An interchange between σ_1 and σ_3 is suggested by the similar orientations of fault planes and the principal stress axes for both tensor solutions. An evolution in time cannot be obtained for the stress field. In both cases the tensor quality is relatively low, and a lot of faults remain unexplained. Observations of overprinted fault slip data do not fit in any of the two tensors, which clearly indicate reactivation of older structures. Therefore, the area may have been affected by at least three deformation events after the middle Miocene.

Rubiana (Figure 3.1.3b)

Just south of the northern border fault of the O'Barco Basin, a mixture of fault rock, cemented colluvial and Miocene sediments is observed. Bedding is hard to recognize, but seems to be oriented 150/75. Striations in this material show the same trend as in the quarry above the border fault: only 2 out of the 20 kinematic indicators show strike-slip movement. The resulting tensor is of very good quality, showing pure compression in N160^o direction, perpendicular to the border fault.
Within the basin, a set of low angle NNE-dipping thrusts places Paleozoic rocks southward over the Tertiary basin fill. These thrusts have a perfect theoretical orientation and dip to have been formed during the observed N160^o compression. The high-angle border faults might have controlled early sedimentation in the basin and were reactivated at a later stage with an inverse component.

Oval (Figure 3.1.3c)

Along the northern border of the O'Barco Basin, the border fault can be observed as a 70^o-80^o northward-dipping plane with Paleozoic in the hanging wall on top of Tertiary sediments in the footwall. NW of Oval, a quarry in Paleozoic quartzite is located just uphill of this high angle northern border thrust. At the scale of the outcrop normal faulting dominates. Kinematic indicators show mainly normal or reverse movement and only 3 out of the 34 measured faults show strike-slip movement. The latter contrasts with the

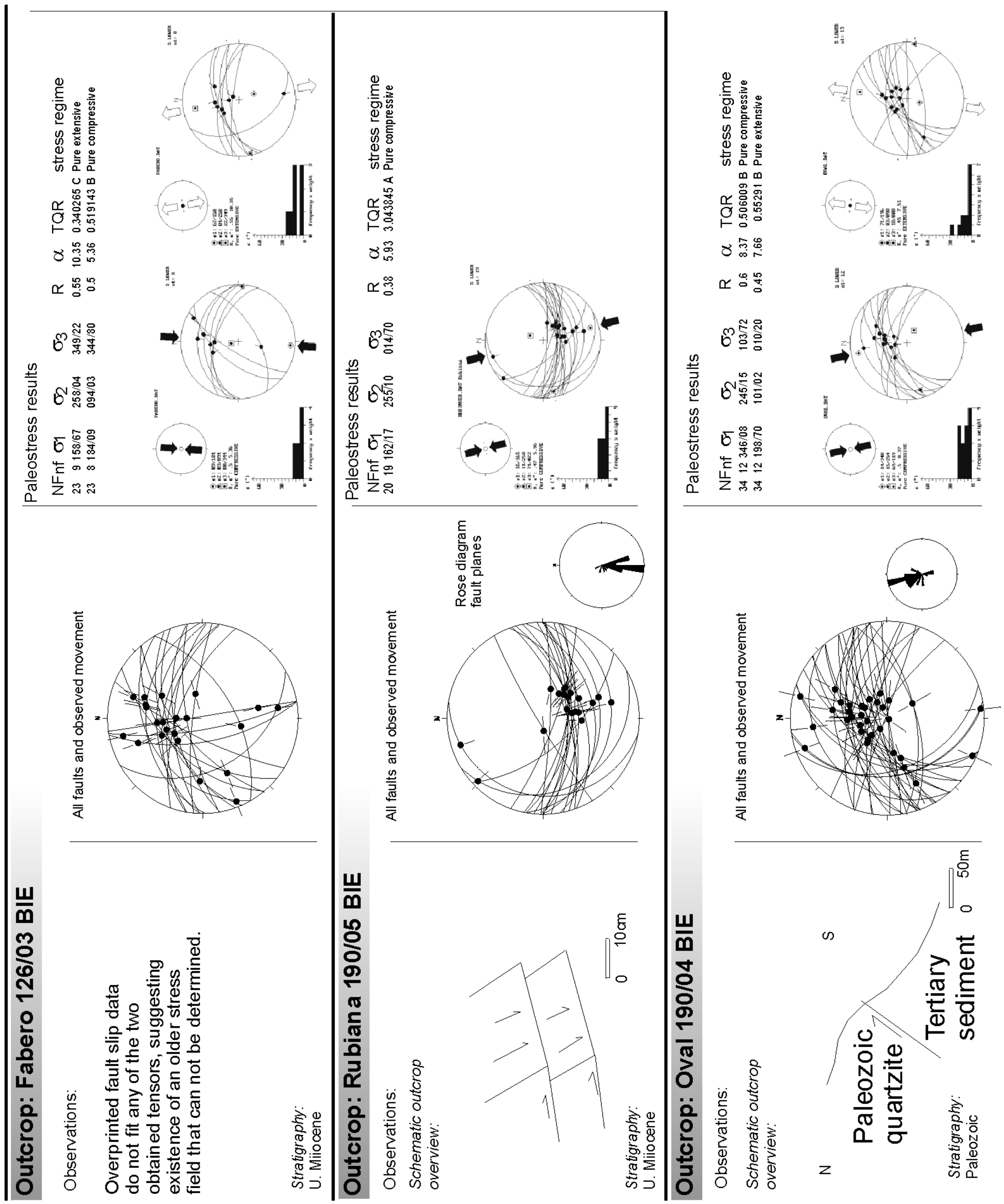


Figure 3.1.3
Observations and paleostress results for Fabero, Rubiana and Oval. See Table 3.1.1 for explanation of abbreviations. See Figure 3.1.2 for location of the stations.

strike-slip deformation suggested by Santanach Prat [1994]. The resulting tensors from this outcrop are: N346^o directed pure compression and N101^o directed pure extension. The compression is clearly related to southward thrusting, whereas the extensional event is a little enigmatic.

Ribón

The Romans mined the alluvial deposits of the Bierzo and NW Duero Basin for gold. They washed down huge parts of the red sediments by special techniques and gathered the gold flakes in the sediments in wool soaked in grease placed in the bedding of the man-made sedimentary fans. The most well known mine, Las Medulas, is located near the southwestern limit of the Bierzo Basin. North of Ribón, another of these ancient gold mines of the Romans created a cliff in the red sediments with in front of it a large fan, which can be dated rather confidently at being around 2000 year old. A very flat terrace of Rio Burbía consisting of well-rounded coarse pebbles cuts this fan. Presently the river is eroding its own terrace under which in the riverbed layers of red sediments are visible, dipping approximately 20^o to the south. This setting shows that the area has experienced significant vertical motions in the last 2000 years leading to erosion of the anthropogenic fan, to deposition of the terrace and finally to a renewed erosional stage. The contact between the Tertiary red beds and basement is not normal since the near horizontal beds of the cliff end to the north abruptly against Paleozoic basement. The vertical offset along the steep contact can be estimated to be at least of the order of 100m, which is the height of the cliffs from the valley floor. The contact itself cannot be observed and therefore the nature of the offset cannot be determined. Parallel to the mapped contact between basement and red sediments on the eastern side of the valley, a fault in the Paleozoic basement on the opposite bank (west) of Rio Burbía has been observed. A few reverse-sinistral striations have been found, from which unfortunately no good tensor could be obtained.

Toral de Merayo1 (Figure 3.1.4a)

Along the southern border of the Bierzo sub-basin, near Toral de Merayo, a sand and clay-pit offers excellent outcrop conditions. An approximately 1m deep and 6m wide paleochannel is observed that has been draining towards the W, parallel to the present-day southern basin border. Interestingly, directly to the east, from where the channel has drained from a highly elevated basement block occurs presently. This proofs that relative vertical motions occurred after deposition of the Miocene sequence. The paleochannel is cut by several steep faults that cut an older normal fault. Small-scale inverse structures were observed and the steep faults reflect strike-slip motion. The tensor results show two deformation phases: an early pure extensive (Sh_{min} ~190^o) and a later pure strike-slip deformation, with Sh_{max} oriented due N. Just some 100 meters to the west (Toral de Merayo2) in an abandoned pit, nearly pure strike-slip is observed with a N336^o oriented Sh_{max}, consistent with the phase observed in Toral de Merayo1.

Ponferrada (Figure 3.1.4b)

An abandoned gravel/sand quarry is located southwest of Ponferrada along the road to Molinaseca at kilometer 1.5. Nearly vertical Paleozoic quartzite (S_0:230/80) is covered by a very coarse (U. Miocene?) conglomerate along a red clay tapered contact dipping gently to the north (350/10). This red clay based conglomerate is described as the base of the Miocene sediments [IGME, 1982a]. In the conglomerate some larger scale structures are present and many of the pebbles, up to the highest levels under the carbonate cemented Late Quaternary cap, are broken and show pressure solution marks. The compression direction inferred from these pebbles is ~N130^{o}E, a direction that is observed in the fault inversion results at the same locality as well. A well-constrained tensor is obtained that indicates compressive strike-slip for the majority of the faults.

Salas (Figure 3.1.4c)
Crossing the locality Salas de los Barrios uphill, on the left side of the road an outcrop shows a steep northwestward (340/60) dipping sequence of conglomerate, sandstone and silt. This outcrop is very close to the southern border of the basin: a few tens of meters uphill Paleozoic basement outcrops. The contact cannot be observed directly. Reverse faulting along ~N320^{o} and ~N150^{o} planes is obvious from the outcrop, showing zones of sheared pebble beds. Several of the conglomerate pebbles show kinematic indicators, and many pebbles of Paleozoic basement are broken indicating rather intense deformation. Both fault slip data and kinematic indicators at pebbles show a ~N310^{o} directed maximum horizontal compression. Some hundred meters down the road normal faulting in nearly horizontal bedding can be observed. Spatial distribution of deformation types and dip direction trends in the Tertiary sediments suggest sinistral transpressive movement along this fault.

General results

The results obtained by pressure solution and striated surfaces on pebbles yield a very consistent pattern of stress orientations. In all of the sites where the direction of Sh_{max} has been determined from both pebbles and fault slip data, the solution of the first was reflected in the latter as well. The quality of the tensors is reasonable to good in most of the stations (see Table 3.1.1) even though for many of the outcrops, only approximately 70% of the kinematic indicators fit the calculated tensors. Moreover, most of the faults that can be explained by the calculated tensor are considered to be reactivated, not newly formed. Earlier phases of deformation that cannot be deduced using the paleostress method might be responsible for faults that cannot be explained by the obtained tensors. Strike-slip is the dominant state of stress, and the direction of Sh_{max} is on average NNW.

It is hard to reconstruct a temporal evolution of the stress field, because only for two outcrops it was possible to determine multiple tensors. Only in Toral de Merayo1 the stress fields have been dated relatively: the younger stress field is extensive, with extension direction near N-S. Based on this observation, a similar temporal evolution could be validated for the site Fabero. Obviously, more data are required to be able to conclude whether this extension is a local phenomenon, a later stage in the evolution of the basin or whether this represents a simultaneous coaxial N-S compression with N-S extension.

Geomorphology and spatial distribution of Tertiary sediments

Combining the results obtained from the paleostress measurements with other independent data about displacements of the border faults might enable us to determine the tectonic evolution of the Bierzo Basin and surrounding sub-basins. One such data source is the spatial distribution of the Tertiary sediments. A compilation of the minimum and maximum altitude of occurrences of the two Tertiary sequences is presented in Figure 3.1.5b. Both along the basin borders, between the sub-basins and within the basins several irregularities can be observed. Because both sequences consist of fine detritic alluvial fan units, apart from a limited coarse base of the first sequence, the assumption is made that the sequences have been deposited along gentle slopes.

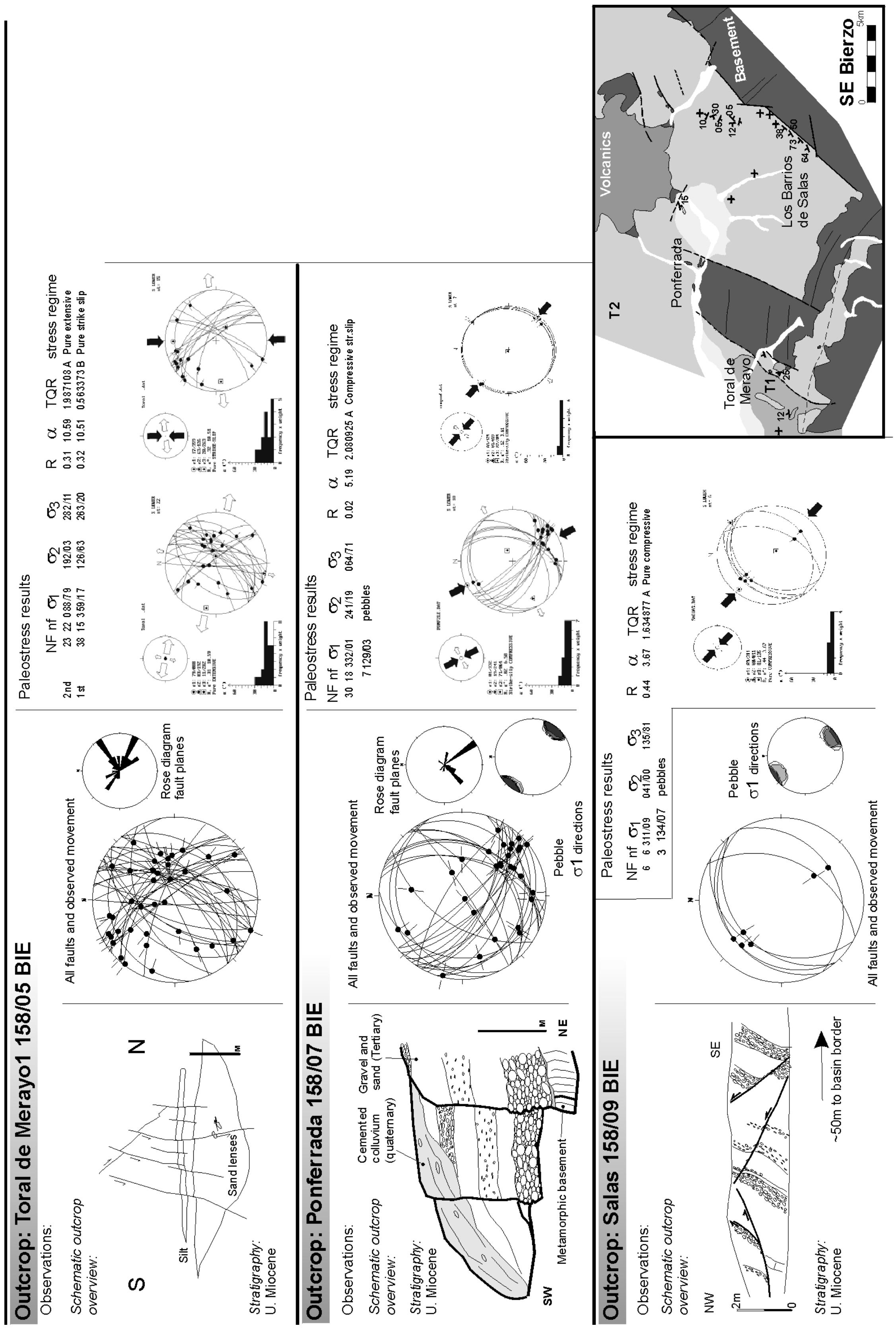


Figure 3.1.4
Observations and paleostress results for Toral de Merayo1, Ponferrada and Salas. See Table 3.1.1 for explanation of abbreviations paleostress results. See Figure 3.1.2 for location of the stations.

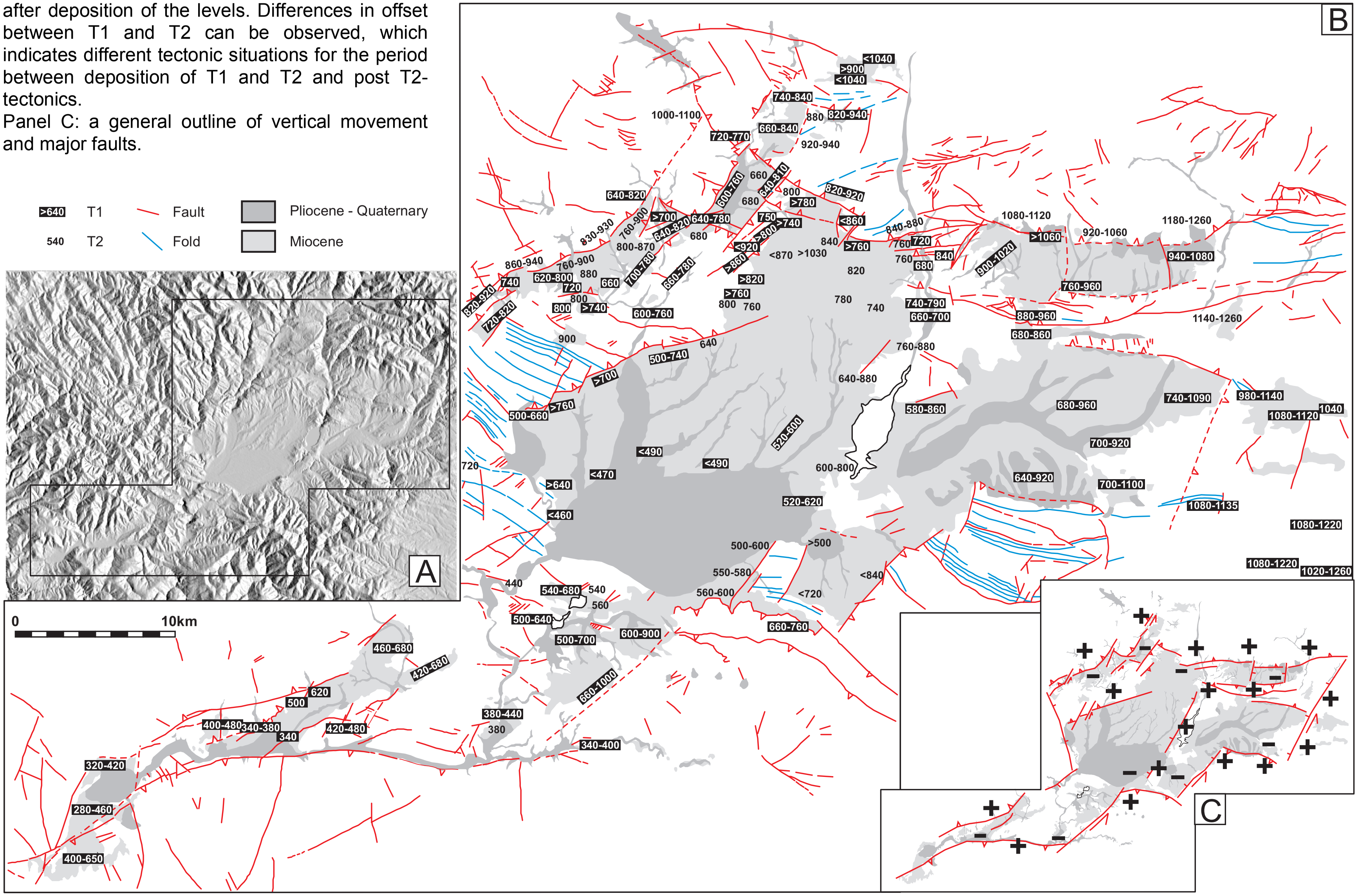
Paleo-topography can be inferred where the lower topographic limits differs on both sides of such an irregularity while the upper limits are coincident. Where the base and top level are displaced by the same order of magnitude, tectonic activity is assumed to have caused the anomaly.
Interestingly, for the first interval a source of sediments has been inferred to be located far to the southwest of the basin [Corrochano and Carballeira, 1983]. The base of sequence T1, however, slopes in a direction towards the SW. Unfortunately; it is impossible to determine whether the base of the T1-sequence has the same age throughout the entire basin. This leaves two possible explanations: (a) the basin filled progressively with the development of the T1-sequence, onlapping the basement in a northeastern direction through time (in this case its base is not time equivalent), or (b) late stage tilting 'reversed' the direction of the depositional slopes (so the base is time equivalent).

One of the main observations is, that if the sediments of T1 can be correlated to sediments in the Duero Basin, then either the Bierzo Basin has subsided or the western Duero Basin has been uplifted significantly since deposition of these sediments. Between the eastern Bierzo and western Duero Basin the elevation difference of the unit amounts up to 300m. This hypothesis is supported by the sequence of middle to upper Miocene sediments in the western sector of the Duero Basin, representing several alluvial depositional systems. The lower sequence is composed of typical distal alluvial inundation plains without any coarse sediment with sourcing from the west (via the Bierzo Basin), but the middle and upper sequences contain a high amount of clasts [Corrochano and Carballeira, 1983]. These upper alluvial systems indicate a reactivation of the western margin of the Duero Basin, just as the coarser deposits of T2 in the Bierzo Basin indicate reactivation of reliefs. The inferred reactivation during the Middle-Late Miocene was most likely associated with normal movement along steep NNE trending faults. This reactivation of the basin margins and tilting of blocks not only divided the Bierzo Basin from the Duero Basin, but 'disintegrated' the Bierzo Basin into several sub-basins as well. In spite of the neotectonic overprinting that has complicated the setting, three eastward tilted blocks can still be recognized in Figure 3.1.2 (panel B and C): (1) the western Duero, (2) the Bembibre/Noceda block and (3) the Ponferrada block. The latter two are separated by an elevated basement structure running in NNE direction from Ponferrada.

Both the T1 and T2 sequences, which were deposited subsequently during Late Miocene and Pliocene, have been affected by younger tectonic activity. Especially along the northern border compression has activated approximately E-W trending low angle thrusts, which lifted up the massifs around the basin and separated the Noceda sub-basin (NE) from the Bembibre Basin.

Additional information on recent vertical motions and block tilting can be obtained from an analysis of the drainage pattern of the area. Small rivers (Burbía, Valcarce, Cua, not indicated on map) running through the Paleozoic basement have cut deep and steep valleys, suggesting uplift during a late stage. Along the Noceda River, a remarkable high number of terraces are present given the small size of the river and the location of the terraces at the headwaters. Moreover, the terraces are all located on the right bank of the river, which indicates that neotectonic movements are tilting the Noceda sub-basin, lifting its western part up [IGME, 1982a]. Rio Boeza (provenance from the Bembibre

Figure 3.1.5
Height-distribution of the two sequences in the Tertiary sediments in the Bierzo Basin (s.l.). Panel A: shaded topography of the area. Panel B: lower and upper altitudes of level T1 (in black boxes) and level T2 (normal). Large steps in altitude along the basin borders show tectonic movement after deposition of the levels. Differences in offset between T1 and T2 can be observed, which indicates different tectonic situations for the period between deposition of T1 and T2 and post T2-tectonics.
Panel C: a general outline of vertical movement and major faults.



sub-basin) and Rio Sil show a peculiar pattern of incision and deposition: (a) deep incisions occur in elevated basement blocks, for example just east and north-northeast of Ponferrada, and at the 'outlet' of the Bierzo Basin, in its southwestern extreme where the canyon of Rio Sil is impressively steep. In the first case, the incision results in a very peculiar setting: Rio Sil is flowing through a canyon cut into Paleozoic basement at elevations of up to 800 meters, while on both sides of this basement block basins occur of which the basin floor is at an elevation of about 500 meter only. (b) in contrast, when the rivers flow through the Bembibre, Ponferrada and O'Barco sub-basins, sedimentation and terrace formation are active. In the O'Barco the accumulation of Quaternary sediments occurs in a ~E-W trending valley of rio Sil nowadays and not anymore in the ~ENE trending Miocene/Pliocene basin. Quaternary terraces in the Ponferrada basin are lowering southward and form an extensive plane. River Sil runs along the southern border of the basin and is eroding Tertiary sediments, suggesting an additional southward tilting of the Ponferrada Basin. These features and patterns illustrate that blocks are still actively moving with respect to one another, resulting in tilting, subsidence and uplift, sedimentation, and incision, see Panel C of Figure 3.1.5.

Synthesis of new stress indicator data and geomorphology

Figure 3.1.2 shows the results of the paleostress determinations and observations of dip and dip directions of bedding. For the early development of the basin, a model like that proposed by Santanach Prat [1994] relating the development of the Bierzo basin to its intermediate position between regional uniaxial compression in the Cantabrian and strike-slip deformation in north Portugal and Galicia is very plausible. However, as shown by a fracturing period between Early Miocene and Late Miocene and faulting of up to Quaternary sediments, the development of the Bierzo Basin is not solely related to the Pyrenean compression. To the contrary, results of the paleostress observations indicate stress directions that can be related to the Middle Miocene to present-day Betic compression. The inferred orientation of Sh_{max} for the region during the Pyrenean compression would have been ~N-S, at only small angles to the results obtained in this study. Therefore, the numerous observations of reactivation of faults suggest that deformation related to older (Pyrenean) compression has contributed a great deal to the formation and deformation of the Bierzo basin. Unfortunately, due to the high amount of overprinting, it has not been possible to quantify any older stress field.
The important extensional component observed in the paleostress results and the present-day stress field might have been relatively more important during periods when the compression related to the Betic orogeny was of minor importance.

Monforte and Sarria Basins

Two small basins, located to the west of the Bierzo Basin (Figure 3.1.1). The mountains surrounding these rather flat basins are lower than around the Bierzo Basin and well rounded, a geomorphology resembling a region that was formed mainly during the Hercynian orogeny. This fact suggests minor uplift related to Alpine compression in this region when compared to the Cantabrian Range. The presence of Tertiary sediments however indicates limited Alpine deformation of this part of Iberia as well. Some Paleozoic outcrops can still be found within the basins. It cannot be determined in the field whether these are structurally controlled or remnants of considerable paleo-topography filled in by Miocene sediments. Outcrops of Tertiary sediments are rare, and in the few that are present, nearly no tectonic structures have been observed. In only one outcrop, east of the village of Sarria, was it possible to determine the direction of Sh_{max}, which is oriented N125^{o} in this region according to SIGMA [1998].

Station	*code*	*age sediments*		*NF*	*nf*	$\sigma 1$	$\sigma 2$	$\sigma 3$	*R*	α	*TQR*		*stress field*
Fabero	126/03	U. Miocene		23	9	158/67	258/04	349/22	0.55	10.35	0.34	**C**	Pure extensive
				23	8	184/09	094/03	344/80	0.5	5.36	0.52	**B**	Pure compressive
Barcena	158/04			7	6	122/82	350/05	260/04	0.83	6.2	0.83	**B**	Strike slip extensive
Toral de Merayo1	158/05	U. Miocene	2nd	23	22	088/79	192/03	282/11	0.31	10.59	1.99	**A**	Pure extensive
			1st	38	15	359/17	126/63	263/20	0.32	10.51	0.56	**B**	Pure strike slip
Toral de Merayo2	158/06	U. Miocene		18	17	336/04	076/68	245/21	0.6	7.55	2.13	**A**	Pure strike slip
Ponferrada	158/07	U. Miocene		30	18	332/01	241/19	064/71	0.02	5.19	2.08	**A**	Compressive str.slip
			pebbles	7		129/03							
Salas	158/09	U. Miocene	pebbles	3		134/07							
				6	6	311/09	041/00	135/81	0.44	3.67	1.63	**A**	Pure compressive
Barrios	158/08	U. Miocene	pebbles	6	6	347/30							
Campo	158/10	U.Miocene	pebbles	3	3	325/05							
Oval	190/04			34	12	346/08	245/15	103/72	0.6	8.37	0.51	**B**	Pure compressive
				34	12	198/70	101/02	010/20	0.45	7.66	0.55	**B**	Pure extensive
Rubiana	190/05	U.Miocene		20	19	162/17	255/10	014/70	0.38	5.93	3.04	**A**	Pure compressive
A Proba	190/06	U.Miocene		13	9	115/08	208/19	002/69	0.41	9.18	0.68	**B**	Pure compressive
Ambas Aguas	190/07	U.Miocene	pebbles	4		157/05							

Table 3.1.1
Table showing all results of the observations at the paleostress stations in the Bierzo region. Code equal to the SIGMA-classification [SIGMA, 1998]. NF= total number of faults, nf= number of faults explained by tensor, orientations of the principal axes of stress and the stress ratio R. α= angle of deviation between the calculated striation and the observed one on a plane. TQR= Tensor Quality Rank, following Delvaux [1994]. TQR has not been classified (A, B, or C for good, reliable, and unreliable respectively) for the results obtained from deformed pebbles in the conglomerates.

The area is the locus of many shallow earthquakes of moderate magnitude (up to 5.4) over the last years, just as the entire NW of Iberia experienced an increase in seismic activity (see http://www.geo.ign.es/, the online database of the Instituto Geográfico Nacional of Spain). Focal mechanism solutions [SIGMA, 1998] show an extensional regime for N-S trending fault planes, dipping near vertical. Because seismics do not coincide with existing basin borders, it could be the onset of a future basin. Given the nearly NW-SE trending maximum horizontal compression direction inferred for this region, the mechanisms imply that a large perpendicular component of extension exists. Possible reasons for this extension are discussed in Chapter 6.

N. Duero Basin

The Duero basin is the largest Tertiary basin in Iberia and is considered to be a foreland basin related to the southward thrusting of the Cantabrian Cordillera during the Pyrenean collision [Alonso *et al.*, 1996]. The basin has been the locus of continental sedimentation from the Paleocene to Pliocene/Quaternary (see Chapter 4). Fluxes of alluvial fan sediments along the rims of the basin record periodical reactivation of the basin margins; these fans grade laterally into fine distal alluvial fan sediments while in the center of the basin lacustrine environments prevailed [Portero Garcia *et al.*, 1983]. Sedimentary infill of the basin reaches well over 3500 meters close to the Cantabrian front. Along this front steeply inclined Tertiary sediments are observed [Jiménez Fuentes *et al.*, 1983]. Observations within the basin show the absence of foreland deformation in horizontal and undisturbed Neogene strata suggesting that foreland deformation is of only minor importance in the basin. Although the straight valleys of several rivers (e.g. Arlanzon, Pisuerga) in the Duero Basin suggest a structural control, investigation of cliffs that are actively eroded by those rivers did not yield a single deformation related structure. A seismic reflection line (ESCIN3) through the Cantabrian Range and the northern Duero Basin [Pulgar *et al.*, 1997] has revealed that deformation is limited in extent and concentrated along the southern border of the Cantabrian Cordillera. Another observation in the seismic line is the absence of flexural bending of the 'Iberian' plate under the loading by the Cantabrian Cordillera, while this loading is estimated to be significant [Alonso *et al.*, 1996]. Therefore, it appears that either the crust under the

Cantabrian range and Duero Basin is very strong, transmitting stress to internal regions of Iberia, or the basement is extremely weak, leading to very localized isostatic compensation.

Cantabrian/Asturian coast

Along the coastline of Asturias and Cantabria, a limited number of outcrops of Tertiary sediments can be observed. They are restricted to basically two areas: the synclinal structure near San Roman/Santander and the area around San Vicente de la Barquera (see Figure 3.1.6, based on the geological maps of Spain [ITGME, 1994] and Cantabria [ITGME, 1990a]). The lower boundary of the sedimentary sequence is a major disconformity separating the Mesozoic from the younger sediments, restricted to the lower to middle Paleogene and subdivided in two sequences: (1) the lower part (L. Paleocene-Eocene) consists internal platform calcarenites with abundant bentonic fossils (Nummulites, Alveolinas), (2) the upper part (Eocene to lower Oligocene) shows differentiation into areas with calcareous turbidites and conglomerates (major part of the outcrops), while in other areas shallow platform sediments of Priabonian age were deposited. This differentiation suggests that the first deformation related to the Pyrenean collision started in this region around the latest Eocene. From regional studies and Shell exploration data, show offshore folding, is inferred that deformation related to Pyrenean collision terminated towards the end the Oligocene- Early Miocene.

Lepvrier & Martínez-García [1990] carried out a paleostress study in the region from San Vicente de la Barquera in the east to Gijon in the west. Based on measurements in mainly Mesozoic rocks, the Tertiary evolution of the stress field in the region was linked with the general Iberian-Eurasian convergence and collision. In principle this seems justified, because the only regional compression phase supposed to have affected the area since the Mesozoic was related to the L.Cretaceous-Tertiary Pyrenean collision. The stress orientation obtained in all sites shows a very consistent NNW-SSE compression with in some cases additional perpendicular extension, except in one site near San Vicente de la Barquera. Interestingly, this is exactly the only site where kinematic indicators have been measured in Tertiary sediments and a deviating NNE-SSW directed maximum horizontal compression results from the inversion of fault data. Lepvrier & Martínez-García [1990] relate this feature to a late stage of stress when Iberia became part of Eurasia. In order to obtain better constraints on the Tertiary stress field, kinematic indicator data were gathered in Tertiary sediments in the region, focusing on the area near San Vicente de la Barquera (see Figure 3.1.6). This could shed light on the following two major questions: (1) did a reorientation of the stress field occur during the Tertiary as proposed by Lepvrier and Martínez-García [1990]? and (2) are extensional components, as observed in the kinematic indicator results obtained by the latter authors, related to Mesozoic rifting that affected the region (see García Mondéjar *et al.* [1996]) to form the Bay of Biscay or are these related to more recent tectonics?

Kinematic indicator data

During a field campaign in April 1997, together with SIGMA-project partner Dr. Miguel Rodriguez Pascua (Universidad San Pablo Madrid), 217 fault slip data were measured in 12 different sites. These sites were predominantly outcrops of the calcareous L. Eocene to Middle Oligocene sediments located around San Vicente de la Barquera. Just west of San Vicente de la Barquera, repetitions of the stratigraphy occur due to several thrusts related to a major low angle thrust that places Mesozoic (Aptian) over Eocene sediments. Displacement to the west along this structure is estimated to have been as

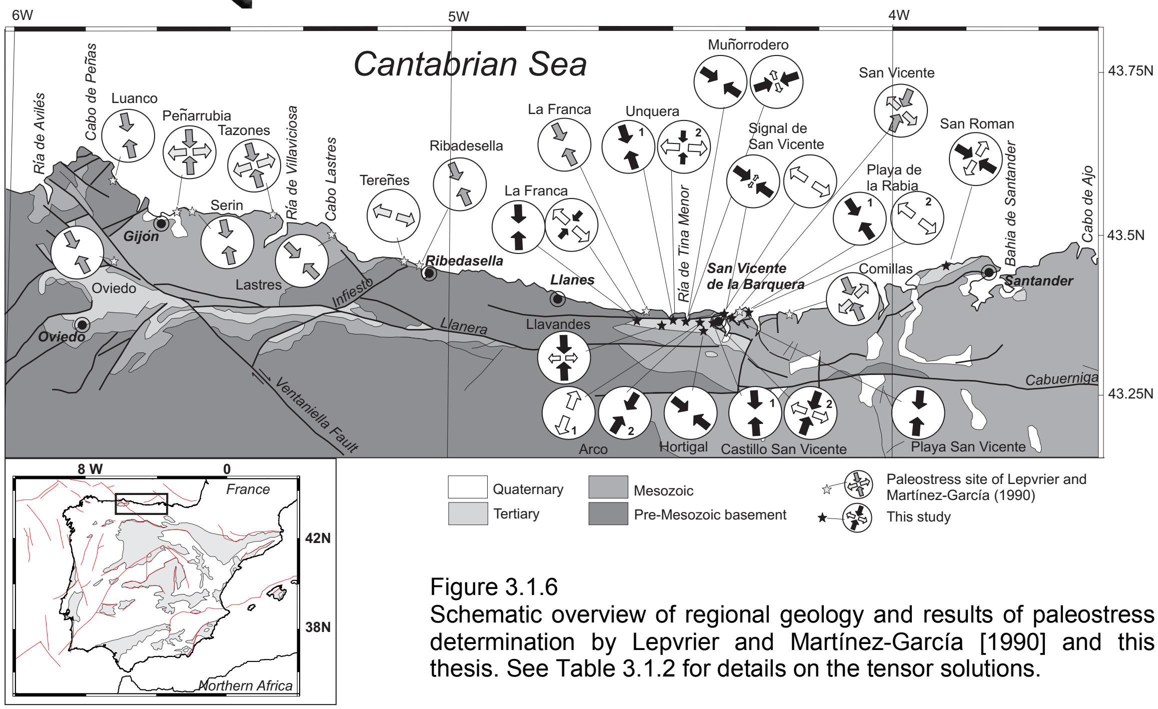


Figure 3.1.6
Schematic overview of regional geology and results of paleostress determination by Lepvrier and Martínez-García [1990] and this thesis. See Table 3.1.2 for details on the tensor solutions.

much as 7 kilometer [ITGME, 1990a]. Age constraints on the latest activity of this structure were obtained from Lower-Middle Oligocene rocks that are cut by the frontal thrust. A few outcrops will be discussed in more detail, whereas the general results are presented in Table 3.1.2 and discussed at the end of this section.

Signal de San Vicente (see Figure 3.1.7a)
At the entrance to the harbor of San Vicente de la Barquera, near vertical Eocene limestone with Nummulites form a natural sea barrier. A conjugate set of normal faults with gentle strike-slip component is recognized in ~310/80 and ~130/60 oriented faults. A second family of faults is a set of ~160/30 oblique reverse faults. From both sets a different tensor solution is obtained: a pure compressional one with Sh_{max} oriented N303^{o} and a purely extensional one with Sh_{min} oriented N304^{o}. These might well be due to permutations of the principal axes of stress in the area.

Hortigal (see Figure 3.1.7b)
West of the village Hortigal, in a set of double bends of the road to Estrada, Lower Eocene limestone with Nummulites and Alveolinas contain centimeter-scale calcite steps that have been formed by inverse motion along faults oriented ~340/50. All calcite steps show the same orientation (~030^{o} angular difference with the strike of the faults) and result in a straightforward tensor solution: N129^{o} directed maximum compression.

Playa de la Rabia/Oyambre (see Figure 3.1.7c)
This outcrop is located in a gentle syncline just south of a north-verging thrust that puts overturned Oligocene silt on top of itself. Low-angle thrusts (parallel to the major thrust) and steep faults, slightly offsetting the thrusts, are observed in the outcrop. Closer examination of the outcrop reveals two sets of striations on a fault plane, the overprinted (thus older) set is indicating reverse movement, the overprinting set shows strike-slip displacement. A good tensor solution is obtained from the first set, explaining 10 out of 17 faults and indicating pure compression with Sh_{max} oriented N327^{o}. All faults that in the

field were classified as 'older' fall into this group. This result can be related directly to thrusting. The strike-slip set indicates reactivation of the faults during a subsequent extensional event with Sh_{max} directed N121°, while additionally a few new strike-slip faults developed.

The Tensor Rank Quality is in general acceptable to good in this region and, although results are far from homogeneous, in general N-NNW directed Sh_{max} prevails. No distinction can be made between results obtained from Eocene or Lower Oligocene sediments. In general such an observation is interpreted as an indication that the major deformation occurred after the Early Oligocene. Based on regional knowledge (see Chapter 4 and 5 for more detail), however, progressive deformation related to the short-lived subduction with a similar state of stress since Late Eocene should not be discarded. The rather inhomogeneous pattern of the stress results near San Vicente de la Barquera might be related to the complex thrust structure mentioned before. Although obscured by this structural complexity, a relatively clear development in time and place of the stress field can be observed. The older stress field is generally pure compressional, with a small extensional component. The orientation of maximum horizontal compression is N-S to NNW-SSE. In all of the four outcrops where the relative age of the stress orientations have been determined, the younger stress field shows a large extensional component (predominant stress fields is extensive strike-slip) and the maximum horizontal compression is oriented on average NNE.

Station	*code*	*age sediments*		*NF*	*nf*	σ_1	σ_2	σ_3	*R*	α	*TQR*		*stress field*
Arco	33/05	M. Eocene	1st	35	17	281/56	098/34	189/01	0.42	8.45	0.98	**B**	Pure extensive
			2nd	18	7	211/03	301/08	101/82	0.5	15.11	0.18	**C**	Pure compressive
Hortigal	33/06	L. Eocene		10	10	129/03	036/49	222/41	0.4	6.62	1.51	**A**	Pure compressive
Playa de la Rabia	33/02	Oligocene	1st	17	10	327/04	236/05	096/83	0.46	6.61	0.89	**B**	Compressive str.slip
			2nd	17	5	284/78	031/03	121/11	0.5	4.07	0.36	**C**	Pure extensive
Unquera	33/04	M. Eocene	1st	20	5	341/12	073/07	193/76	0.75	6.56	0.19	**C**	Pure compressive
			2nd	15	10	011/62	277/02	186/28	0.68	7.63	0.87	**B**	Strike slip extensive
San Vicente	33/01	Oligocene		10	6	005/12	274/03	171/77	0.34	6.1	0.59	**B**	Pure compressive
Llavandes	32/01	L. Eocene		2	2	000/10	268/08	137/78	0.1	2.45	0.82	**B**	Compressive str.slip
La Franca	32/03	L.- M. Eocene		15	8	003/15	102/30	250/56	0.44	6.94	0.61	**B**	Pure compressive
				15	4	222/10	112/61	318/27	0.98	8.18	0.13	**C**	Extensive strike slip
Castillo	33/03	L. Eocene		68	36	176/04	267/09	062/08	0.4	10.51	1.81	**A**	Pure compressive
San Vicente				68	12	021/10	124/53	284/36	0.5	6.64	0.32	**C**	Pure strike slip
San Roman	34/01	L. - M. Eocene		13	7	121/14	269/73	029/08	0.56	5.33	0.71	**B**	Pure strike slip
Signal de	33/08	L. Eocene		36	14	067/83	211/06	302/04	0.5	6.06	0.90	**B**	Pure extensive
San Vicente				36	13	303/12	212/02	116/78	0.47	6.74	0.70	**B**	Pure compressive
Munorrodero	33/07	L. Eocene		14	5	305/27	038/08	143/62	0.5	9.44	0.19	**C**	Pure compressive
				14	9	074/01	343/28	165/62	0.31	14.27	0.41	**C**	Pure compressive
El Peral	32/02	U. Eocene		2	2	263/13	29/001	58/152	0.5	0.8	2.50	**A**	Pure compressive
Quintanaortuno	200/01	M. Miocene		10	8	067/84	269/05	179/02	0.09	9.43	0.68	**B**	Radial extensive

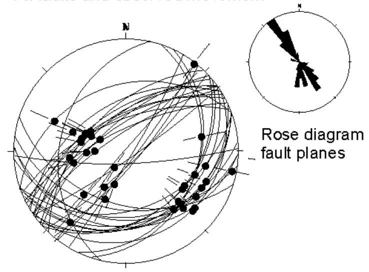
Table 3.1.2
Table showing all results of the observations at the paleostress stations in the Asturian region. Code equal to the SIGMA-classification [SIGMA, 1998]. NF= total number of faults, nf= number of faults explained by tensor, orientations of the principal axes of stress and the stress ratio R. α= angle of deviation between the calculated striation and the observed one on a plane. TQR= Tensor Quality Rank, following Delvaux [1994]: A, B, or C for good, reliable, and unreliable respectively.

Outcrop: Signal San Vicente 33/08 AST

Observations:

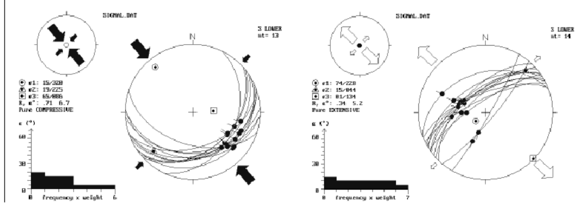
Stratigraphy:
L. Eocene

All faults and observed movement



Paleostress results

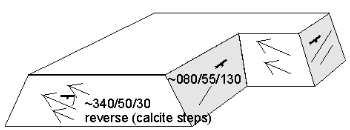
NFnf	σ_1	σ_2	σ_3	R	α	TQR	stress regime
36 14	067/83	211/06	302/04	0.5	6.06	0.898423 B	Pure extensive
36 13	303/12	212/02	116/78	0.47	6.74	0.696505 B	Pure compressive



Outcrop: Hortigal 33/06 AST

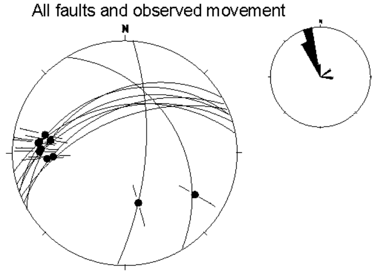
Observations:

Schematic outcrop overview:



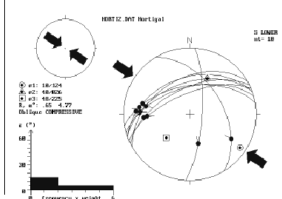
Stratigraphy:
L. Eocene

All faults and observed movement



Paleostress results

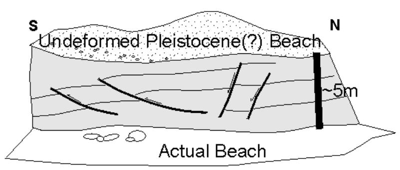
NFnf	σ_1	σ_2	σ_3	R	α	TQR	stress regime
10 10	129/03	036/49	222/41	0.4	6.62	1.510574 A	Pure compressive



Outcrop: Playa de la Rabia/Oyambre 33/02 AST

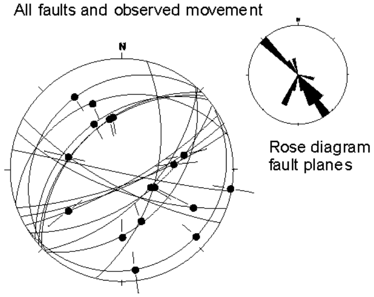
Observations:

Schematic outcrop overview:



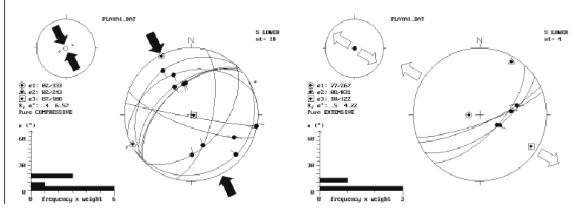
Stratigraphy:
Oligocene

All faults and observed movement



Paleostress results

	NFnf	σ_1	σ_2	σ_3	R	α	TQR	stress regime
1st	17 10	327/04	236/05	096/83	0.46	6.61	0.889917 B	Compressive str.slip
2nd	17 5	284/78	031/03	121/11	0.5	4.07	0.361324 C	Pure extensive



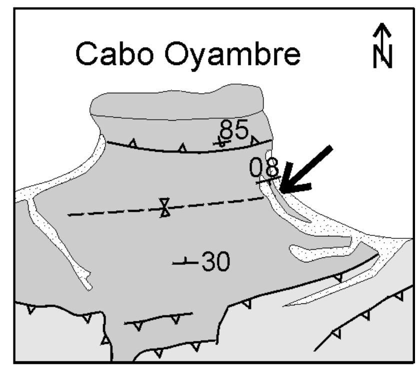


Figure 3.1.7
Observations and paleostress results for Signal de San Vicente de la Barquera, Hortigal and Playa de la Rabia/Oyambre. See Table 3.1.2 for explanation of abbreviations. See Figure 3.1.6 for location of the stations.

These results justify the assumption of Lepvrier & Martínez-García [1990] on a late stage reorientation of the stress field, but an a-priori relation to a late stage in the development of the Pyrenean/Cantabrian systems does not have to exist. The present-day state of stress as derived from a few focal mechanism solutions for the Cantabrian sub-region indicates a strike-slip with maximum horizontal compression oriented N010° [SIGMA, 1998]. This state of stress is very similar to the youngest phase of deformation as inferred from kinematic indicator data in the region. Based on the observations by De Vicente *et al.* [1996b] that the stress field in central Iberia has remained relatively uniform from Middle Miocene to present-day, the late stage reorientation inferred from the fault slip inversion can be considered to be the active state of stress in the region since upper Miocene. Unfortunately, no direct evidence can be presented for this interpretation, due to the lack of upper Miocene sediments in the region and the limited and poor outcrop conditions of Quaternary sediments.

Implications of the new data for the evolution of the stress field in NW Iberia

Combining the results of the new data with published information about the present-day stress field in northwestern Iberia reveals the following deformation history of the region. (1) A first compressional event was related to the Pyrenean collision and subduction offshore northern Iberia. Sh_{max} directions for this phase are oriented roughly N-S to NNW-SSE. The state of stress is near pure compression, with a small extensional component perpendicular to it in the Cantabrian region. Under this stress field lower-middle Oligocene sediments along the Asturian coast were deformed and related activity of the As Pontes Basin started during the Late Oligocene. The onset of basin formation and sedimentation in the Bierzo Basin during the Late Oligocene (the Paleogene age suggested by Delmaire Bray [1977]) would fit better in the regional context than contributing the first sediments in this basin to the lower Miocene. The indirect way of dating the sediments in the basin might have yielded too-young ages. (2) During the Early Miocene tectonic activity of the region is not documented for any part of the northwestern peninsula. The lack of sediments from this epoch in the area might obscure any deformation that took place, but as far as Iberia is concerned, the entire Peninsula went through a relatively tectonic quiet interval (see Chapter 5).
(3) A middle Miocene fracturing phase affected the Bierzo Basin, separating two sedimentary sequences. This phase can be related to a plate-wide deformation phase at around Serravallian times (~12Ma) that must be related to the collision of the Betics with the southern margin of Iberia (see Chapter 5). This renewed compression with NNW-directed compression in the northwest and near N-S compression along the Cantabrian coast might be responsible for much of the deformation that occurred in northwestern Iberia. Whereas this stress field is purely compressional in the Betic foreland close to the active collision zone, in northwest Iberia an additional important component of extension is documented, resulting in predominantly strike-slip activity here. (4) Displacement of upper Miocene-Pliocene sediments and deformation of even younger sediments indicates that this was not the last deformation phase that affected the region. During the Pliocene, a regional shift towards more extensional states of stress is documented in many areas in the Peninsula, contemporaneous with general uplift of mainland Iberia (see Chapter 5 for references and more detail). The observations of a relatively extensional stress field in the Bierzo Basin and along the Asturian coast might be related to this change in state of stress. The close resemblance between the obtained tensors and the present-day stress regime [SIGMA, 1998] indicates that this stress field has been active and stable for a longer time. Although the stress had more or less constant

directions, its level might have varied through time, as is documented for the stress field since M. Miocene in central Iberia [De Vicente *et al.*, 1996a].

3.2 Tectonic activity of the Spanish Central System during the Paleogene evidenced by structural and sedimentary geology, and apatite fission track analysis

After the Mesozoic rift events that affected eastern and central Iberia (see e.g. Salas and Casas [1993] and references therein), the latter underwent during the Late Eocene to Middel Miocene intense intraplate deformation related to the collision of Africa and Iberia/Eurasia [De Vicente *et al.*, 1996c; Salas *et al.*, 2001]. The tectonic evolution of central Iberia between these regional events is hardly documented, although indications for tectonic activity during this period (i.e. Paleogene and Early Miocene) do exist.

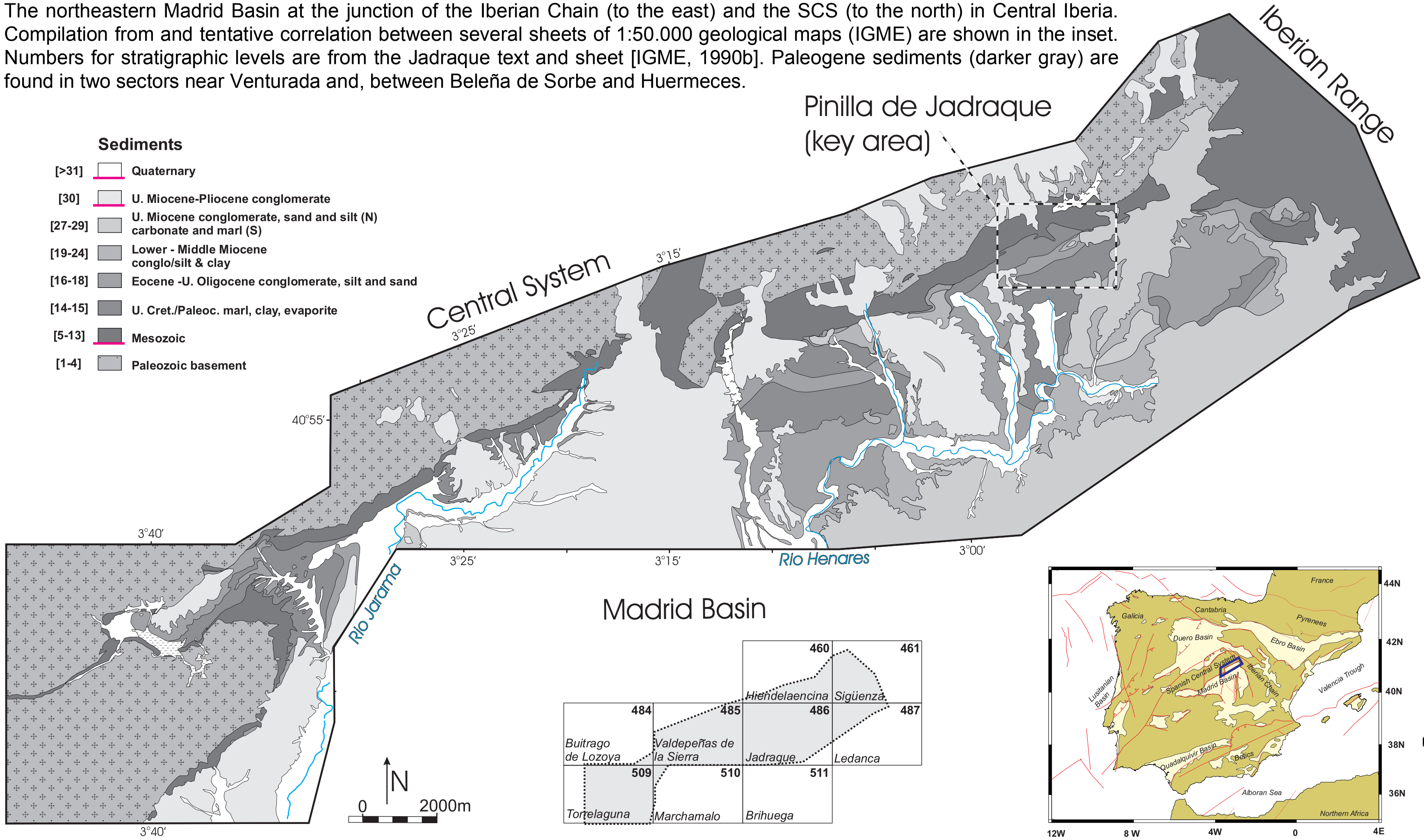
Seismic lines and drilling [Querol, 1983] in the Madrid Basin (MB) that borders the Spanish Central System (SCS) to the south show Paleogene sediment thicknesses of up to 1400m. Large parts of this section consists of marl, limestone and partly evaporite, but also several hundreds of meters of clastic sediments have been observed. The first can be interpreted as sediments of a late continental stage of the Cretaceous Iberian Basin; the latter however indicate tectonic activity in the region. Sediments of similar age crop out along the northeastern edge of the Madrid Basin and the bordering SCS and in the eastern part of the Loranca basin. In the northeastern Madrid Basin alluvial fans of Eocene to Upper Oligocene age are observed that contain clasts of gneisses that are restricted to the basement of the eastern SCS. This clearly indicates that at least the northeastern part of the SCS has been eroded during the Paleogene and, therefore, must have been significantly uplifted before the major intraplate deformation during the M. Miocene. To quantify this tectonic activity, we conducted a study combining several disciplines that provided us with mutually independent data on the tectonic development of the area: conventional detailed geological mapping, sedimentary logging, kinematic indicator data measurements, and fission track analysis. The advantage of such an integration of independent data from several fields in Earth sciences is the possibility to draw conclusions about the geological evolution that, based on any of the components only, would not have been reliable.

In this section of the thesis, the study area will be introduced and several models that have been proposed for its tectonic framework reviewed. Subsequently new paleostress, sedimentary, and fission track data will be presented and implications of these new data for the reconstruction of the development of the SCS and MB discussed. Finally, a modified model is proposed for the tectonic and sedimentary evolution of at least the NE part of the SCS from the Paleogene to Miocene.

Introduction to the study area:

The study area (Figure 3.2.1) is situated near the junction of the Tertiary Madrid Basin in the SW, the WSW-ENE trending SCS in the NW, and the NW-SE trending Iberian Chain (IC) in the east. The latter unit is the inverted Mesozoic Iberian Basin (see Alvaro *et al.*

Figure 3.2.1
The northeastern Madrid Basin at the junction of the Iberian Chain (to the east) and the SCS (to the north) in Central Iberia. Compilation from and tentative correlation between several sheets of 1:50.000 geological maps (IGME) are shown in the inset. Numbers for stratigraphic levels are from the Jadraque text and sheet [IGME, 1990b]. Paleogene sediments (darker gray) are found in two sectors near Venturada and, between Beleña de Sorbe and Huermeces.



[1979] for the classical evolutionary model on this area). During the Mesozoic rift events that affected large parts of SW Europe [Ziegler, 1988], central Iberia formed the western border of the Iberian Basin [Salas and Casas, 1993]. This is still reflected in the different types of substratum beneath the Tertiary sediments. In the western and central part of Iberia, the substratum consists of Proterozoic and Paleozoic metasediments and intrusives with a condensed Mesozoic sedimentary sequence. To the east, in the Iberian Chain it comprises eastward-thickening Mesozoic sequences, including important decollement levels. Thus, the area investigated is located adjacent to two of the most important Cenozoic intraplate deformation belts of the Central Iberian Peninsula. As will be shown, tectonic activity of the bordering basement structures has been recorded in the basin fill of the northeastern corner of the Madrid Basin. At this end of the basin, a key area around Pinilla de Jadraque has been selected (see Figure 3.2.1) where interrelations between sedimentation and tectonic evolution could be studied in detail. The validity of the inferences from this key area for the regional geological evolution is supported by data collected elsewhere in the study area. The existing geological map of the key area around Pinilla de Jadraque [IGME, 1981a] shows a detailed analysis of the metamorphic basement structures, but a gross oversimplification of structures in the Tertiary clastic sediments. Therefore, the first objective of this study was detailed mapping of the Pinilla area. Within the Mesozoic to upper Miocene sedimentary cover evidence for Tertiary tectonic activity was derived from mesoscale folding, including growth strata, striations on fault planes, and striations and pitted surfaces of pebbles have been used for this purpose.

Proposed tectonic models for the evolution of the SCS

The Alpine tectonic evolution of the study area (see Figure 3.2.1) was characterized by rigid deformation of the Hercynian basement along reactivated late Hercynian weakness zones [Doblas *et al.*, 1994]. The overlying Mesozoic-Tertiary sedimentary cover was folded and faulted associated with block movements of the basement, due to the absence of a major decollement level. Some levels of Late Cretaceous-Paleogene evaporites are present and produce local disharmonic deformation. Central Iberia was subjected to stresses transmitted from the plate boundaries into the interior of the plate, which resulted in multiple reactivations of Late Hercynian basement faults [Andeweg *et al.*, 1999a]. Several models have been proposed to explain the Tertiary geological evolution of the SCS.

1. As early as the first half of the last century Schmieder [1953] (but published in German in 1915) and Schwenzer [1943] (translated from a German paper of 1936) proposed a horst-and-graben structure on the basis of the geomorphologic character of the system with high-elevated plateaus, intramontaine basins (Lozoya and Amblés) and intraplate basins (Duero and Tajo). This model implies extension as the governing process in forming the system. Dominance of compression in the development of the system has been suggested for the first time in the early eighties and has become accepted widely during the last decade. Some recent geomorphologic models however, are also based upon the 'horst-and-graben' model [de Pedraza Gilsanz, 1989], but are unaware of the implications of this term for the tectonic setting of the structure.

2. Crustal up arching [Vegas and Banda, 1982]

This model is the first that tried to explain the development of the SCS in terms of compression. The authors proposed rigid areas in the interior of the system deformed into great arches bounded by reverse faults. From a gravity profile they interpret the SCS as an unrooted structure. However, such a rootless crustal arch cannot be in local isostatic equilibrium and would require a very high level of dynamic intraplate stress to maintain the relief.

3. Crustal pop-up [Ribeiro *et al.*, 1990]
This model suggests the existence of an important mid-crustal decoupling, running from the Betics in the south of the Iberian Peninsula all the way to the Northern Border Fault of the SCS, carrying the MB as a piggy back basin northwards. However, some major problems with this interpretation are:
(a) The development of the SCS is uniquely linked to the Betic collision (starting around Middle Miocene).
(b) The existence of such a mid-crustal decollement level is still a matter of debate. Some indications exist for decoupling, e.g. the Altomira phase [Muñoz Martín *et al.*, 1998]. However, the decollement took place in the supra-crustal sediments at the level of the Keuper marl. This sedimentary decollement level pinches out west of the Sierra Altomira and therefore is not present under the Madrid Basin sediments.
(c) The fault geometry of the SCS does not support this model. The Southern Border Fault (SBF), in this model the backthrust, is much steeper than the 'frontal' Northern Boundary Fault (NBF) and more deformation took place along the SBF (offset of about 5000m versus an estimated 1000m). This geometrical distribution of the deformation would rather suggest the inverse of the proposed model: the SCS as a frontal expression of a mid crustal detachment running from the northern Cantabrian Range to the SBF, carrying the Duero Basin as a piggy-back basin. Pulgar *et al.* [1997] interpreted mid-crustal delamination from deep seismic lines across the Cantabrian Range and northern border of the Duero Basin. A 'Cantabrian' wedge is interpreted to indent into and to split the Iberian crust apart. Such a mid-crustal detachment would provide a hypothesis for the complete absence of deformation in the Duero Basin apart from its margins.
4. Block rotation [Vegas *et al.,* 1990]
This model is based on the interpretation of wide-angle seismic profiling [Suriñach & Vegas, 1988], from which (moderate) crustal thickening was interpreted to be the result of Betic-originated intraplate compression. This strain is supposed to have localized in the SCS due to a previous dextral shear zone. Strike-slip was inferred along N030^{o} trending faults in the Sierra de Gredos (western SCS) prior to the middle Miocene N150^{o} compression that inverted the same fault planes. Therefore, a model is proposed of Late Cretaceous simple shear and clockwise rotation of crustal blocks, followed by a Middle-Late Miocene pure shear within the lower crust, causing reactivation of rotations, uplift and high-angle faults at boundaries. Block rotations due to strike-slip movement along the southern and northern border fault and along parallel faults in the SCS are interpreted as the mechanism governing its deformation. However, the model requires a large set of near vertical faults, trending more or less parallel, enabling the block rotations. This holds for the intramontaine late Tertiary(?) Avila Basin, but major parts of the SCS do lack evidence for such faults. Large-scale block rotations are not recognized either.
5. Pop-up structure [De Vicente *et al.,* 1996c]
De Vicente *et al.* [1996b] and De Vicente *et al.* [1996c] have described in detail the late-stage tectonic evolution of central Spain and the tectono-sedimentary evolution of the Madrid Basin and the SCS from the M. Miocene intraplate deformation (related to the collision of Africa and Iberia/Eurasia). These authors relate the development of the SCS and its northern and southern foreland basins solely to NNW-SSE compression due to the collision of Africa and Iberia/Eurasia. Based on a seismic velocity model, surface geology, restoration of the Mesozoic cover over the SCS and shallow seismic reflection data in the Madrid Basin, De Vicente *et al.* [1996c] proposed a pop-up structural model for the SCS. The model consists of a system of pop-ups and 'pop-downs' with a steep SBF, thrusting the SCS over the Madrid Basin foreland. Flatter faults along the northern

border of the SCS are oriented parallel to preexisting weakness zones in the metamorphic basement. Therefore, loading of the northern foreland is restricted, creating a less pronounced basin (the Duero Basin) due to a large horizontal but smaller vertical displacement than along the SBF. A minor problem with this model is that it explains the entire activity of the SCS as a consequence of the Betic compression from the Middle Miocene until today and disregards any effect of inheritance of prior pre-Miocene deformation. As a model for the late stage development of the SCS it seems to be very convenient. Nevertheless, the continuation at depth of the major faults and the existence of an upper crustal detachment level remain questionable. Deep seismic reflection lines are required to solve these problems.

Constraints from seismic data

In the Madrid Basin, Amoco, Shell and Teneco carried out seismic reflection profiling in the late seventies and early eighties in a search for hydrocarbons. The seismic lines [Querol, 1983] offer limited resolution with depth, so information about the crustal configuration is restricted or absent. The lines, however, show in detail the sedimentary sequences that filled the basin and their interrelation. Tectonic activity of the basin border can be inferred from the internal architecture in the sedimentary sequence. Two profiles (Line M-7922 and Line M-7916) that run from the northern basin border (SCS) in SSE direction through part of the basin are presented in Figure 3.2.3 (see middle panel Figure 3.2.2 for location) and discussed.

The NNW of the line M-7922 (Figure 3.2.3a) is located in the study area near Pinilla and the sedimentary sequence is tied by the projected wells of Baides and Santa Barbara. It reveals important constraints on episodes of fault activity. Combined with surface information (see section), growth strata dipping steeply southward can be inferred at the extreme NNW of the line. The southern flank of this growth syncline is characterized by north-dipping Paleogene reflectors. These reflectors run parallel, showing that tilting of this block occurred after the deposition of this sequence.

The Mesozoic sequence shows important thickness reduction towards the Baides well, while in the Madrid Basin the Mesozoic sequence is thick and even distributed (0.5s TWT). This shows that the zone around Baides has been active as a paleohigh during Mesozoic sedimentation. The assumption of normal fault movement during the Mesozoic would fit best in the setting of the Iberian Basin. The superficial SBF interpreted by Querol [1983] cannot have acted as a normal fault, because of the low dip towards the north. Most likely, the interpreted thrust is the near-surface expression of motion along a deeper crustal fault, which might have been a normal fault during earlier stages. This thrust fault is the M. Miocene SBF of the SCS in this area, offsetting the basement about 2.5 km. In the Santa Barbara well an intra-Paleogene unconformity is observed that can be traced northwest-wards and indicates gentle uplift of the inner Madrid Basin during this period. This uplift could be related to the active thrust just SE of the well, but the unconformity is displaced by the fault itself. An alternative explanation for uplift might be the formation of a gentle bulge related to foreland basin development under the load of the SCS.

Line M-7916 (Figure 3.2.3b) runs from the SCS basement just north of Madrid into the Madrid Basin. The SBF of the SCS is observed in the extreme NNW of the profile. One of the most interesting features in the profile is a similar intra-Paleogene unconformity as observed in Line M-7922. Upper Paleogene sediments onlap truncated Lower Paleogene sediments, clearly indicating an intra-Paleogene tectonic activity. This tectonic activity seems to reflect a first stage of loading by the SCS and related foreland basin development. The unconformity is tied to ~Oligocene in the nearby El Pradillo well. At this location up to 1450m of late Oligocene to early Miocene deposits have been

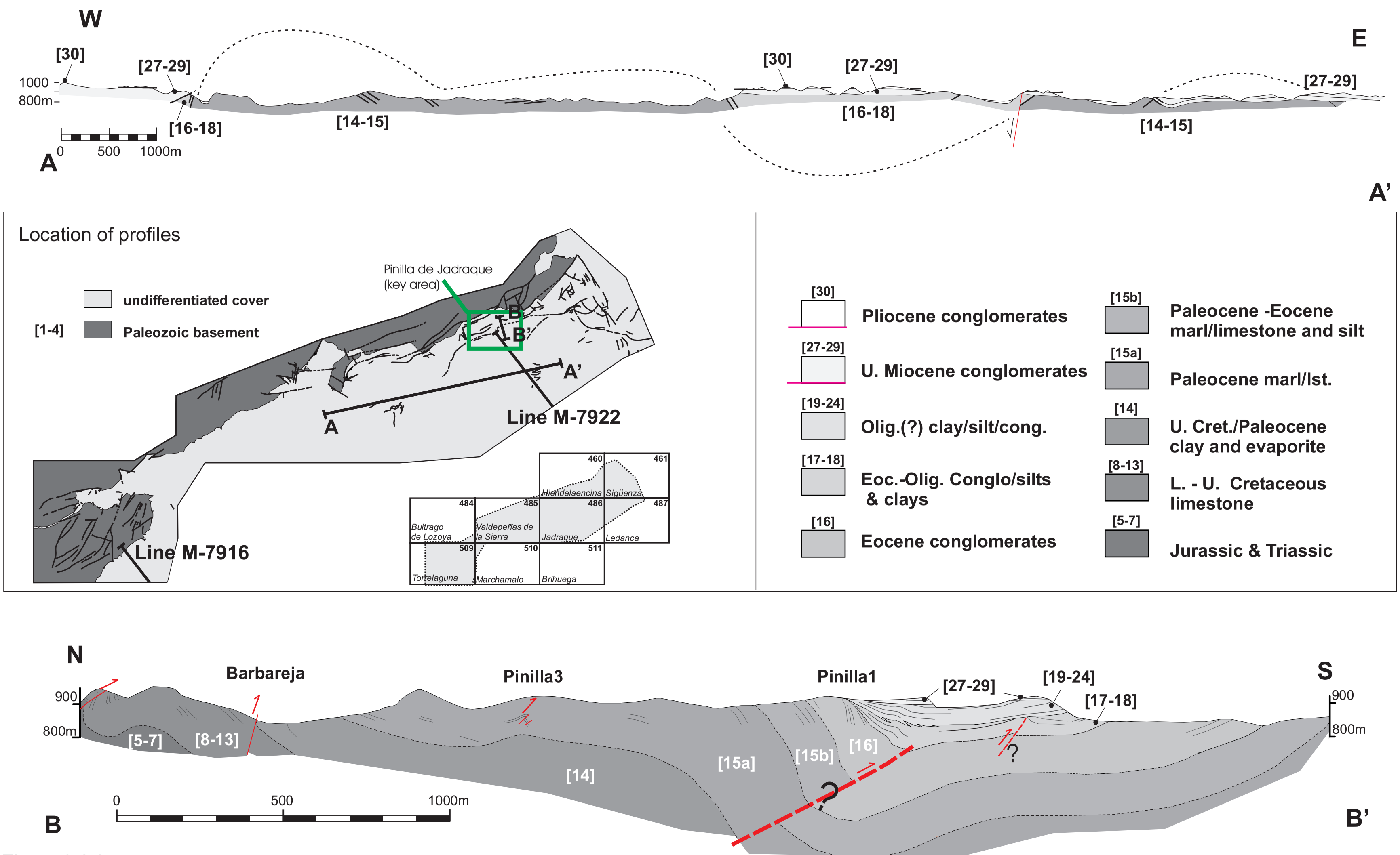


Figure 3.2.2
Upper panel: approx. E-W profile through the northeastern Madrid Basin (see middle panel for location) to indicate folding of the Mesozoic-E. Tertiary cover related to ~N050°-090 compression. Middle panel: location of profiles and seismic lines (see Figure 3.2.3). Lower panel: a N-S cross-section through the key area along Cañamares valley. Sites for which paleostress determination has been carried out are indicated.

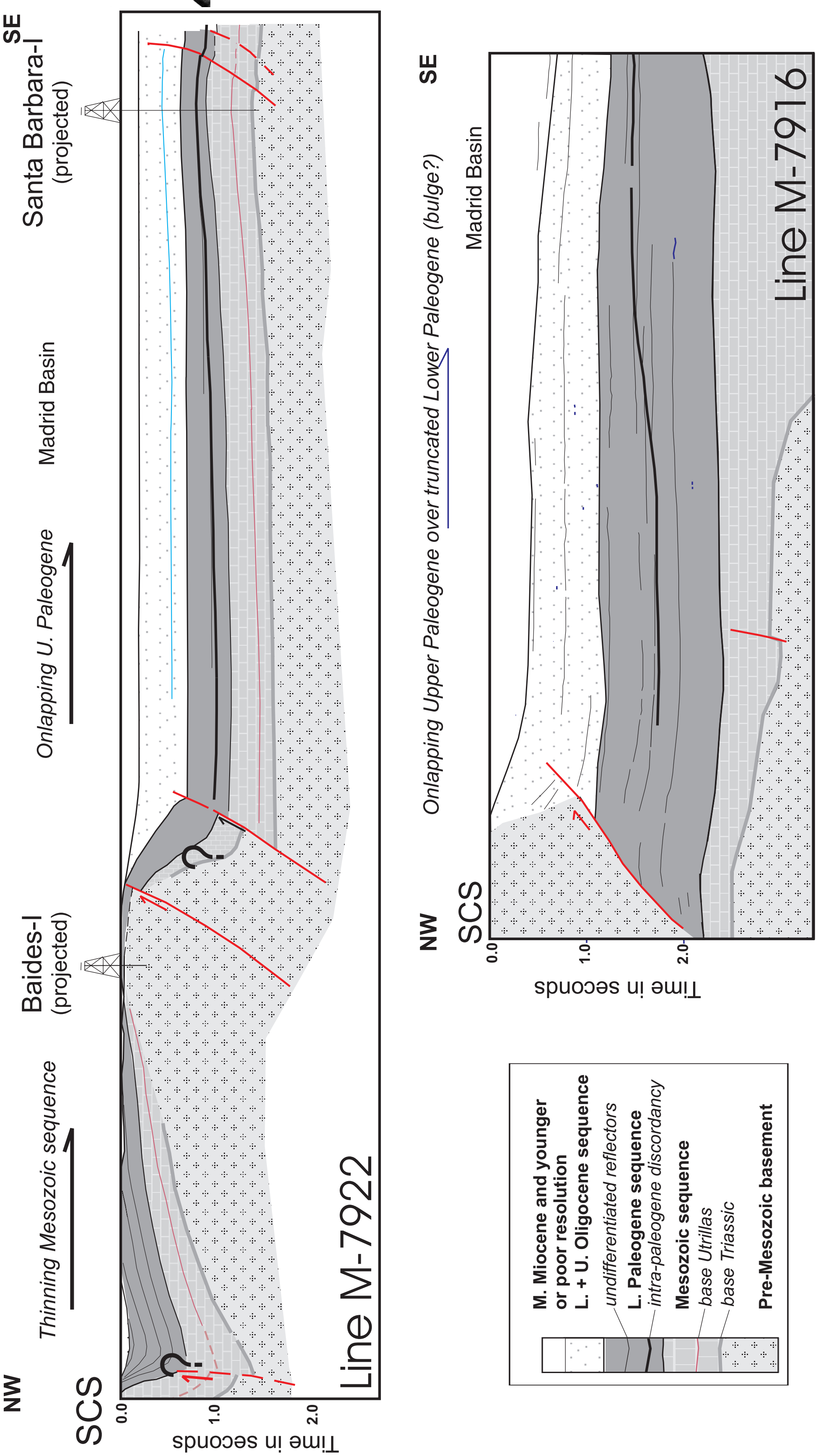


Figure 3.2.3
Interpretation of two seismic sections through the northern Madrid Basin, perpendicular to the basin border (see middle panel Figure 3.2.2 for location). Seismic sections after Querol [1983].

drilled, but to the east (Santa Barbara), this level is reduced to around 800m. The unit below this sequence has not been divided into smaller segments than Maastrichtian-middle Oligocene.

Paleogene sediments drilled in the well are lacustrine-evaporitic deposits and represent distal foreland basin sediments and do not have a terrigenous nature, nor is the reflectivity pattern of the sediments interpreted as terrigenous [Querol, 1983]. The middle-upper Miocene sediments are coarse sediments, indicating a more proximal position to the thrust belt.

General outline of the sedimentary sequence in central Iberia

A synthesis of the information from 6 sheets of 1:50.000 geological maps (Hiendelaencina [IGME, 1981a]; Sigüenza [IGME, 1981b]; Buitrago de Lozoya [ITGME, 1991a]; Valdepeñas de la Sierra [ITGME, 1990d]; Jadraque [ITGME, 1990b] and Torrelaguna [ITGME, 1995]), has provided an overview map of the entire southern border of the SCS (see Figure 3.2.1). Outcrops of Paleogene sediments are scarce and limited to two zones (1) Venturada and (2) Beleña de Sorbe – Huermeces. Correlation of these limited outcrops revealing Paleogene successions all along the northern border of the Madrid Basin has been problematic due to lateral facies changes and different subdivision of sedimentary units in the different sheets of the geological maps. For example, almost 80% of the map Hiendelaencina [IGME, 1981a] comprises metamorphic rocks of Precambrian-Permian age. Subdivision and detailed mapping of Tertiary and younger sediments has not been carried out as accurately as for example in the sheet located directly south of it (Jadraque [ITGME, 1990b]), which is entirely covered by Tertiary sediments and from more recent date. A tentative correlation of the Tertiary sediments along strike the contact of the SCS and MB is proposed in this section. In the study area, a large scale subdivision of the sedimentary cover can be made by defining a Mesozoic-Tertiary part consisting of Triassic, Cretaceous and Paleogene sediments and a Tertiary upper part made up of M. to U. Miocene. Numbers in brackets refer to the subdivision used in the Jadraque geological map [ITGME, 1990b] and the geologic maps presented in this section.

Mesozoic-E.Tertiary

During this period, the area formed the western margin of the NW–SE trending Mesozoic Iberian Basin. Therefore, the Mesozoic series overlying the metamorphic basement of the Madrid Basin is far from complete, of a marginal type, and relatively thin (several hundreds of meters). Towards the east, the thicknesses of Mesozoic strata (Muschelkalk, Keuper, and Buntsandstein) increase rapidly up to several kilometers in the Iberian Chain. For the same reason, the Keuper in the study area is formed dominantly by calcareous and siliciclastic sandstone, whereas in main part of eastern Iberia it contains significant levels of evaporites that can act as decollement level.

The latest Cretaceous-Paleogene succession presents the gradual change from the marine L. Cretaceous series to the terrigenous Paleocene and younger series. Three units can be differentiated based on lithology: (a) levels of evaporites of up to 90m alternating with mud [14-15] characterize the first 800-1000m, of Maastrichtian-middle Eocene age. This is followed by (b) an approximately 200-300m thick marly series with terrigenous intercalations [16] (Eocene-Lower Oligocene) passing gradually to (c) the third unit, which reaches a thickness of 450m, consists of terrigenous sediments with carbonate levels of Late Oligocene age [17-18]. The sandstones of the middle (Eocene-Lower Oligocene) unit contain the first fragments of metamorphic rock of the SCS hinterland. The development of units [17-18] shows in the Jadraque area both vertical and lateral diminishing lacustrine environments by progressive building out of a fluvial system, most likely related to tectonic activity. Towards the east, the lacustrine carbonates become more dominant.

E.Tertiary-Pliocene

The Madrid Basin is filled with up to 3500 meters of Cenozoic sediments [Querol, 1983]. During large time spans of the development of the basin, lacustrine conditions prevailed in its center. Along the rims, clastic sediments shed into the basin from the active borders progressively filled the basin. The interrelations between these two facies enable an understanding of the rate of erosion in the SCS and therefore, an estimate of its tectonic activity. The Neogene series filled the Madrid Basin in endoric circumstances, forming a system of alluvial fans entering terrigenous sediments in the basin, gradually passing through complex transition facies to the lacustrine evaporites deposited in the center of the basin. All of this series is topped by the detritic-calcareous Paramo facies. Along the borders of the basin, angular unconformities within the series can be observed that towards the center of the basin change into paraconformities, clearly showing tectonic activity along the basin margins.

All of the Mesozoic-E.Tertiary series have subsequently been folded and partly eroded and are covered by an angular discordant terrigenous unit that is the base of the Miocene series in the area. The oldest Miocene sediments form an undated unit of quartzitic conglomerates and calcareous breccias grading upward into red mud and intercalated marl near Arbancon [20]. In the map of Jadraque [ITGME, 1990b] this unit is attributed to lower Aragonian (~Burdigalian, L.Miocene, ~19-18Ma). To the south, near e.g. Cogolludo or Espinosa de Henares, a unit of alternating conglomerate and mud, which shows evidence for mass transport [19] discordantly covers the 'Paleogene' series. In the Jadraque map [ITGME, 1990b] this level is attributed to the 'most likely lower-middle' Aragonian (L. – M. Miocene, ~18-15Ma) based on cartographic correlation to other units in the center of the Madrid Basin that have been dated accurately. However, in both the map for Hiendelaencia [IGME, 1981a] and Sigüenza [IGME, 1981b], the top of this same unit is correlated to de Loranca del Campo outcrop, in the Madrid Basin to the south of the region, dated at upper Agenian (Lowermost Miocene, ~Aquitanian, 24-22Ma). An early Miocene age is considered in our study.

The Middle Miocene is represented in the basin by series of near horizontal marl, mud, sand [21-22] and carbonate levels [23]. It shows a discordant relationship with the older units. Reptile and micro mammal findings date the top of this series at the Aragonian-Vallesian boundary (M.-U. Miocene boundary, ~12Ma, Serravallian-Tortonian).

Along the Mesozoic rim at the northern basin margin, a discordant conglomerate series forms growth synclines near Arbancon and San Andres del Congosto [24]. The unit grades upward into finer materials to the top (limestone and marl). The southern flanks of these structures are up to 2-3 times as thick as their steep northern segments. The limits of this unit have been dated as U. Vallesian - M. Turolian as base and top respectively. The progressive discordance shows tectonic activity of the border for this time-span.

In the basin, the Middle-Upper Miocene sequence is topped by an approximately 50-60m carbonate and marl sequence, the 'Blanca' formation [25-26], which forms large plains with numerous karst features at an average altitude of 1020m. Their age is uppermost Aragonian-lower Vallesian, based on several micro mammal datings and correlation.

At the basin borders, erosion products of the SCS have been deposited in several units of conglomerates [27-29] during the upper Turolian –Alfambrian (late Miocene, Messinian-early Pliocene). These series of uppermost Miocene to lowermost Pliocene

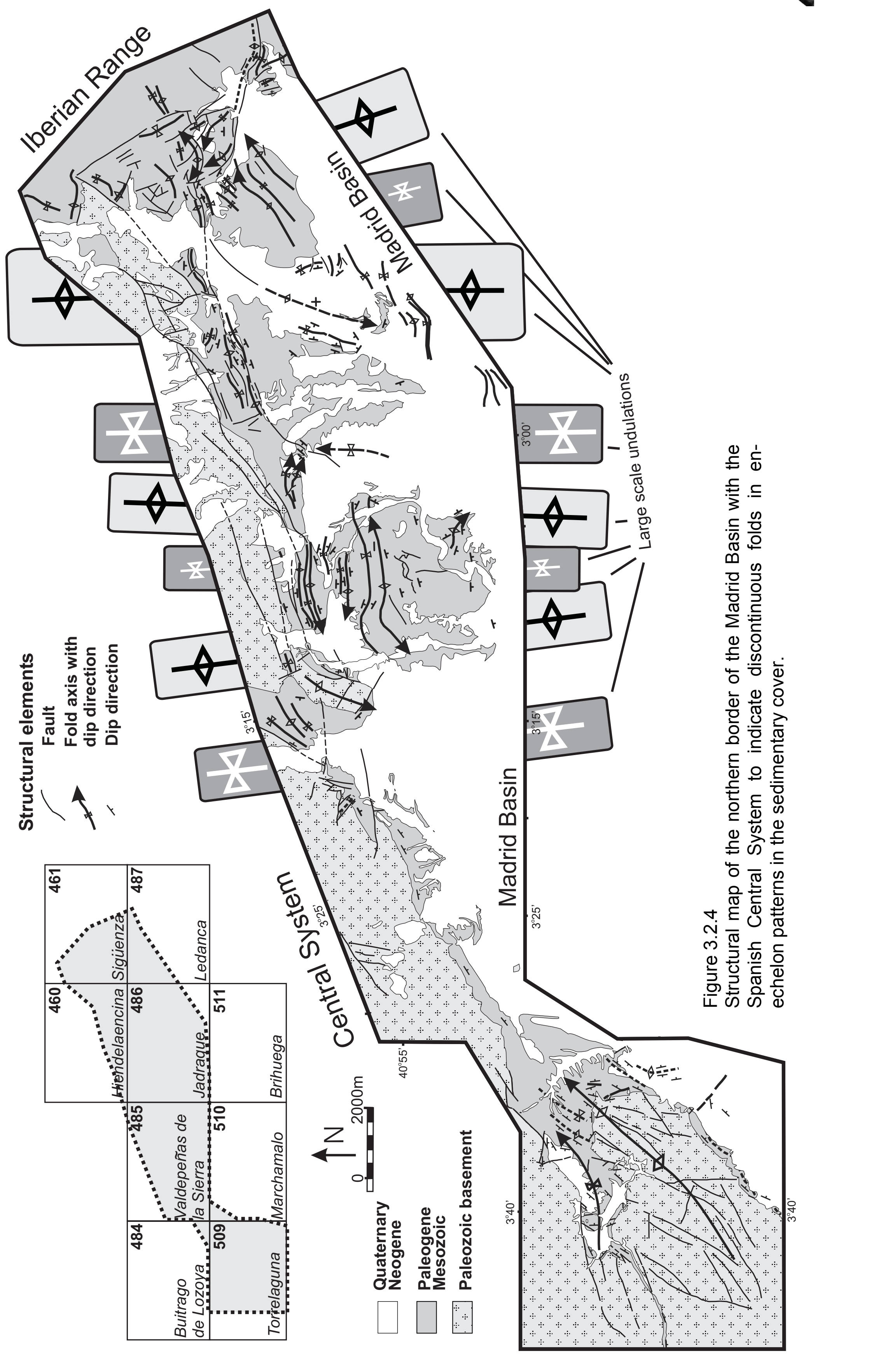


Figure 3.2.4
Structural map of the northern border of the Madrid Basin with the Spanish Central System to indicate discontinuous folds in en-echelon patterns in the sedimentary cover.

alluvial fans discordantly overly all the underlying basement structures. Alonso Zarza *et al.* [1993] has described the fan systems and the paleogeographical control on their development.

The last sediments of the Neogene succession in the northeastern Madrid Basin consist of 8-10m thick quartzite pebble conglomerates of late Pliocene age [30]. This unit forms extensive platforms at high elevations of about 1080 meter, and covers older upper Miocene units, e.g. [27], along an erosive unconformity that can be recognized on map scale.

Younger (Quaternary) sediments are restricted mainly to terraces along the rivers that have cut through the upper Pliocene levels, into the underlying basement.

Observations in the study area

Structural data

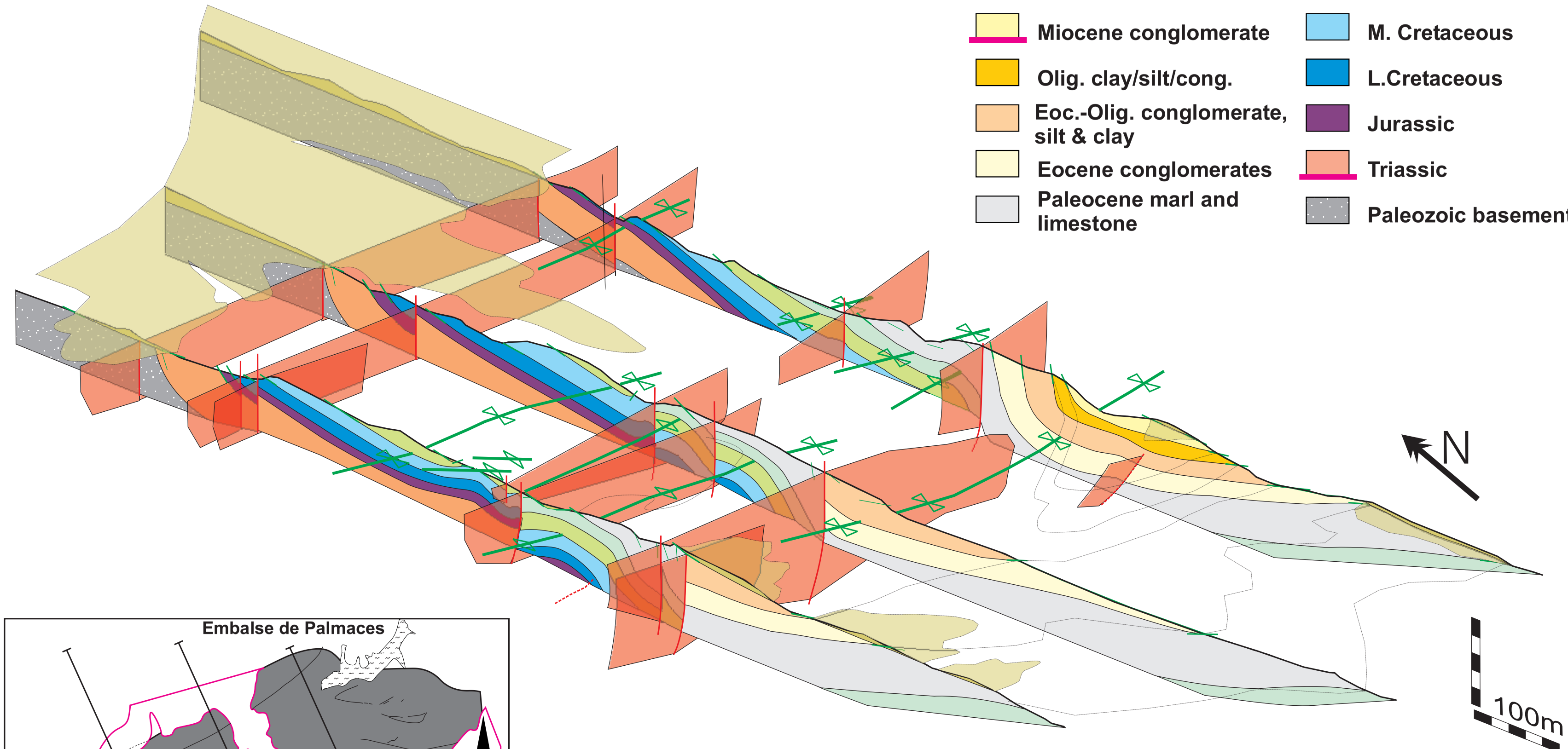
In Figure 3.2.4 the trends of the most important structures in the Mesozoic to present-day sedimentary sequence of the NE Madrid Basin is shown. E-W, ENE-WSW and SSE-NNW are dominant directions for the large-scale folds and faults. Figure 3.2.2 shows a cross section perpendicular to the border structure (panel A) and a profile parallel to it. The latter shows broad undulations in the Mesozoic- L. Paleogene cover. Folds and faults in the thin Mesozoic-E. Tertiary cover tends to be highly discontinuous and the fold axes are not straight but show in general an E-W direction in the central parts. The southern border of the SCS is oriented at ~N070^o, at a small angle (20^o) with the above mentioned fold trend. This structural outline suggests that the folds in the cover formed en-echelon above a blind basement fault, which was active as a sinistral strike-slip fault during some stage in the development of the region. In two-dimensional sections, en-echelon patterns of faults and folds related to strike-slip tectonics cannot be revealed. Therefore 3 parallel sections have been constructed, based on new field observations, to be able to present a three-dimensional block diagram of the key area in this study, the Pinilla area (Figure 3.2.5). This view shows the flower tulip structure, en-echelon faults and folds in the area, as well as the growth strata near Pinilla.

Sedimentary data

A field study was carried out in order to describe the sedimentary sequence in the Pinilla area in detail, providing control on the correlation of the observed stratigraphy with the units in the map of Jadraque [ITGME, 1990b]. The sequence has been logged in great detail to unravel the internal structures, sedimentary features and interrelations between units that have been recognized by macro-analysis, by careful mapping at 1:18.000 and by aerial photograph study. The result of this is shows in Figure 3.2.6.

The Mesozoic series can be correlated to the regional sequences, just as the lower Paleogene sequence on top of it. This is related to the nature of the latter sediments: the monotonous alternation of thin mud, evaporite and carbonate layers is interpreted as playa-like sediments, which implies broad plains without pronounced tectonic activity. The base of the sequence is dominated by mud; the middle part is a characterized by thin pale mudstone layers and the mud is coarsening upwards to siltstone.

Deposits of Eocene to Oligocene age show growth strata and have been subdivided in 3 units (see for more details on the sediments De Bruijne [2001]). Unit 1 (140m thick) consists predominantly of massive sheet conglomerates with blocks up to meter scale; towards the top finer grained lenses and intercalation of sandstone occur. It is considered to have been deposited in a high energetic, fast accumulating alluvial fan system in a broad accommodation space. The base of unit 2 shows a highly lateral varying set of small erosive, channeled bodies of pebbly sandstone. They grade upward



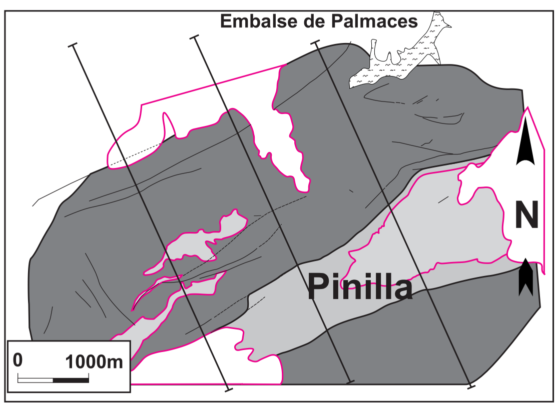


Figure 3.2.5
Three parallel NNW-SSE profiles through the Pinilla key area showing lateral connection of structures and important strike-slip component in deformation (discontinuous folding and faulting). Inset shows profile locations in simplified version of figure 3.2.6. (see www.geo.vu.nl/~andb/iberia for full color version)

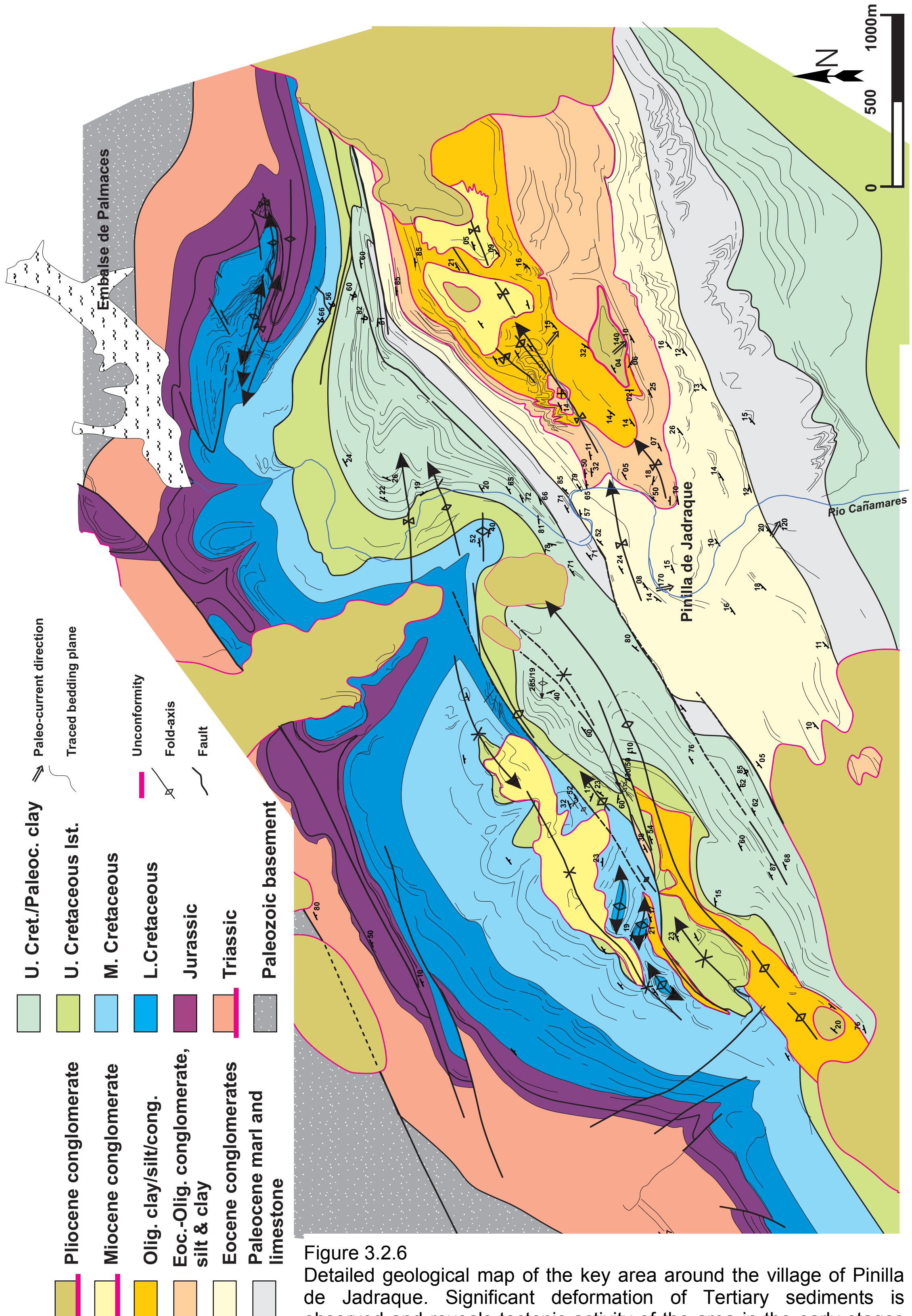


Figure 3.2.6
Detailed geological map of the key area around the village of Pinilla de Jadraque. Significant deformation of Tertiary sediments is observed and reveals tectonic activity of the area in the early stages of the Tertiary before the major M. Miocene event that shaped much of the present-day physiography Spanish Central System.
(see www.geo.vu.nl/~andb/iberia for full color version)

into silty marls, clays and thin sandstone with abundant paleosols. This clearly indicates a sudden change of depositional setting between units 1 and 2: the base of unit 2 can be considered to be flood deposition of an alluvial fan, but most of the unit is attributed to more distal fan to playa-lacustrine facies. Unit 3 displays an erosive contact with unit 2 and consists of ribbon-formed conglomerate bodies alternating with marly and pebbly sandstone. In the base debris/mudflow deposits and paleosols are common. The succession fines upward into red sandy silt alternated with clean pink sandstone. Unit 3 is interpreted as deposits of a relatively small and immature fan, in comparison with the fan of Unit 1. The entire sequence is topped by erosive and only slightly folded M. Miocene conglomerates. The thicknesses of units 2 and 3 vary significantly due to synsedimentary folding (tapering). Together they form a progradational small fan system in an area with small-scale topographic differences. Unit 1 can be attributed to larger scale topography, possibly related to important fault activity in the source area (the junction between SCS and IC). Fan architecture and stacking patterns, as well as synsedimentary deformation structures indicate that at least the northeastern part of the SCS has been tectonically active from the Early Paleogene onward.

Near Beleña de Sorbe and Cogolludo, the first appearance of erosion products of the SCS occurs in Upper Eocene - Lower Oligocene sands containing fragments of schist (up to 5% of the grains) [ITGME, 1990b]. Upper Eocene to Oligocene conglomerates even contain over 40% of clasts > 2cm of quartzite and schist, which show clearly provenance of the eastern SCS. While Paleocene to M. Eocene sand contains up to 15% fragments of dolomitic rocks [ITGME, 1990d] (erosion of Mesozoic cover), U. Eocene to Oligocene sand show deeper erosion into the SCS: 30% dolomite and limestone fragments and 5% fragments of schist. Increased tectonic activity of the SCS is shown by the increasing size of the erosion products: the Oligocene sediments consist of a coarsening up sequence of up to 660m mud, sand and conglomerate. The fraction of pebbles larger than 2cm show an average of ~55% Mesozoic provenance (15-35% limestone, 25-40% dolomites) and ~45% basement (35-45% quartzite, 0-7% slate and schist). The higher levels however contain higher contents of slate and schist and therefore show ongoing unroofing of the SCS. Clearly these sediments are synorogenic.

Fission track data

The fission track (FT) technique has been used to contribute independent data on vertical motions and uplift/denudation of the study area. Fission tracks are deficits formed in a crystal lattice by spontaneous fission of radioactive elements of uranium. Originally they typically have a specific length of about tens of micrometers, depending on the material they were formed in. At high temperatures, these tracks close (anneal) fast after formation, while at low temperatures annealing can be disregarded. The thermal level for which this relation changes, is different for a variety of minerals. In the case of the mineral apatite, the tracks disappear immediately ("anneal") at temperatures higher than 120^{o} Celsius. Between 120^{o} and 60^{o} annealing is taking place at a considerable rate, and this zone is called the Partial Annealing Zone (PAZ, see gray box in Figure 3.2.7b). When apatite is cooling below 60 degrees, tracks are not altered. This implies that when a sample moves quickly through the PAZ, the tracks are relatively long and show a low scatter in length. Slower cooling through the PAZ causes reduced track lengths and a broad track length distribution. The temperatures defining the PAZ for apatite are low when compared to other minerals and therefore allow a reconstruction of the last part of the cooling trajectory. Using information on the increase of temperature with depth in the Earth's crust makes it possible to infer a thermal history for the sample and 'translate' cooling into uplift towards the surface. An age can be inferred for the

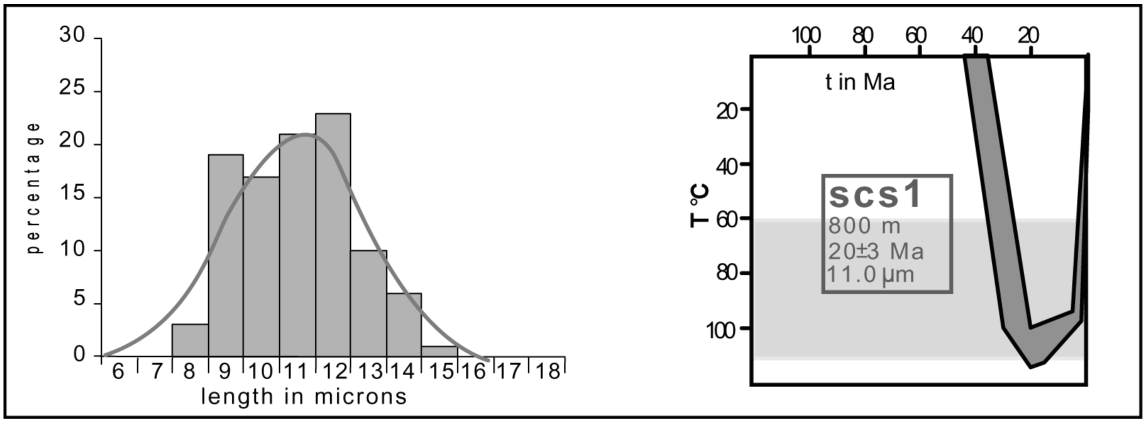


Figure 3.2.7
Example of the results of fission track analysis. Left panel: track-length distribution in sample (bars) and calculated from modelled thermal history (line). Right panel: modelled thermal history and age for the sample (after de Bruijne [2001]). See text for brief explanation.

moment the sample entered the partial annealing zone on its way to the surface (FT-age). In order to be able to reconstruct uplift and denudation from the inferred cooling history, information is required on the geothermal gradient and topography through time. In many cases this information is not available, causing one of the main uncertainties in inferring vertical motions from fission track data. Another source of concern is the variations in chemical composition of the mineral apatite and thermal activity.
This rather brief and condensed outline of the fission track method is sufficient to understand the data and inferred conclusions presented in this section. More concise reviews of the method and the involved analytical and numerical techniques can be found in amongst others Gallagher *et al.* [1998] and Andriessen [1995]. For this purpose, samples were taken from both the Paleogene fan deposits as the Precambrian basement of the SCS.

Samples of the Paleogene (~45-40 Ma old) fan deposits yield Miocene FT-ages (~20Ma). This means that they experienced temperatures >120^{o}C after deposition. Assuming a paleogeothermal gradient of 30^{o}C/km, the thermal history of the samples has been modelled, which indicates that the sediments have been buried to a depth of 3-4km. A huge amount of sediments must have accumulated over the area between Eocene and earliest Miocene. Moreover, the same amount of overburden must haven been eroded in combination with uplift to the present elevation of 800m from ~20Ma until present. Independent results from a sample of basement (Precambrian gneiss) just north of the Paleogene fans yielded slightly older ages (~29Ma). Length distribution shows a nice peak and therefore uplift must have been rapid. An increase in uplift rate for the same period as uplift of the Paleogene sediments is inferred from the modelled thermal history. Samples of basement material more to the northwest in the SCS show very old ages for the FT-data of up to 180Ma [De Bruijne, 2001] and the thermal history for these units shows very slow cooling through the PAZ. Between these sample points, intermediate ages have been observed, which have been interpreted as resulting from block movements according to the 'pop-up' interpretation of De Vicente *et al.* [1996c]. These fission track results have been combined in a model for the evolution in time and place of uplift of several of the separate basement blocks in the SCS [De Bruijne & Andriessen, 2000]. The model suggests onset of limited uplift of the northern blocks during L.Eocene times, with an important increase up to 20Ma, and related shedding of coarse detritic material into the Madrid Basin. In the late stage evolution (middle-upper

Miocene) the southern border fault that was activated during the initial uplift became inactive and the border stepped basinward to the present-day basin edge. This sequence of events would explain the absence of coarse Paleogene deposits along the edge of the basin in this area: uplift of the block they were deposited on in earlier stages has removed them by erosion. Uplift along the southern border of the SCS occurs mainly along the northward dipping faults; the back thrusts play a minor role in this model. The less steep northern border fault of the SCS causes only limited uplift of the northern SCS, as shown by the high ages for samples from this part of the mountain belt.

A much more detailed description of fission track results for the entire SCS and their implications on the evolution of this intraplate mountain chain are addressed in a PhD thesis by De Bruijne [2001]. The fission track data and thermal histories presented in this section are taken from this thesis.

Kinematic indicator data

Some publications on paleostress data are avialable for the area under consideration. Sanchez Serrano [1991] measured kinematic indicators in the region at 5 sites in both the Mesozoic basement sequence and the Miocene infill of the Madrid Basin. A predominant N140^{o} compression was observed, but in the Mesozoic sequence an additional N060^{o} compressional event was inferred from the fault slip data. Paleostress determination in the Madrid Basin shows a more or less consistent N140^{o}-155^{o} direction of Sh$_{max}$ from Middle Miocene to present-day [De Vicente *et al.*, 1996a]. Kinematic indicators measured in Upper Cretaceous rocks yield similar Sh$_{max}$ directions of N320^{o}/N150^{o} (sites 1,2,3,12&18 in Table 1 of [De Vicente *et al.*, 1996a]) and have been attributed to the Middle to Upper Miocene stress field as well. Muñoz Martín [1997] documented the stress field at the border of the Iberian Chain (IC) and the Loranca Basin (see Figure 2.2.3.1). This author showed that the stress field changed from a predominantly N055^{o} ('Iberian', Oligocene) through a N100^{o} stage ('Altomira', Upper Oligocene-Middle Miocene) to the Middle Miocene to present N155^{o} 'Guadarrama' field. The Altomira stage has been explained [Muñoz Martín, 1997] to be the result of superposition in time and place of the Iberian and Guadarrama far field stresses caused by the Pyrenean and the Betic collision, respectively. Further constraints on the stress field in the region come from the nearby Almazan and Zaorejas basins. The Almazan Basin is located between the two branches of the Iberian Chain; Maestro González and Casas Sainz [1995] performed an extensive study of kinematic indicators in the basin. 17 out of 55 measurement sites are located in Tertiary sediments, but the resultant tensors are only dated relatively with respect to each other. Bond [1996] offers a general tectonic evolution scheme for the Almazan basin based on detailed seismic data interpretation. Combining this evolution scheme with the tensors presented by Maestro González and Casas Sainz [1995] enables establishment of the following deformation sequence: (1) Mid Eocene NE-SW compression, (2) Late Eocene/Oligocene N-S compression, (3) Mid-Late Oligocene N-S to NNE-SSW and finally (4) Early to Mid Miocene NW-SE compression. The Zaorejas Basin is located in the western Iberian Chain and formed by an E-W striking synclinal structure related to a fault-propagation fold [Rodríguez Pascua *et al.*, 1994]. The sedimentary infill of the basin can be divided into two sequences that are separated by an unconformity. The lower sedimentary sequence (of presumably Eocene-Oligocene age) shows growth strata and therefore is syntectonic. Maximum horizontal compression in this sequence shows a N150^{o}-160^{o} trend. The upper sequence, overfilling the basin, is of Oligocene- Early Miocene age and shows N-S to N20^{o} maximum horizontal compression due to late stage folding of the area. These results suggest the existence of a stress field before the Late Oligocene with the same Sh_{max} as the Middle Miocene to present-day stress field. Both branches of the Iberian Chain and the southern edge of the Ebro Basin provide additional data by studies of kinematic indicator data ([Alvaro, 1975]; [Simón Gómez and Paricio Cardona, 1988] and [Perez Lorente, 1990]).

Because the stress field in the region under consideration from M. Miocene to recent times was already well documented [De Vicente *et al.*, 1996a], observation of kinematic indicator data for the E. Tertiary to M. Miocene has been a primary goal in order to unravel the tectonic evolution during this time span. Therefore kinematic indicator data (fault slip, joints, striated and pitted pebbles) were gathered in Upper Cretaceous - E. Miocene sediments along the southeastern border of the SCS. To examine the effect of the deformation of the IC on the stress field in the study area, observations were expanded sideways along the SBF. In Figure 3.2.10 the distribution of 10 sites where kinematic indicator data were gathered is shown. Extra attention was paid to the area around Pinilla de Jadraque because meso-structures in this area enabled relative and even absolute dating of several of the deformation stages. The paleostress method (see Chapter 2) was applied to determine the stress directions related to different stages of deformation. Using the method proposed by Schrader [1988], (see Chapter 2 for theoretical background) σ1-directions were determined from pitted and striated pebbles at 6 outcrops, four of which are situated within the Pinilla-area. Development of this type of kinematic indicators was facilitated by the nature of the Paleogene and Miocene sediments in the study region, consisting of quartz-matrix supported conglomerates containing a large amount of limestone clasts.

Table 3.2.1 shows all the results for the different sites where kinematic indicator data have been observed; several of the sites will be discussed below in further detail. A first overview of the data suggests the existence of reactivated faults: it clearly shows a multiple deformation history and it is hard to detect clear conjugate sets of faults. Figure 3.2.2a shows a section along the Cañamares River along the village of Pinilla de Jadraque to elucidate the position and tectonic setting of outcrops Pinilla1 and Pinilla3 that will be discussed subsequently.

Pinilla1 (Figure 3.2.8a)
In steep southward dipping conglomerates (S_0: 170/79), a total of 20 pebbles and 26 fault surfaces with kinematic indicators have been observed. The maximum compression direction derived from the pebbles indicates a mean of around 180/15. The population however can be divided in two subsets: One set (14 orientations) with dips less than 30^o and a smaller set with dips up to 70^o. This seems to indicate a late stage tilt of the small set, possibly related to folding. The general fracture pattern trending N355^o fits well in this nearly N-S compression. Interrelations of the faults and striations on them can help to deduce the relative age of the observed stress fields in the region.
Although the tensor solution is good, reactivation of the observed faults is more than likely: many of the observed faults reveal oblique slip. On a few planes dipping ~045/30 a second set of overprinted, faint dip-slip striae are observed. It is neither possible to determine movement sense nor to obtain confidence whether these are younger or older than the oblique slip components. If, based on regional knowledge these striations are supposed to show up-dip (inverse) motion, than together with more confidently determined sense of movement at a single fault plane (oriented 135/48) it is possible to obtain a confident tensor solution.

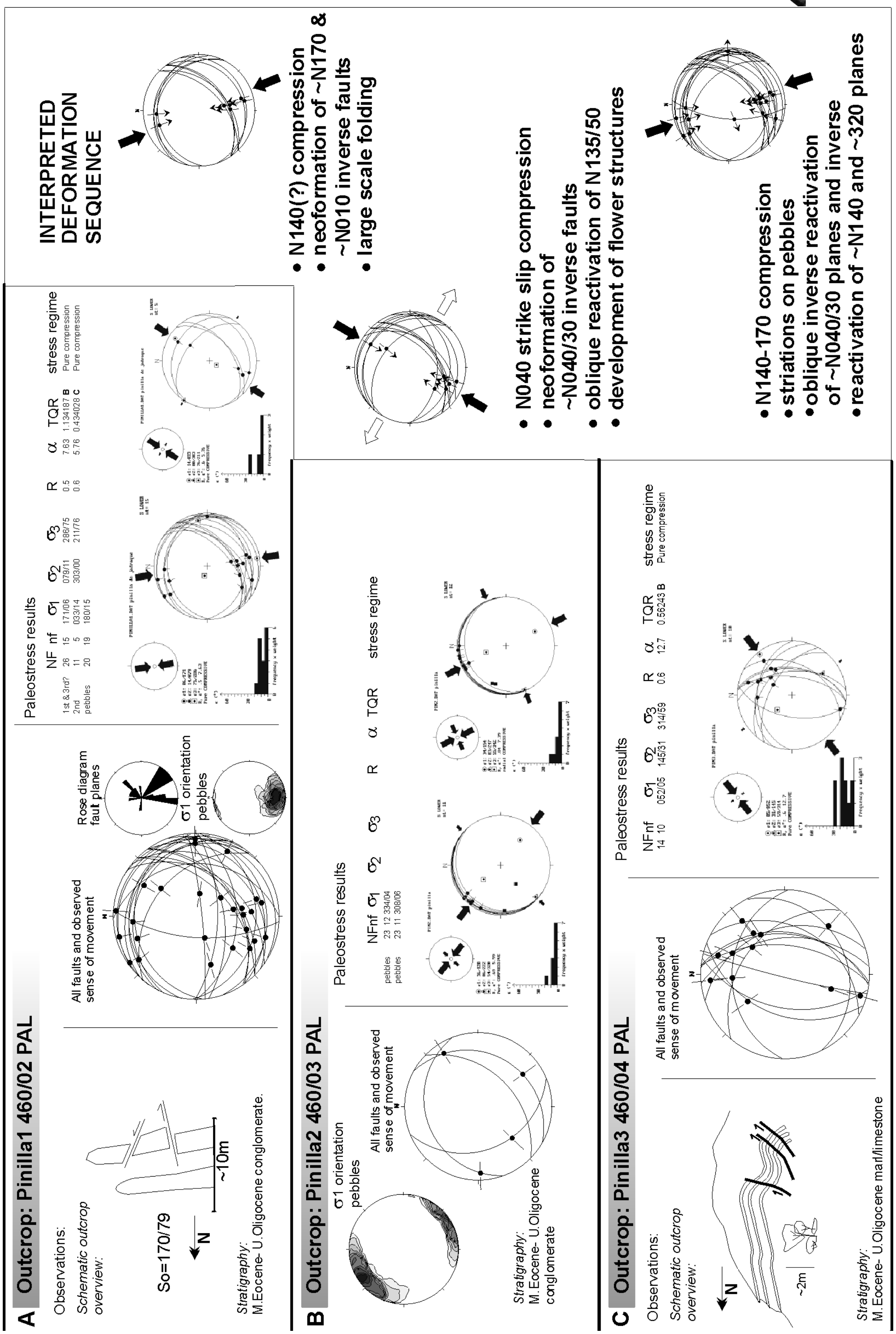


Figure 3.2.8
Observations and paleostress results for Pinilla1-3. See Table 3.2.1 for explanation of abbreviations. See Figure 3.2.4 for location of the stations.

Pinilla3 (Figure 3.2.8c)
This key outcrop, with respect to relative dating of structures is positioned directly north of the steeply dipping U. Eocene- L. Oligocene conglomerates of the Pinilla1 outcrop. A nice fold has developed in the M. Eocene marl-limestone succession. In the core of this frontal anticline, several low angle, top to the SSW, thrusts are observed related to the first compressive deformation of the study area during the Tertiary. Closer examination reveals rather oblique striae in one case overprinting faint dip-slip striae, which suggests late stage reactivation.

Aleas (Figure 3.2.9a)
An outcrop located a few kilometer north of Aleas, in the core of a gentle near E-W trending syncline. The σ_1 direction as inferred from pitted pebbles (N321°) is reflected in a tensor for few (6) of the fault slip data (355/10). Although the quality of this tensor is mediocre, it has been included in the analysis based on the results of the pebbles and the occurrence of a similar regional stress field. A second, better tensor is obtained in this section for a pure compressive stress regime with a small perpendicular extensive component with Sh_{max} ~N050°.

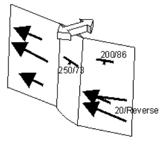
Cerezo de Mohernando (Figure 3.2.9b)
In a very recent road cut just west of Cerezo de Mohernando up to 27 fault planes and 11 pebbles with kinematic indicators have been measured. The resulting σ_1 direction from the pebbles, N354°, was more or less reflected in the resulting N334° Sh_{max} of a strike-slip deformation regime that explains 14 out of the 27 faults. In this area, the resulting stress fields have a larger extensional component to them than the results in the Pinilla area. Most likely this is related to minor halokinematic movements in the triangle Aleas-Cerezo-Espinosa.

Outcrop: Aleas 486/02 PAL

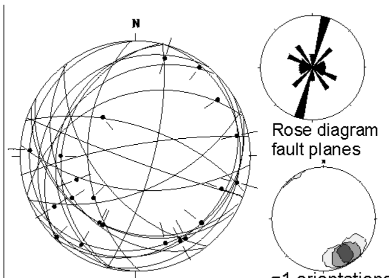
Observations:

Stratigraphy:
U. Eocene-
U. Oligocene
coblomerate

Schematic outcrop overview:

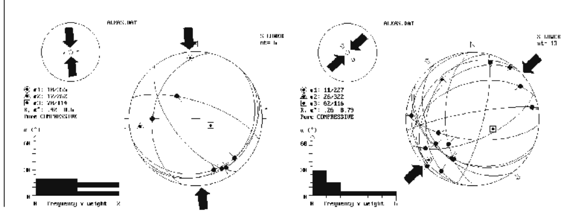


All faults and observed sense of movement



Paleostress results

	NF	nf	σ_1	σ_2	σ_3	R	α	TQR	stress regime
1st	21	13	227/11	322/26	116/62	0.26	8.79	0.915543 **B**	Pure compressive
2nd	21	6	355/10	262/17	114/70	0.42	8.6	0.199336 **C**	Pure compressive
pebbles	3	3	140/05						

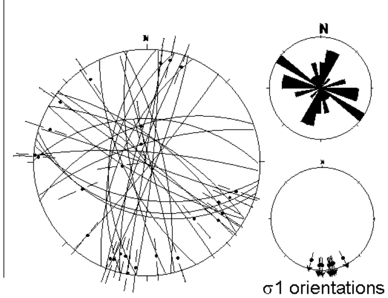


Outcrop: Cerezo de Mohernando 468/01 PAL

Observations:

Stratigraphy:
U.Oligocene
conglomerate and
sandstone

All faults and observed sense of movement



Paleostress results

	NF	nf	σ_1	σ_2	σ_3	R	α	TQR	stress regime
	27	14	334/10	145/79	244/02	0.53	9.66	0.751476 **B**	Pure strike slip
	27	10	036/81	252/08	161/06	0.96	8.91	0.415679 **C**	Extensive strike slip
pebbles	11	11	174/05						

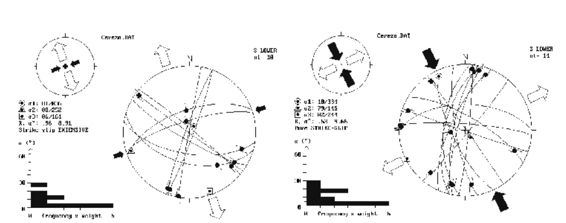


Figure 3.2.9
Observations and paleostress results for Aleas and Cerezo de Mohernando. See Table 3.2.1 for explanation of abbreviations paleostress results. See Figure 3.2.4 for location of the stations.

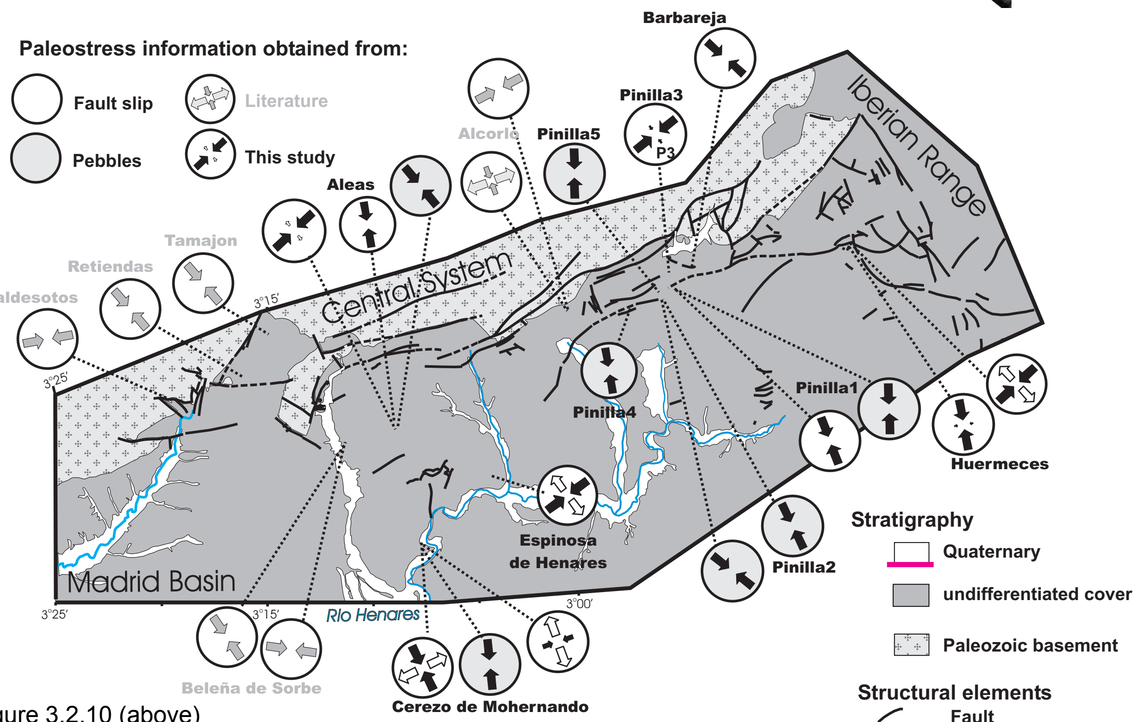


Figure 3.2.10 (above)
Results of the paleostress analysis combined with result from previous studies.

Table 3.2.1 (below)
Table showing all results of the observations at the paleostress stations in the study region.
Code equal to the SIGMA-classification [SIGMA, 1998]. NF= total number of faults, nf= number of faults explained by tensor, orientations of the principal axes of stress and the stress ratio R. α= angle of deviation between the calculated striation and the observed one on a plane. TQR= Tensor Quality Rank, following Delvaux [1994]: A, B, or C for good, reliable, and unreliable respectively.

Station	*code*	*age sediments*		*NF*	*nf*	σ1	σ2	σ3	*R*	α	*TQR*		*stress field*
Aleas	486/01	U.Eocene- U. Oligocene	1st	21	13	227/11	322/26	116/62	0.26	8.79	0.92	**B**	Pure compressive
			2nd	21	6	355/10	262/17	114/70	0.42	8.6	0.20	**C**	Pure compressive
			pebbles	3	3	148/05							
Barbareja	460/01	U.Cretaceous		3	3	312/01	042/07	210/83	0.5	0.53	5.66	**A**	Pure compression
Cerezo de Mohernando	486/02	U.Oligocene		27	14	334/10	145/79	244/02	0.53	9.66	0.75	**B**	Pure strike slip
				27	10	036/81	252/08	161/06	0.96	8.91	0.42	**C**	Extensive strike slip
			pebbles	11	11	354/26							
Espinosa	486/03	L.Oligocene		6	6	234/01	347/86	143/04	0.42	5.55	1.08	**B**	Pure strike slip
Huermeces del Cerro	461/01	M.Eocene- U.Oligocene		38	15	170/18	261/04	003/73	0.57	9.17	0.65	**B**	Pure compression
				38	14	048/11	332/78	140/02	0.46	7.45	0.69	**B**	Pure strike slip
Pinilla1	460/02	M.Eocene- U.Oligocene	1st & 3rd?	26	15	171/06	079/11	286/75	0.5	7.63	1.13	**B**	Pure compression
			2nd	10	5	033/14	303/00	211/76	0.6	5.76	0.43	**C**	Pure compression
			pebbles	20	19	339/06							
Pinilla2	460/03	M.Eocene- U.Oligocene	pebbles	23	12	154/34							
			pebbles	23	11	128/36							
Pinilla3	460/04	M.Eocene- U.Oligocene		14	10	052/05	145/31	314/59	0.6	12.7	0.56	**B**	Pure compression
Pinilla4	460/05	M.Eocene- U.Oligocene	pebbles	5	4	351/39							
Pinilla5	460/06	M.Eocene- U.Oligocene	pebbles	4	4	178/15							

In general two different states of tectonic stress have been detected in the study area. A compressive regime with σ_1 oriented ~N140°-180° and a strike-slip regime with a N030°-060° orientation for σ_1.

Generally, the σ_1-direction derived from striated pebbles shows a very consistent near horizontal 140°/320° trend. For many of the outcrops this direction is sub-parallel to the bedding of the conglomerates. However, in Pinilla1 this direction is at high angles with the sub-vertical S_0. The steeply inclined beds of the growth strata show late stage shortening by nearly conjugate sets of thrusts that fit well the ~N320° oriented

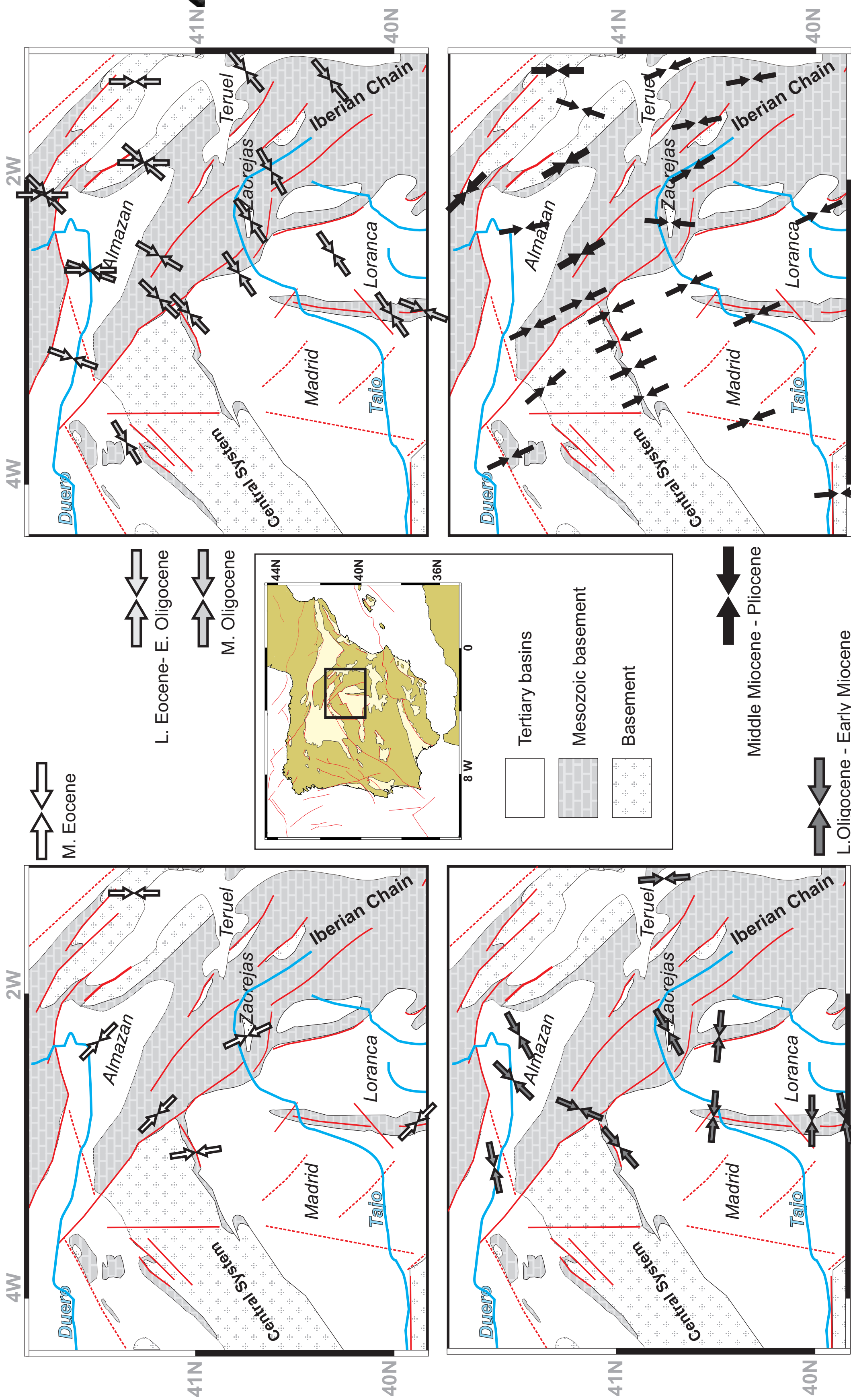


Figure 3.2.11
Overview of development of the stress field through geological time in the region, based on the compilation of paleostress data in this thesis.

compression derived from the pitted pebbles. This setting forms a lower limit for the age of the development of these striated pebbles and shows clearly that folding of the Lower Paleogene series was prior to the pebble deformation. In previous studies in the area, none of the Miocene outcrops yielded another stress field than a ~N140°-155° directed Sh_{max}. Therefore, the striated pebbles formed during the Middle Miocene to present.
In the Cogolludo area, the orientation of the stress field as inferred from the pitted and striated pebbles shows changes in σ_1-direction from at around 320/05 to about 140/05 pointing to recent tilting or gentle folding, most likely related to limited halokinematic motions in the area.
However, other directions are present in Mesozoic to upper Oligocene levels. The strike-slip field with σ_1 oriented ~N040°-050° is found in up to upper Oligocene sediments (Espinosa), so this age can be considered as the oldest age of this stress field. A cross section perpendicular to the structures formed under ~N155° compression reveals large wavelength, low amplitude folding of the Paleogene cover (see upper panel of Figure 3.2.2). This folding that can be related directly to this stage of ~N040°-065° oriented compression affected sediments up to Upper Oligocene as well, whereas Lower-Middle Miocene sediments display an angular difference with the folded strata (N. of Jadraque).

Apart from some indications in outcrops Pinilla3 and Pinilla1, no hard proof can be found for an older approximately N-S compressional stress field. On the other hand, observation of the same sort of stress field in Cretaceous cover and Miocene deposits in the Madrid Basin does not a priori exclude a different age for both. A compilation of the new data on the stress field with data from literature (Figure 3.2.11) shows a clear regional evolution, which is very similar to the observations in the study area. Going back in time: (a) the present-day N-S to N140° directed Sh_{max} trend, is observed in the entire region. In the east N-S prevails, while in the western part the NW-SE directed Sh_{max} is dominant. This fanning of the present-day stress field is observed as well by the SIGMA results [SIGMA, 1998]. (b) The early to middle Miocene stress field was oriented near E-W in the Sierra Altomira and rotated towards NE-SW in the eastern sector. (c) During the late Eocene to late Oligocene, the dominant Sh_{max} direction was in general between N015° and N060°. (d) Some dispersed results indicate a pre-L. Eocene near N-S orientation for Sh_{max}.

Discussion and new model for the tectonic evolution of the SCS

The Paleogene sediments drilled in the Madrid Basin and their internal structure indicate that during the Paleogene an initial stage of limited loading and foreland basin development in combination with limited foreland deformation (bulge development and erosion) occurred. The distal type of Paleogene sediments suggests that the loading thrust belt was located NW-wards of the present-day location of the SBF. The thrust near Pinilla, Beleña de Sorbe, and north of Venturada might very well have been the active southern border fault during this stage. Similar timing of deformation is observed in the nearby Almazan basin. In the Mid Eocene, erosion of the Cretaceous cover of the SCS occurred, is documented in the study region, while in the Almazan region active basin subsidence started. During the Late Eocene- early Oligocene N-S oriented compression and related basin formation as observed in the Almazan basin (northwest of the SCS), which coincided with the first appearance of SCS basement erosion products in the sediments in the study area, indicate regional uplift.

The Eocene fan deposits near Pinilla have been buried by up to 2-3 km of younger sediments, as revealed by fission track data. In the El Pradillo well up to 1450m of late

Oligocene to early Miocene deposits have been drilled, but more to the east (at Santa Barbara), this level is reduced to around 800m. The unit below this sequence has not been divided into smaller segments than Maastrichtian- middle Oligocene, so part of this (1400-800m thick) sequence can be taken into account for burying the Eocene sediments.

The subsequent middle Miocene – present-day uplift of the SCS was more prominent towards the west. This variation can be deduced from the fact that the proximal Paleogene alluvial fan type sediments that crop out extensively near Pinilla have been largely eroded near Venturada, which is the westernmost outcrop of Paleogene sediments along the northern Madrid Basin border. Further west, only metamorphic and plutonic basement outcrops in the same tectonic block. The same pattern is shown by the fission track results. Uplift of 2-3km for the Paleogene fans increases to up to 5km near the Sierra de Gredos. This variation can be explained by M. Miocene active strike-slip faulting accommodating a lot of deformation along and even within (west of Beleña de Sorbe) the eastern part of the region, while the same amount of shortening is accommodated in the central and western SCS by mainly thrusting.
From both the model inferred from the fission track observations and the seismic reflection profiles through the basin edge, we concluded that thrusting in the M. Miocene occurred more basinward than the border fault that was active during the Eocene-Oligocene. The latter was not very active during the late stage (M. Miocene) compression as proven by fission track data. A possible reason for this is that the fault has been locked by the Oligocene strike-slip deformation.

The proposed scenario has been tested in a quantative way by a 2D numerical model that simulates lithospheric compression and calculates the thermal consequences of this compression [Ter Voorde *et al.*, 2001]. With the SCS geometry and the proposed scenario as input, this numerical model can reproduce the thermal histories of the fission track samples.

Some of the models proposed by others for the development of the SCS can be discarded based on the data presented and synthesized here. The demonstrated tectonic activity of the SCS during the Paleogene-Oligocene took place before the main collision of Iberia with the Betic/Alboran microplate (starting M. Miocene). Therefore, models that explain the evolution of the SCS as being the result of the M. Miocene event only should be disregarded. This includes models for the SCS incorporating a crustal detachment running from the Betics to the Northern Border Fault of the SCS, transporting Iberian upper crust and the Madrid Basin as a piggyback basin northwards [Ribeiro *et al.,* 1990]. The model proposed by De Vicente *et al.* [1996c] explaining the SCS as a set of pop-ups being active during M. Miocene only, seems to be incomplete with respect to the initial phase of deformation. The data presented show that some of the faults that were active during the Eocene-Oligocene were not reactivated in a later stage. Moreover, the previous deformation in the entire evolution of the SCS was of major importance in the more recent tectonic evolution. Because strike-slip deformation in an early stage of deformation has been observed, the block rotation model by Vegas *et al.* [1990] is appealing. However, block rotations in the northeastern SCS have been very minor, if they occurred at all.

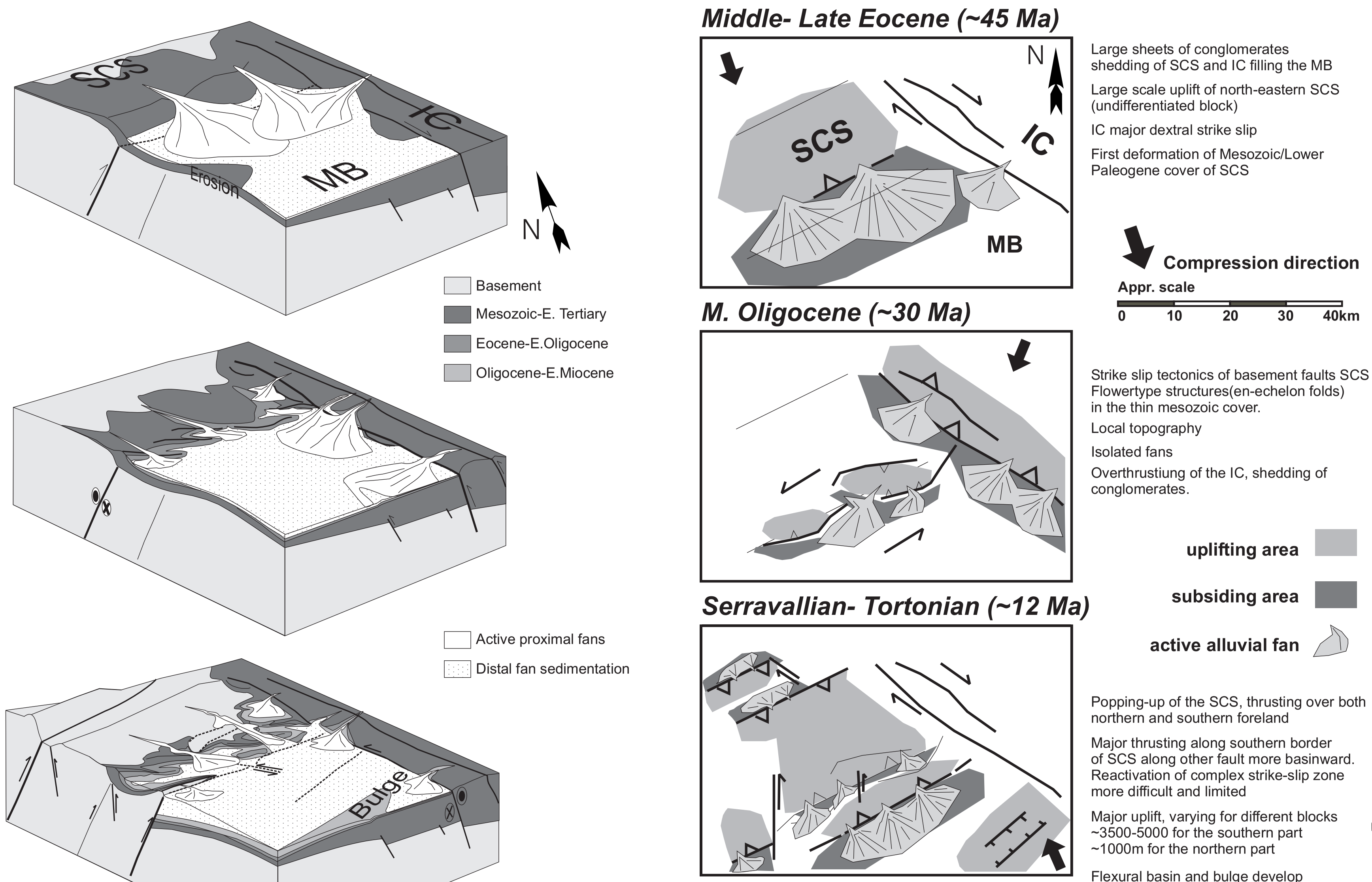


Figure 3.2.12
Schematic illustration of the three main stages in the new model for the Cenozoic tectonic evolution of the area located at the junction of the Spanish Central System and the Iberian Chain.
Left series shows a block diagram of this evolution, while the right shows a map view perspective.

By combining parts of the previously proposed models with the new data, new and in time (Paleogene- Miocene) extended model for the evolution of the SCS (see Figure 3.2.12) is proposed:

(1) *Middle –Late Eocene (~45Ma)* General but limited uplift occurs of at least the NE SCS, which leads to erosion of this hinterland and sedimentation of large conglomerate (proximal) and silt/clay (distal) sheets in the MB. Deformation of the Mesozoic/Lower Paleogene cover under NNW-SSE compression begins, which is related to the start of convergence between Eurasia and Iberia (the very onset of Pyrenean collision).

(2) *M. Oligocene (~30Ma)* NNE-SSW to NE-SW compression occurs, caused by collision of Eurasia and Iberia along the NE margin of the Iberian plate, inverting the Mesozoic Iberian Basin into the Iberian Range. The Iberian Range is thrust onto the eastern edge of the Madrid Basin and this deformation causes left-lateral transpressional strike-slip motion along a ~N070° oriented crustal Late Hercynian fault. The thin Mesozoic-lower Paleogene cover on top of the basement is folded en-echelon. As a result of transpressional flower structures, local relief develops. Progressively, structural highs develop while sedimentation continues, resulting in growth structures and isolation of local basins. These local basins eventually become filled with isolated conglomerate bodies. The strike-slip deformation related to this phase diminishes away from the active Iberian Range front.

(3) *Middle to late Miocene (~12-9Ma)* Major differential uplift (1000-5000m) of the SCS with respect to the surrounding basins occurs. Inherited basement faults are reactivated to form a series of pop-ups and ‘pop-downs’ under NNW-SSE compression. The tectonic activity along the southern border steps basinward by activation of a new thrust.

At least the NE part of the Spanish Central System has been tectonically active during the middle Paleogene. A first stage of deformation in the area took place under a stress field similar to that active during M. Miocene to present-day, so it is hard to discriminate features formed during either of the events. Deformation during this first stage of development of the mountain range and related basins has been limited, compared to the late stage evolution for the region. However, both Eocene and Oligocene compressional deformation events have contributed significantly to the distribution and type of deformation during the M. Miocene to present-day in the southeastern SCS, resulting in the present-day configuration of the Madrid Basin and Spanish Central System.

The combination of data from several fields in Earth Sciences has unraveled the tectonic and geological history of the study area. This proves how important integrated studies are in present-day geology. Using either of the components as a stand-alone study, it would never have been possible to end up with a model that explains the geological structure of the region through time.