The Iberian Massif: a Carboniferous assembly

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Abstract
A protracted history of strike-slip movements in Southwestern Iberia, throughout Carboniferous times, Westphalian and Stephanian in particular, has resulted in subparallel strips of terrain which are difficult to recompose into the original configuration. The nature and timing of major strike-slip movements have become apparent as a result of detailed work on the early Westphalian basin of Peñarroya (Córdoba province) and, also, by interpreting the published information on upper Westphalian and upper Stephanian strata in the Valongo structure northeast of Oporto, the Stephanian C (lower Autunian) basin of Buçaco near Coimbra, the Santa Susana Basin west of Évora, and the mid-Autunian basin of Valdeviar (Sevilla province). The geological history of the Peñarroya Basin is summarised; research data are analysed, and comparison is made with the Tertiary basins in California controlled by transform faulting. Published information on the Valongo, Buçaco, Santa Susana, and Valdeviar areas suggests similar histories to that of Peñarroya, with the corollary that major sinistral strike-slip operated in what is presently the Iberian Massif for most of Pennsylvanian times, perhaps some fifteen million years. The conclusion is reached that at least three major transforms existed, with additional subparallel strike-slip faults, which produced an assembly of different plate segments in late Carboniferous (Pennsylvanian) times. An Iberian Massif thus came into being from Permian onwards. Structural interpretations of Ossa Morena and the adjacent part of the Central Iberian Zone should take cognisance of the important effects of Carboniferous transform faulting.

Keywords: Pennsylvanian, Westphalian, Autunian, Sierra Morena, Iberian Massif, Iberian Peninsula.

Resumen
Las fallas laterales de tipo strike-slip que se hicieron notar en el Oeste-Suroeste de la Península Ibérica en todo el Carbonífero, aunque principalmente en tiempos westfalienses y estefanienses, han resultado en franjas subparalelas de terrenos que son difíciles de restituir a su configuración primitiva. La naturaleza y datación de los movimientos principales, de tipo transformante, han quedado patentes sobre todo como resultado de una investigación detallada sobre la cuenca westfaliense inferior de Peñarroya (Córdoba), provocada y deformada tectónicamente por una falla transformante; además de las interpretaciones posibles sobre la cuenca del Westfaliense superior y Estefaniense superior en el área de Valongo, cerca de Oporto, del Estefaniense C (= Autuniano inferior) de Buçaco, cerca de Coimbra, y de la cuenca del Viar (Sevilla), de edad Autuniense medio.

La historia geológica de la cuenca de Peñarroya se relata de forma resumida, con un análisis de los datos obtenidos, que la han permitido ver el gran parecido con Ridge Basin del Terciario de California, emblemática por su estrecha relación con fallas strike-slip de tipo transformante (Falla de San Andrés, sobre todo). La información publicada sobre las cuencas de Valongo, Buçaco, Santa Susana y Valdevar sugiere que hayan tenido un origen parecido al de la cuenca de Peñarroya, lo cual induce a pensar que fallas transformantes actuaban durante buena parte del Pensilvánico, quizá unos 15 millones de años. Se llega a la conclusión que había tres transformantes como mínimo, y que el Macizo Ibérico no se consolidó en su configuración actual hasta los comienzos del Perímnico. Cualquier interpretación estructural de Ossa Morena y parte colindante de Centroibérica debe tener muy en cuenta el papel de las fallas transformantes carboníferas.

Palabras clave: Pensilvánico, Westfaliense, Autuniano, Sierra Morena, Macizo Ibérico, Península Ibérica.
1. Introduction

The geological literature on Sierra Morena, an essential part of the Iberian Massif, shows the structural complexity of this area which is characterised above all by approximately NW-SE striking faults along the grain of structurally deformed rocks of various Palaeozoic ages and showing various degrees of metamorphism. The Ossa-Morena Zone of Lotze (1945) coincides largely with Sierra Morena, with the Valdeviar Basin of early Permian age lying along part of its SW delimitation with the South Portuguese Zone, whilst the granitic intrusion of Pedroches was chosen by Lotze as its northeastern limit. The strike-slip controlled Valdeviar Basin seems to coincide with a major suture of earlier (Pennsylvanian?) age, which is generally accepted as a valid separation of two major areas of different geological characteristics, but the northeastern delimitation of the Ossa-Morena Zone has proved more controversial. It is certainly of a very different nature geologically. Whereas it may be argued that Valdeviar coincides with the site of a major transform fault zone separating different terrains, the Pedroches intrusion cuts through Carboniferous (Mississippian?) strata belonging to one and the same basin. This cannot be regarded as a separation between different geological terrains. Transform faults separating different terrains exist in the general area SW of Pedroches, e.g. at Peñarroya and further South at the Azuaga Fault, and these might be considered as a more proper delimitation of the Ossa-Morena Zone. This point of view has already been put forward by different authors (e.g. Robardet, 2002). Lotze’s zonal scheme, useful though it may have been, now needs to be critically reexamined in the light of modern, plate tectonic criteria, with transform faulting becoming a major consideration. Figure 1 shows currently accepted tectono-stratigraphic zones (Julivert et al., 1974) with the location of Carboniferous occurrences related (and possibly related) to major strike-slip faults.

The pioneer work of Burg et al. (1981) has drawn attention to the presence of a major NW-SE striking tectonic shear zone, the Coimbra-Córdoba shear (called by later authors the Badajoz-Córdoba fault zone), which has been linked by some geologists to the Coimbra-Tomar shear zone in Portugal. This runs not quite parallel to the Valongo Anticlinal shear zone NE of Oporto (Fig. 2). The structural analysis by Burg et al. (1981) suggested strike-slip movements with a displacement of at least 72 km and they mentioned the possibility of a transform fault. They also included a mention of two different Lower Palaeozoic palaeogeographic domains being represented on different sides of the shear zone, referring to data published by Robardet (1976). Whilst acknowledging the importance of the Córdoba-Badajoz Fault, the different authors of later papers have variously emphasised the strike-slip and compressional tectonic regimes detected with regard to this fault zone. These two regimes are by no means incompatible since the analysis of major strike-slip faults based, in the main, on the knowledge of Tertiary basins in California (Crowell, 1982; Christie-Blick and Biddle, 1985), has shown the alternation of tensional and compressional regimes along these faults. However, the main question in the case of the Badajoz-Córdoba fault zone seems to be the different time frames for major compressional tectonic
history shows their relationship. The Badajoz-Córdoba shear zone has the Azuaga Fault on its southwestern side and the Peñarroya transform fault on its northeastern side (after Wagner, 1999).

2. Peñarroya Basin

The knowledge of this sedimentary basin is based on a detailed study of the Peñarroya-Belmez-Espiel Coalfield of early Westphalian age in the province of Córdoba. This narrow, elongate coalfield, c. 50 km long at 0.7-1.2 km width at outcrop (Fig. 2), strikes approximately NW-SE along the grain of the country. Geological mapping was combined with 1:100 scale logging of up to 60,000 m-

(thrust) and strike-slip (transform faulting) events. This would not be the first case in which a major fracture zone experienced different kinds of tectonic movement at different times. Perhaps, the main discrepancy between the different authors lies in emphasising one or the other kind of movement without due regard for the times involved and in being sometimes rather selective in marshalling the evidence. A case in point is the recent paper by Martínez Poyatos et al. (2001) where the evidence of thrusting is emphasised with strike-slip faulting being mentioned but in the context of a collisional regime. Transform faulting is rarely, if at all considered. It is noted that the major strike-slip faults in the southwestern part of the Iberian Peninsula cut through and displace tectonic structures of pre-Carboniferous age, with Mississippian sediments forming an unconformable cover and Pennsylvanian basins of local occurrence being intimately related to the strike-slip faulting. Their location alongside major strike-slip faults as well as their sedimentary (basinal) and tectonic (deformational)
tres of continuously cored boreholes drilled for coal at a time when the present writer was head of exploration of the state coal company ENCASUR. This allowed detailed analysis of the stratigraphic history of different parts of the coalfield and the understanding of lateral variations. Specialist studies on the sedimentology (Andreis and Wagner, 1983), palaeobotany (Álvarez-Vázquez, 1995), and palynology (R. Coquel, unpublished) completed the information which was summarised by Wagner (1999).

The coalfield (Fig. 3) is bounded on its southwestern side by a NE-directed late thrust fault covering the original basin margin, whilst the northeastern margin presents a normal sedimentary contact, which is marked by alluvial fan lobes and interlobes along a syn-sedimentary fault line with a topographic relief of a few hundred metres beyond this line. Figure 4 depicts the sequence of events relating to the SW margin of the coalfield. Geological cross sections through the coalfield show a strongly asymmetrical profile, with low dips of 5-20° on the northeastern margin and steadily increasing dips southwestwards, leading to steeply dipping strata just before a faulted contact is reached with a generally overturned, sheared succession of strata on the southwestern side (Fig. 5). The opposed facing of strata at this tectonic contact creates the impression of a synclinal structure, which is compatible with a basinal sag, although the synclinal core is nowhere visible. This is presumably due to shearing on a faulted contact, and it may be assumed that this fault separating the northeastern and southwestern flanks of the coalfield structure is a minor strike-slip fault parallel to the major transform fault (Principal Displacement Zone in the sense of Christie-Blick and Biddle, 1985), on the SSW margin of the basin. The strongly asymmetrical profile, with a wide normally dipping flank and a narrow, steeply dipping opposed flank, is characteristic of strike-slip controlled basins as exemplified by Ridge Basin of Tertiary/Quaternary age in California (Crowell, 1982). This is one of the better studied sedimentary basins alongside the San Andreas Fault,

Fig. 3.- Outline map of the Peñarroya-Belmez-Espiel Coalfield showing the unconformable contact on the NNE border and a late thrust fault covering the SSW basin margin. The position of the transform fault on the SSW basin margin is shown by the occurrence of a high angle thrust fault (upthrust) delimiting a band of high grade metamorphic rocks. (for an explanation of the history of events on the SSW basin margin, see Fig. 4). After Wagner (1999).

Fig. 3.- Mapa esquemático de la cuenca minera de Peñarroya-Belmez-Espiel en el que se muestra el contacto discordante del borde NNE, y el SSW cabalgante. La posición de la falla transformante en el borde SSW de la cuenca sedimentaria viene dada por una falla inversa que se sitúa en relación con las rocas metamórficas de alto grado al SSW de la cuenca, y que viene a ser una reactivación de la fractura antigua. Para una explicación de la secuencia tectónica, véase la Fig. 4. Según Wagner (1999).
which is a well known transform fault separating two different terrains in western North America. Although Ridge Basin is larger than the Peñarroya Basin, there is a clear similarity. Steep dips accompany the dominant strike-slip fault, with the opposed facing being partly attributable to basinal sag, with later compressional movements strengthening the impression of an apparent synclinal structure. These compressional movements were probably due to restraining bend conditions following upon a releasing bend episode on the transform fault (transpression following upon transtension in another terminology.) (see Wagner, 1999, for further details.)

The sequence of events detected in the Peñarroya Basin (Wagner, 1999) show shifts in depocentre southeastwards, along the strike of the basin (Fig. 6). This involves major shift in the sense of successive basinal areas with different time frames and a temporal separation of perhaps up to half a million years between two adjacent basinal areas, during which tectonic deformation of the earlier depositional area took place; and more minor shifts southeastwards within each of these successive basinal areas. At least two successive basinal areas have been conclusively demonstrated, i.e. one centred on the general region of Peñarroya (area I), and the other on Belmez-Espiel (area II) (Fig. 6). A third basinal area, further Southeast, in the area of La Ballesta (only partially shown in Fig. 6), is suggested by a different stratigraphic succession and a somewhat different fold structure. However, no appreciable time gap has been detected between the latter two areas, which are therefore marked IIA and IIB in Figure 6,
even though later work may show the latter to have had an individual existence. The first basinal area (I), perhaps some 30 km long and an estimated 2-3 km wide originally (and less than half this width after tectonic deformation), has been dated on a collection of several thousand plant megafossils as late Langsettian and early Duckmantian (Álvarez-Vázquez, 1995). A coal petrographic analysis by Marques (1993) has shown a regional maturity of coking coal grade, with natural coke produced by diabase sill intrusions. These sills were folded together with the intruded sediments prior to the establishment of the second basinal area, and are thus dated as Duckmantian. The coals (and including the natural coke) in most of the first basinal area were transformed into a low grade anthracite by a later heating event, of uncertain, but almost certainly post-Carboniferous age. A compressional tectonic event folded this first basinal succession during a relatively short time span, perhaps half a million years, in Duckmantian times. A second basinal area (II) to the ESE, which came into being after the first area had been tectonically deformed, impinged slightly on the previous one, provoking the local steepening of fold axes in the earlier basin structure, where it was overlapped by the second basin sag in the vicinity of Peñarroya-Pueblonuevo (Fig. 6). Palaeobotanical dating (Álvarez-Vázquez, 1995) shows a late Duckmantian age for the second basinal area, and coal petrography has demonstrated a regional coking coal grade which has remained essentially unaltered. Tectonic deformation of area II is apparently limited to a steepening of the dip to near-vertical in the southwestern flank bordering the transform fault, with substantial shearing parallel to this fault, and to the generation of some minor folds in the wide, normally dipping northeastern flank of the general basin structure. Figure 5 gives a cross-section through area IIa after tectonic deformation. Minor thrusting on the small, accessory anticlines in the overall monoclinal succession on the wide northeastern flank of the basin produced small tectonically induced coal accumulations in the anticlinal cores. Quite a different stratigraphic succession and a somewhat different fold structure is found in subarea IIb in the southeastern most part of the coalfield, the La Ballesta region, but stratigraphic dating on megafossil assemblies has suggested the same late Duckmantian age as for the Belmez-Espiel area. However, it is noted that late Duckmantian

Fig. 5.- Cross section through the Peñarroya-Belmez-Espiel Coalfield in the Belmez area showing tectonically deformed basinal areas IIA and IIB (the small syncline on the left), both of Duckmantian age. Opposed facing is indicated by arrows. The synclinal core shown at depth is interpretative, not based on actual observation. The overturned flank on the SSW side is extensively sheared in parallel with the transform fault controlling the Peñarroya Basin. Decollement thrust underlying lower Namurian sediments is shown on the SSW side (after Wagner, 1999).

Fig. 5.- Corte geológico a través de la cuenca minera de Peñarroya-Belmez-Espiel en el área de Belmez, mostrando las áreas de sedimentación IIA y IIB (el pequeño sinclinal a la izquierda), ambas de edad Duckmantiente. Las flechas indican la polaridad opuesta de los dos flancos de la estructura principal. El núcleo del sinclinal dibujado en profundidad es interpretativo. El flanco invertido del borde SSW está muy laminado, con fallas paralelas a la transformante que controlaba la cuenca sedimentaria de Peñarroya. El borde SSW de la cuenca minera viene dado por un cabalgamiento por despegue de los estratos del Namuriente inferior del “basamento” de la cuenca westfaliense. Según Wagner (1999).
of reworking is understandable in the light of tectonically active basin margins, only a few kilometres apart. Viséan and lower Namurian strata constitute an unconformable succession on top of Lower Palaeozoic sediments and earlier metamorphic rocks, and occur in the immediate vicinity of the Peñarroya Basin. These strata show dislocation into a number of local successions which are difficult to relate mutually (Cózar and Rodríguez, 1999), probably as a result of early Westphalian strike-slip movements.

The sedimentary analysis of bore logs and surface mapping shows a consistent pattern of facies distribution which reflects the relative importance of the SSW border, which is interpreted as being coincident with the transform fault controlling basin subsidence and the shifts in depocentre. The NNE border had a less permanent location, but the similar stress regime at different times produced....
an alignment of fractures provoked by synthetic faulting subparallel to the main strike-slip fault, i.e. the Principal Displacement Zone (in the sense of Christie Blick and Biddle, 1985). The position of this synthetic fault changed with time as the different finds of alluvial fan breccia in the area SE of Belmez have shown, but the alignment of alluvial fans of different ages and corresponding to successive basinal areas creates a semblance of continuous fracture on the NNE border of the Peñarroya-Belmez-Espiel Coalfield. Indeed, this northeastern border which is undisturbed by later tectonics, displays an almost continuous line of alluvial fan lobes with interlobes. These are indicative of a tectonically active border with upstanding relief of the order of several hundred metres (Andreis and Wagner, 1983). Basin analysis has shown these fans to be of different ages, younging from WNW to ESE, with the shifts in depocentre in this direction. The alluvial fans grade both upwards and laterally (basinwards) into a system of braided stream deposits leading into an alluvial plain which bordered onto a lacustrine area near the Principal Displacement Zone (Fig. 7). This pattern is repeated in the successive basinal areas existing at different times; thus showing that the tectonic controls on the basin were basically the same at various times. Temporal variations in the relative width of the different facies belts may have been due to the degree of closure at the two ends of the basin, in northwestern and southeastern directions; generating either a larger or a smaller lake and consequently restricting or enlarging the alluvial plain area. Climatic control on the size of the lake is excluded because the composition of the fossil flora is similar throughout the entire time span represented (some 3 million years, as suggested by the absolute ages for the late Langsettian-Duckmantian interval, according to Burger et al. 1997). The southeasterly shifts in depocentre within each of the successive basinal areas do not appear to have resulted in any substantial change in the facies distribution which may have been due to tilting of the basin floor towards the transform fault where there was a greater loss of cohesion. Facies belts thus strike WNW-ESE in parallel with the faults controlling the basin.

Whilst the northeastern border of the basin is accessible to direct observation, due to the absence of later tectonic deformation, the southwestern basin margin is hidden from view as a result of a late thrusting event which moved lower Namurian strata of the basin margin on top of an already deformed lower Westphalian basin fill (Fig. 4). As a result of this thrusting there is a general lack of information on the sediments generated along this basin margin, which coincided with the transform fault controlling basin subsidence and the successive shifts in depocentre. Only in the vicinity of Belmez, corresponding to basinal area IIa of late Duckmantian age, there are outcrops of breccias interpreted as alluvial fan deposits near the southwestern border of the coalfield, thus suggesting that the southwestern basin margin also generated alluvial fans (as indicated in Fig. 7).

In the course of the history of each successive basinal area, it is assumed that the SSW basin margin as determined by the transform fault, on which continual movement would have taken place, occupied approximately the same place permanently. The alluvial fans generated on the ENE basin margin as provoked by subparallel synthetic faulting as a result of stress generated on the plate functioning as the passive tectonic unit alongside the transform fault, show the effects of backfaulting by which the width of the sedimentary basin marginally increased during the life span of each basinal area. The clast composition of these alluvial fans show provenance from the subsiding plate which constituted the basin floor. These clasts are phyllites and quartzites of presumed Cambrian age. The actively moving plate on the other, southwestern side of the transform fault, contains metamorphic rocks including gneisses, representing a different terrain corresponding to a much lower structural level.

The amount of lateral movement can only be estimated, but it is likely to have been considerable. Azor et al. (1994) mentioned a figure of 200 km lateral displacement between the Central Iberian and Ossa-Morena Zones, placing the zonal boundary on the northeastern side of the Badajoz-Córdoba shear zone; this boundary is here regarded as coincident with the transform fault on the southwestern border of the Peñarroya sedimentary basin. They pointed out that strike-slip faulting, though mainly involving horizontal movement, would also have had a vertical component and that this would explain the marked difference in metamorphic grade between the different tectonic units on the SW and NE sides of the fault. This very reasonable argument was backed up by structural measurements such as stretching lineations which were not completely horizontal but dipping 10°. Since measurements are always local, there is inevitably a certain amount of extrapolation, but a cumulative vertical throw of ten kilometres or more, as Azor et al. (1994) suggested, may be a reasonable estimate. It is interesting to quote their conclusion that their “kinematic and geometric” (i.e. structural) “data and the different metamorphic histories of the differentiated units integrate into a model involving development of a zone of oblique crustal thrusting that progresses southeastward and whose hanging wall is affected at the rear by an important extensional left-lateral shear zone, causing the exhumation of a unit with high pressure metamorphism”. This model based on the structural analysis of pre-Car-
Boniferous strata in the general region agrees largely with the data obtained from the tectono-stratigraphic history of the Peñarroya Basin of early Westphalian age, although the present writer finds no evidence for "oblique crustal thrusting" beyond the temporary, local thrusting associated with restraining bend tectonic deformation at certain intervals on a transform fault. Indeed, a transform fault as that which controlled the history of the Peñarroya Basin would almost certainly combine some vertical movement with the predominantly horizontal strike-slip. The actively moving plate with metamorphic rocks on the southwestern margin of the basin would have functioned as an upstanding area with regard to the subsiding basin floored by markedly less metamorphic rocks of the more passively deformed plate. In agreement with data provided by Ridge Basin in the Tertiary of California (Crowell, 1982), a major transform fault would not move in an entirely straight line and this would provoke releasing bend (transtensional) and restraining bend (transpressional) situations. During the transpressional episodes the actively moving plate would thrust itself onto the basin, increasing the vertical component on the transform fault. This kind of behaviour is obvious in the tectonic deformation of basinal area I near Peñarroya, where compression generated a composite of two synclines with an intervening anticline, with overturning of the SSW flank nearest the transform fault. Continuing strike-slip produced a local repetition of the steeply dipping, overturned SSW flank of the synclinal
structure (Fig. 8) (the site of Mina María, the last working underground coal mine), and is also supposed to have produced the internal shearing within the steeply dipping overturned flank parallel to the upthrust SSW basin margin. Numerous small tectonic lenses were thus created in the overturned southwestern flank of the basinal structure in lower Westphalian sediments, and this resulted in an overall thinning of the stratigraphic succession, which is well attested to by the coal-mining experience.

Of course, thrusting of this kind is local and steeply angled. In this tectonic regime there is no room for large-scale movement across the strike as proposed by Martínez Poyatos et al. (1998), who postulated successive Carboniferous basins being carried "piggy-back" northeastwards. These authors interpreted largely out-of-date stratigraphic data culled from the literature, and did not study the Peñarroya Coalfield directly. They displayed only a sketchy knowledge of the different Carboniferous successions, and failed to separate a Viséan to early Namurian marine basin from the early Westphalian intramontane, terrestrial basin (i.e. the Peñarroya Basin proper), although these two basins are quite different in origin and palaeogeographic configuration, and separated in time by several million years during which no sedimentation took place. Since they were also unaware of the southeasterly shifts in basinal areas and depocentres in the Peñarroya Basin, they did not realise the fundamental contradiction with their "piggy-back" model, which required continual northeasterly shifts in basinal area. Insufficient local geological information thus led to an invalid, rather simplistic model.

The minimum time allotted to movements on the transform fault which provoked subsidence followed by deformation and, subsequently, by subsidence of another basinal area southeast of the earlier one, is that corresponding to the late Langsettian and Duckmantian. The time interval involved is variously calibrated by the different authors, but is about 3 Ma, during which horizontal movement was consistently in one direction. If the passively fractured, subsiding plate on the northeastern side of the fault is regarded as more or less static, and the actively displaced, uplifted high metamorphic area on the southwestern side has been the one moving southeastwards, this will have...
produced the successive transtensional, transpressional, and, again, transtensional and transpressional situations during these c. 3 Ma. The two successive basinal areas (I and II) produced by a releasing bend (transtensional) situation seem to have been each about 30 km long. Since there is an intervening interval of restraining bend situation, during which tectonic deformation took place, another 30 km movement may have been involved. This suggests some 90 km movement southeastwards of the active plate with high metamorphic rocks. The second basinal area has also been tectonically deformed so that approximately a 100 to 120 km displacement may be postulated for a time interval which probably did not exceed 4 Ma. These figures are of a similar magnitude to the 200 km mentioned by Azor et al. (1994). Of course, one wonders how long this transform fault continued to be active. The 3 Ma interval attested to by the Peñarroya Basin represents the minimum time to be considered.

The fairly late, shallowly dipping thrust fault on the SSW side of the Peñarroya-Belmez-Espiel Coalfield extends east-southeastwards well beyond the exposed lower Westphalian deposits, thus preventing the observation of possible additional (later) basinal areas further along the transform fault in this direction. This means that the 100 to 120 km lateral displacement is very much a minimum figure. It is also possible that earlier basinal areas lay along the transform fault in west-northwestern direction. A 200 km displacement as suggested by Azor et al. (1994) thus appears within the realm of possibility.

3. Evidence of other strike-slip basins in the Carboniferous/Early Permian of SW Iberia (Fig. 1)

3.1 Valdeinfierno

The earliest example of a strike-slip controlled basin in Sierra Morena refers to a small pull-apart, the Valdeinfierno Basin (Roldán and Rodríguez, 1989), which straddles the Córdoba-Sevilla provincial boundary south of Fuenteverganza (Fig. 2). Although pull-aparts are different to the basins formed alongside a transform fault, the Valdeinfierno pull-apart basin, of late Tournaissian age (Wagner, 2001) shows that stress fields producing predominantly horizontal slip were already in evidence at a very early date in the Carboniferous of Sierra Morena.

3.2 Sierra de San Pedro

A poorly known conglomeratic occurrence with lower Westphalian floral remains is known from the Sierra de San Pedro, South of Cáceres (Bochmann in Walther, 1977). This is the only occurrence of similar age to the Peñarroya Basin in the general vicinity. Too little is known of this occurrence (Fig. 1) to speculate on its possible link with transform faulting.

3.3 Buçaco

This NNW-SSE striking, narrow elongate strip of Stephanian C (= lower Autunian) strata lies alongside the Coimbra-Tomar Fault which is regarded as the NW extension of the Badajoz-Córdoba shear zone (Domingos et al., 1983). The tectonic structure is apparently synclinal, with a probable cross fault separating the general occurrence into the Santa Cristina Syncline in the South and the Algeriz Syncline in the North (Wagner et al., 1983). Total length of the occurrence is almost 30 km at 0.5-2 km width. Like the Peñarroya Basin it presents a tectonically undisturbed unconformable contact with alluvial fan deposits on the eastern side, whereas it is delimited on its western side by a steeply angled thrust fault. Basement rocks are quite different on these two sides, denoting a tectonic contact connecting two different terrains. Only one stratigraphic section has been measured in detail on the eastern flank of the Algeriz Syncline, and there is no information on possible shifts in depocentre. The 87 m thick succession measured, shows alluvial fan deposits which are followed by alluvial plain sediments with fluviatile conglomerates in the higher part. Fossil plant remains have allowed stratigraphic dating.

If the Coimbra-Tomar fault is indeed the same as the Badajoz-Córdoba fault zone, the nature and configuration of the Buçaco Basin would suggest that tectonic movements on this fault zone lasted at least until latest Carboniferous times. However, this assumption flies in the face of southeastward younging of Carboniferous (Pennsylvanian) basins on the Badajoz-Córdoba transform fault, so the Coimbra-Tomar Fault should probably be regarded as a later fracture which may be partly coincident with the earlier fault zone.

3.4 Valongo

The transform fault which controlled the development of successive depocentres in the Peñarroya Basin, is not the only one of its kind that has been detected in the western Iberian Peninsula. In the area northeast of Oporto, NW-SE striking faults in the complex structure of the Valongo Anticline delimit a narrow strip of squeezed-in terrestrial Carboniferous successions of late Westphalian and late Stephanian ages, with the earlier strata occurring in the northwestern part. Worthy of note is the progression of
stratigraphic ages, younging southeastwards, since this
invites comparison with the progressively younger ages
found in southeasterly direction in the Peñarroya Basin,
from Langsettian to Duckmantian. Little is known about
the structure and stratigraphic history of presumed Bolso
van (Westphalian C) strata in the Casais-Alvarelos area
to the Northwest (and even less of that in the Serra de Rates
further North). Carboniferous strata at Ervedosa, dated as
early to mid-Westphalian D (Wagner and Lemos de Sousa,
1983), lie in apparent continuity southeastwards with the
strata found at Alvarelos. More information is available
on upper Stephanian (B-C) occurrences further southeast-
wards, in a narrow strip, some 90 km long and only a few
hundred metres wide, lying east-southeast of Oporto. This
strip has been mined intensively in what has been called
the Douro Coalfield, with the principal mines at São Pedro
da Cova and Pejão/Germunde. There is apparent structural
continuity between these upper Stephanian coal-bearing
strata and the upper Westphalian deposits to the North-
west, and it is noted that both have been attributed to a sin-
gle basin with progressive younging southeastwards (Do-
migos et al., 1983). This may be so in terms of structural
control, in which case a large time interval, several million
years, without apparent basinal subsidence, separates the
late Stephanian B or Stephanian C deposits of the Douro
Coalfield from the much earlier mid Westphalian D strata
at Ervedosa. Although the tectonic contacts appear as
steeply angled thrusts, Domingos et al. (1983, p. 189) note
that “the shear zone has also an important strike-slip sin-
istral component”. Domingos et al. (1983, p. 190) further
note that “The internal deformation of the sedimentary fill
is quite variable. Near the shear zone all the beds from
Westphalian B to Stephanian C are strongly deformed with
subvertical axial planar slaty cleavage parallel to the shear
zone and a downdip stretching lineation, but where the
trough is wider, as at São Pedro da Cova, the penetrative
def ormation of Upper Carboniferous strata dies out rapidly
southwestwards”.

It would appear that the sum total of the data available
on the Carboniferous strata east of Oporto is compatible
with the presence of a transform fault which operated dur-
ing an interval of at least 6 MA, from late Westphalian
to late Stephanian times. It may well be that the Valongo
transform fault took over in time from the earlier one at
Peñarroya. Both acted in the same direction.

3.5 Valdeviar

An important geological boundary, that between the
Ossa Morena and South Portuguese zones (Lotze, 1945),
coincides with the Autunian basin of Valdeviar, in Sevilla
Province. This basin strikes NNW-SSE and crops out in c.
30 km length and 3.5-5 km width. It is dated on fossil flora
as middle Autunian (basal Permian) (Wagner in Sierra et
and structural context of the Viar Basin, and concluded
that this basin was a half graben with a faulted northeast-
er border where drag produced a marked steepening of
the dip of Lower Permian strata. The undeformed, flat-ly
ping strata on the southwestern side of the basin display an
irregular, undeformed unconformable contact with Lower
Palaeozoic strata and intrusives. Simancas postulated that
the NE boundary fault would represent a reactivated Late
Palaeozoic fracture zone coincident with part of the Ossa
Morena/South Portuguese boundary which he interpreted
as a major strike-slip fault, with some 50 km lateral dis-
placement. A later study by García-Navarro and Sierra
(1998) emphasised tectonic movements across the strike,
which they regarded as extensional during basin subsid-
ence and compressional when the steeply dipping upthrust
on the northeastern side of the basin came into being,
thrusting Ossa Morena rocks onto the Autunian basin sediments. With regard to the stratigraphic succession they
accepted the informal subdivisions proposed by Simancas
(1985), commencing with red conglomerates and basaltic
flows, followed by grey clastic deposits (with volcanoc-
clastics – see Sierra et al., 2000), a more major interval of
basalts, and a red detrital succession. The map shows this
last stratigraphic interval to be overlapping the earlier de-
positions, thus suggesting a southeasterly shift in depocentre.

The overall configuration of the Viar Basin suggests
strike-slip control, similar to that of the early Westphal-
ian Peñarroya Basin. The Ossa Morena/South Portuguese
boundary fault, which is generally regarded as a major
separation between areas of different geological history,
could easily be a transform fault as Simancas (1983) has
suggested. A rejuvenation of this transform fault in earli-
est Permian (mid-Autunian) times would have produced
the Viar Basin as a result of subsidence of the South
Portuguese side of the fault zone. A southeasterly shift in
depocentre is indicated by the onlap relationship, this be-
ing easily understood as the result of a tectonically active
plate moving alongside a more passive plate with marginal
subsidence. In this case, the movement would be dextral,
with the Ossa-Morena Zone moving southeastwards.
However, Simancas (1983) regarded the earlier, pre-Per-
onian movements as sinistral. The Viar Basin would thus
represent a late reactivation of earlier transform faulting,
with a reversal of the strike-slip movements. The thrust
fault on the northeastern side of the Viar Basin is consist-
ent with restraining bend (transpressional) conditions after
the releasing bend (transtensional) conditions leading to
subsidence had ceased.

4.6 Santa Susana

Another late Palaeozoic basin alongside the Ossa Morena/South Portuguese boundary fault is the occurrence at Santa Susana, in South Portugal (Fig. 1). This is a 12 km long and 0.1-5 km wide strip of upper Westphalian D or basal Cantabrian strata of terrestrial facies. Domingos et al. (1983) describe the occurrence as 150 m of conglomerates, arkoses and coal-bearing shales, which overlie possibly Namurian volcanic rocks and shales. These Namurian? strata with unconformable upper Westphalian D or basal Cantabrian cover are thrust westwards on top of possibly Devonian phyllites attributed to the South Portuguese Zone. Too little is known about the Santa Susana Basin to allow speculation on the tectonic controls of this basin, but its position alongside the Ossa Morena/South Portuguese boundary fault suggests a link with this probable transform fault.

4. General discussion

The Viar Basin seems to mark the end of major strike-slip movements in the present-day area of the Iberian Massif. Since strike-slip faulting in Sierra Morena goes back to the late Tournaisian (as shown by the Valdeinfierno pull-apart basin), the stress pattern giving rise to these movements lasted some 30 Ma. However, the most important strike-slip faulting attributed to transform faults seems to correspond to Westphalian and Stephanian times, i.e. some 15 million years. These seem to have been mainly sinistral movements which apparently amount to hundreds of kilometres displacement altogether. This may explain the contention of certain authors (e.g. Oliveira et al., 1979) that the South Portuguese Zone has its nearest equivalent in northwestern Europe. Whatever the total amount of Pennsylvanian transform faulting may have been, it is clear that the Iberian Massif did not acquire its present configuration until the end of the Carboniferous and that the concept of an Iberian microplate, as postulated in some of the literature, cannot be regarded as valid for any configuration prior to the Permian. Even so, the southeastern part of the Iberian Peninsula may be a later addition.

A large question mark looms over Morocco up to and including the Atlas Mountains. (Southeast of the High Atlas lies the northern edge of the Gondwana continent of Carboniferous and Permian times.) This is not the place to analyse the Moroccan evidence, but some of the Carboniferous basins in central Morocco have been explained as being due to strike-slip fault movements. The recognition of Pennsylvanian transform faulting in the Iberian Massif and the possibility that most of Morocco may have to be regarded in a similar context, opens up a wide range of possibilities for Carboniferous plate reconstruction, even across the present-day Atlantic. It also suggests that the contact between the Atlas Range and the Gondwana continent is a very major suture separating different plates during Carboniferous times. (Earlier configurations leading to the accretion of parts of a Lower Palaeozoic Gondwana becoming part of Europe belong to a different time frame.)

A plate tectonic reconstruction of the Iberian Peninsula of Palaeozoic age will have to take into account the transform faulting that took place during the Carboniferous (Pennsylvanian in particular). This reconstruction must perforce ignore the Mesozoic and Tertiary configuration as exemplified by the Betic Cordillera and the Tertiary basins in this area. Only the Iberian (Hesperian) Massif of the present-day configuration may be considered in the

Fig. 9.- Position of the three most major transform fault zones in the western Iberian Peninsula, i.e. from North to South: Valongo (V), Coimbra-Badajoz-Córdoba (C.B.C.) and Ossa Morena/South Portuguese boundary fault (O.M.S.P). Valongo lies within the Central Iberian Zone (C.I.), whereas CBC may be regarded as the boundary between the Ossa Morena (O.M.) and Central Iberian (C.I.) Zones. M.N. is Montagne Noire; M.C. Massif Central.

Fig. 9.- Posición de las tres fallas transformantes mayores del Paleozoico de la Península Ibérica, de Norte a Sur: Valongo (V), Coimbra-Badajoz-Córdoba (C.B.C.) y falla límite Ossa Morena/Sudportuguesa (O.M.S.P). Valongo se encuentra dentro de la zona Centroibérica (C.I.) de Julivert et al. (1974). M.N. significa Montaña Negra; M.C. Macizo Central.
Fig. 10.- Palaeogeographic reconstruction of the different segments of the Western Iberian Peninsula during Carboniferous times. The NW Iberian Peninsula is slightly rotated to emphasise links with Armorica. The Montagne Noire (M.N.) is included with northern Spain in recognition of its Tethyan affinities and connection with the Pyrenees. The principal transform faults are shown with what may be regarded a minimum displacement. M.C. is Massif Central, M.N. Montagne Noire, C.C. Cordillera Cantábrica, C.I. Central Iberian Zone, O.M. Ossa Morena, and S.P. South Portuguese Zone.

5. Conclusions

Detailed study of the Peñarroya Basin has shown major strike-slip faulting (possibly a transform) to be the controlling factor in the genesis of this sedimentary basin and its tectonic deformation. Its geological history parallels that of Ridge Basin along the San Andreas Transform Fault in California. The evidence for major strike-slip (transform?) faulting in the West-Southwestern Iberian Peninsula, in relation to local basins of Carboniferous (Pennsylvanian) age (Casais-Ervedosa-Douro, Buçaco, Santa Susana), is apparently widespread in Ossa Morena and adjacent parts of the Central Iberian Zone, and additional transforms are likely to be present in areas where there is no evidence of strike-slip controlled basins alongside the transform faults. Although the evidence for strike-slip faulting in general includes the Tournaisian pull-apart basin of Valdeinfierno, transform faulting is shown to be essentially of Westphalian and Stephanian ages, an interval of up to 15 Ma. Many hundreds of kilometres of lateral displacement are likely to have been involved, and it is clear that tectonic reconstructions of the West-Southwestern Iberian Peninsula will need to take this into account. Palaeobiogeographic reconstructions for the Lower Palaeozoic (Robardet, 2002) provide support for this contention.

Whereas the Ossa Morena and South Portuguese zones are clearly different, with a probable transform fault intervening, the Ossa Morena/Central Iberian boundary is more questionable. Indeed, part of the Central Iberian Zone seems to be involved in the transform faulting which brought Northwest European elements to the southwestern Iberian Peninsula. This puts into question the validity of Julivert et al.’s (1974) combination of Lotze’s Lusitanian-Alcudian and Galaico-Castilian zones into a single Central
Iberian Zone. The West Asturian-Leonese and Cantabrian zones, which are mutually linked, both tectonically and palaeogeographically, show evidence of Tethyan connections, and may be regarded as essentially in place, without major strike-slip intervening. (Even though it is noted that Martínez-Garcia, 1996, has postulated “late Hercynian” strike-slip along East-West lines for northern Spain and southern France. This is clearly different to the late Carboniferous strike-slip faulting discussed in the present paper.)

The zonal scheme as proposed by Lotze (1945) and modified by Julivert et al. (1974) needs to be reexamined in the light of plate tectonics.

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