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Stratigraphic and structural framework of the Neoproterozoic Paracuellos Group, Iberian Chains, NE Spain

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Key words. – Stratigraphy, Crustal cross-section, Neoproterozoic, Iberian Chains, Spain.

Abstract. – The Neoproterozoic Paracuellos Group of the Iberian Chains constitutes the core of two disconnected faulted blocks, named the Paracuellos and Codos antiforms. Precise lithostratigraphic correlations between both areas are not possible due to the structural complexity and because marker beds do not persist laterally. This paper presents a crustal cross-section of the Neoproterozoic axial core (the Paracuellos antiform) based on surface geology, boreholes and seismic reflection profiles. Seismic reflection data reveal that the basement was directly involved by a major Hercynian structure, named here the Paracuellos fault, which splits longitudinally the Paracuellos axial core. In seismic profiles this fault occurs as a northeasterly-dipping reflector (60-70º steep), evidencing a bivergent geometry of the lateral crustal elements.

The sedimentary evolution of the Neoproterozoic Iberian platform ranges from transgressive, non-cyclic, offshore to hemipelagic, black and green shales (Sestrica Formation) to progradational trends recording shoaling during episodes of rapid sediment influx (Saviñán Formation), presumably in response to a low standing sea-level. The siliciclastic succession is punctuated in the inner platform by deposition of phosphatic limestones (Codos Bed), representing a major shoaling event and demarcating a sharp regional change of sedimentation separating two similar siliciclastic tendencies. A diagenetically induced bedded chert (Frasno Bed) occurs in the outer platform, and is interpreted as being the product of at least two silicification episodes. Both the Codos and Frasno Beds are overlain by the Aluenda Formation, which exhibits nearshore to offshore features. An important sedimentary discontinuity appears across the Neoproterozoic-Cambrian transition. The Cambrian(?) Bámbola Formation is paraconformable with the Paracuellos Group displaying a gradual transition in inner platform areas, whereas an erosive unconformity occurs in outer areas. The horizon of the Neoproterozoic-Cambrian boundary is not identified in the Iberian Chains, where neither Cadomian deformation nor discordances are recognisable.

Stratigraphie et cadre structural du Groupe néoprotérozoïque de Paracuellos, Chaînes ibériques, NE de l'Espagne

Mots clés. – Stratigraphie, Reconstitution structurale, Néoprotérozoïque, Chaînes ibériques, Espagne.

Résumé. – Le Groupe de Paracuellos (Néoprotérozoïque) des Chaînes ibériques constitue le cœur de deux blocs faillés distincts : les antiformes de Paracuellos et de Codos. La complexité des structures et l'absence de suivi des bancs repères entre les deux secteurs rendent toutes les corrélations lithostratigraphiques difficiles. Une coupe transversale synthétique à travers la zone axiale néoprotérozoïque des Chaînes ibériques (l'antiforme de Paracuellos) est présentée ici : elle s'appuie sur la géologie de surface, des sondages et des profils de réflexion sismique. Les données sismiques montrent, au cœur de cet antiforme, une structure hercynienne majeure (la faille de Paracuellos) qui divise longitudinalement sa zone axiale. Sur les profils sismiques, cette faille apparaît comme un réflecteur à pendage 60-70°NE mettant en évidence une géométrie divergente des éléments crustaux latéraux.

L'évolution sédimentaire de la plate-forme ibérique néoprotérozoïque montre le passage de shales noirs et verts, non-cycliques, correspondant à des milieux offshore à hemipélagiques (formation de Sestrica) et inscrits dans une tendance transgressive, à des séquences de progradation enregistrant une diminution de la profondeur d'eau durant des épisodes d'apports sédimentaires silicoclastiques plus grossiers (formation de Saviñán). Sur la plate-forme interne se déposent des calcaires phosphatés (couche de Codos) ; ces calcaires correspondent à une baisse majeure du plan d'eau et marquent un brusque changement régional de la sédimentation entre deux successions silicoclastiques similaires. Des cherts lités d'origine diagénétique (couche de Frasno) sont présents sur la plate-forme externe et sont interprétés comme le résultat d'au moins deux épisodes de silicification induits par des processus d'authigenèse et hydrothermaux. Les couches de Codos et de Frasno sont toutes deux surmontées par la formation d'Aluenda qui correspond à une sédimentation de domaine côtier à offshore. Il existe une importante discontinuité sédimentaire à la transition Néoprotérozoïque-Cambrien : la formation cambrienne (?) de Bámbola montre une transition graduelle avec le groupe de Paracuellos dans les zones de plate-forme interne tandis que le contact est net et érosif dans les zones externes. L'horizon correspondant à la limite Néoprotérozoïque-Cambrien n'est pas identifié dans les Chaînes ibériques où ni déformation ni discordances cadomiennes ne sont reconnaissables.

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INTRODUCTION

During the last two decades, the understanding of the Neoproterozoic geological framework and evolution of the Iberian Peninsula has greatly advanced [Quesada *et al.*, 1990; San José *et al.*, 1990; Quesada, 1991; Valladares, 1995; Fernández-Suárez *et al.*, 2000; Valladares *et al.*, 2000]. However, these efforts have not yet solved the stratigraphic and structural problems of some isolated Precambrian outcrops, such as those of the Iberian Chains (NE Spain). Recently, the construction of new motorways and railways through the axial core of the Iberian Chains [G.I.F., 1997; Álvaro, 1997a] was accompanied by a revision of geological maps, the recording of reflection seismic lines and the drilling of tens of boreholes in Proterozoic and Paleozoic outcrops. These works have provided a great amount of new stratigraphic and geophysical information, which has completed the knowledge of the classical outcrop areas leading to the development of new stratigraphic and structural concepts.

Due to the scarcity of Precambrian outcrops in the Iberian Chains, the interpretation of the Proterozoic history was heavily dependent on the application of geophysical techniques in combination with regional drilling programmes. Both methods have played key roles in the study of the axial core of the Iberian Chains, providing significant information and essential constraints on the structural interpretation. The purposes of this paper are (i) to present the first seismic data from the subsurface of the Paracuellos axial core of the Iberian Chains, and (ii) to provide a new interpretation of the stratigraphy and sedimentary evolution of the Neoproterozoic sediments of the Iberian platform, based on recently processed seismic data, extensive mapping and previously unpublished facies and paleontological evidence.

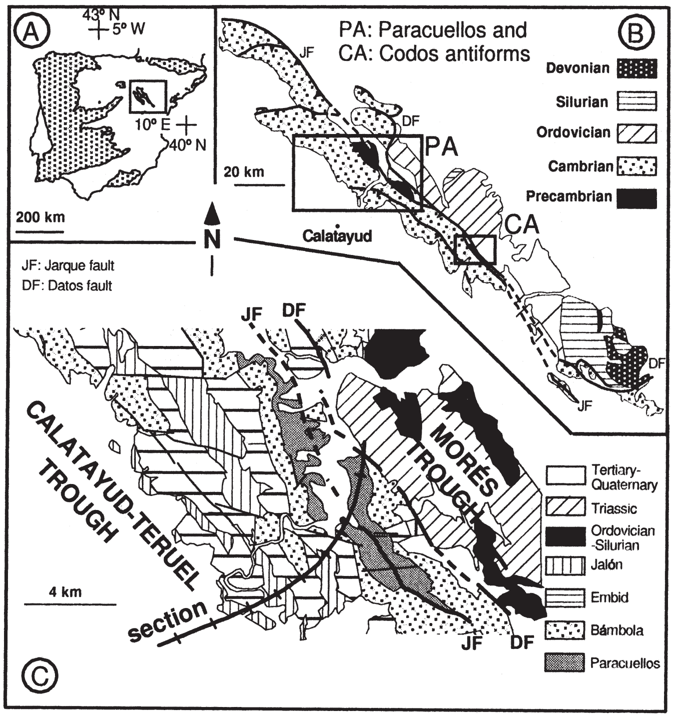

FIG. 1. – A. Pre-Hercynian outcrops of the Iberian Peninsula and setting of the Iberian Chains. B. – Geological map of the pre-Hercynian outcrops of the eastern Iberian chain, and location of the Paracuellos and Codos antiforms. C. Geological sketch of the Paracuellos antiform [after Tejero, 1986; Hernández *et al.*, 1981] and section of the railway summarized in figure 3.

FIG. 1. – A. – *Affleurements pré-hercyniens de la Péninsule ibérique et situation des Chaînes ibériques.* B. – *Carte géologique de la Chaîne ibérique orientale et emplacement des antiformes de Paracuellos et de Codos.* C. – *Schéma géologique de l'antiforme de Paracuellos [d'après Tejero, 1986; Hernández* et al.*, 1981] et position de la section de la voie de chemin de fer présentée en figure 3.*

GEOLOGICAL SETTING

Regional geology

The pre-Hercynian outcrops of the Iberian Chains constitute a relic of the deeply eroded Variscan orogen in NE Spain (figs. 1A-B). The Iberian Chains exhibit a NW-SE-trending pattern and are longitudinally divided (by the Tertiary Calatayud-Teruel trough) into the western and eastern Iberian chains. Traditionally, the pre-Hercynian outcrops have been further subdivided into three NW-SE-trending 'tectonostratigraphic' units, bounded by major faults and mainly characterized by differences on the style of deformation. From southwest to northeast, they are named Badules, Mesones and Herrera units [Gozalo and Liñán, 1988]. The westernmost Badules unit comprises Neoproterozoic to Lower Ordovician rocks; they show monoclinal to thin-skinned geometries, associated with folds and intersected by major nappe structures [Julivert, 1954; Álvaro *et al.*, 1992; Álvaro, 1997b]. The Mesones unit is bounded by the western Jarque and the eastern Datos faults. It is up to 12 km wide but, in some areas, can disappear due to the coincidence in surface of both faults [Álvaro, 1994]. The Mesones unit contains Neoproterozoic to Middle Cambrian rocks and is dominated by complex thrust systems and nappe structures [Vílchez, 1986; Pérez-Lorente, 1991; Navarro Vázquez, 1991]. Finally, to the NE of the Datos fault, the Cambrian-Carboniferous succession of the Herrera unit is deformed into a NE-directed fold and thrust system, in which many thrust faults are blind with tip lines within Ordovician to Devonian rocks [Tejero, 1986; Vílchez, 1986; Navarro Vázquez, 1991].

The pre-Hercynian basement of the Iberian Chains consists of a mosaic of crustal elements fragmented and structured during the Hercynian and Alpine orogenic cycles. These sediments were thrust northeastwards during the late Carboniferous (post-Westphalian A) [Villena and Pardo, 1983] onto a Precambrian continental margin, named Ebroan Land Area [Carls, 1983; Álvaro *et al.*, 2000], which occurs at present-day under the Tertiary Ebro valley. The Hercynian structures of the Iberian Chains are attributable to, at least, three major deformational phases [Capote and González Lodeiro, 1983; Tejero, 1986; Tejero and Capote, 1987; Vílchez, 1986], which were developed under a low to very low grade of metamorphism [Lendínez *et al.*, 1989; Álvaro and Vennin, 1998; Bauluz *et al.*, 1998]. A late-Hercynian deformational regime reflects an evolution from reverse strike-slip tectonics to radial extension [Tejero, 1986; Tejero and de Vicente, 1987] associated with Stephanian-Permian calc-alkaline dyke and sill emplacement [Lago *et al.*, 1992]. Finally, Alpine regional stress regimes affected pre-existing crustal discontinuities, reactivating both Hercynian structures and discordant contacts of Precambrian/Lower Paleozoic rocks with Triassic (Morés trough) and Tertiary (Calatayud-Teruel trough) rocks (fig. 1C). The western contacts of both troughs are discontinuous thrust faults [Julivert, 1954; Colomer and Santanach, 1988; Álvaro, 1994, 1997b; Álvaro *et al*., 1992].

Structural features of the Paracuellos antiform

The Paracuellos Group constitutes the core of two disconnected antiform structures : the northern Paracuellos and the southern Codos antiforms (fig. 1B). The axial plane of the Paracuellos antiform is subvertical and its flanks are up to 12 km long, whereas the Codos anticline shows a Neoproterozoic core up to 1 km long and 200 m wide.

A cross section through the axial core of the Paracuellos antiform is reported here, constructed from surface maps, seismic exploration and extensive drilling (fig. 2). The seismic line is drawn approximately perpendicular to thrust and fold axes and, hence, parallel to the direction of primary tectonic shortening. Reflection seismic data have been acquired along a 5 km profile. The data image the structure of the upper part of the crust to depths of approximately 0.7 km. The Paracuellos rocks probably do not contain significant lithological contrasts in an undeformed state to generate reflections; however, when sheared, lithological variations related to formation of mylonites may have developed then. These variations have included large enough contrasts in velocity and/or density to generate reflections. Details of the surface structure along the well-exposed studied cross-section are given by Capote and González Lodeiro [1983], Tejero [1986], Tejero and Capote [1987] and Álvaro [1997a].

Seismic reflection data reveal that the structural geometry of the Paracuellos core consists of one parautochthonous Precambrian/Lower Cambrian basement and, at least, four distinct thrust systems (fig. 2) : (i) the thrust sheet A composed of imbricated Precambrian and Bámbola sediments, (ii) the thrust sheet B also composed of imbricated Precambrian-Lower Cambrian sediments, (iii) the thrust sheet C made up by Lower Cambrian sediments and bounded by the Tertiary Calatayud-Teruel trough, and (iv) the easternmost thrust sheet C’ comprising Precambrian-Bámbola sediments and bounded at the east by the Datos fault and the Triassic Morés trough. The depth of the parautochthonous basement was approximated from the thickness of the thrusted stratigraphic section, the seismic reflection data, and one tunnel railway. The style of the thrust sheets B and C is thin-skinned : the thrust faults end downward in a main level of décollement and do not involve the cratonal basement on which the sedimentary prism was transported. By contrast, the basement was directly involved by the thrust sheet A, which is bounded at the west by a prominent tectonic structure named here the Paracuellos fault (PF). The PF is here reported as a major Hercynian structure splitting longitudinally the Paracuellos antiform. On the surface, the fault zone is recognized as a mélange zone, up to 200 m wide, which comprises a heterogeneous assemblage of imbricated Precambrian to lowermost Lower Cambrian rocks. In seismic profiles, the PF occurs as a thin, shallow to moderate, northeasterly-dipping reflector. The PF represents a thin zone of steeply-dipping basement faults. Subsurface and seismic studies document a steep (60-70^o), NE-dipping major thrust, which could become listric at depth in a zone of lower crustal reflectivity. The PF displays a bivergent geometry of the lateral crustal elements : to the west of this axis, southwest dipping reflections are associated (reflecting a dominant northeastward transport direction), whereas northeast dipping reflections occur to the east. To the east of the PF, the Paracuellos outcrops form an anticlinal with a widespread eastern flank bounded by the Datos fault. Finally, the seismic information shows the record of transcurrent shearing episodes as ‘flower structures’ produced by right– and left-lateral wrenching with at least 500 m of displacement, observed by surface mapping. The wrenching is associated with the widely developed, late-Hercynian phase of deformation.

STRATIGRAPHIC PATTERNS OF THE PARACUELLOS GROUP

The Paracuellos Group was defined from a lithostratigraphic point of view by Lotze [1929] and assigned to the Precambrian by the same author [Lotze, 1956]. Older Proterozoic sediments of the Iberian Chains are not exposed in outcrop but are known from several boreholes. Igneous rocks do not occur in the area, excepting rhyolitic dykes of Stephanian-Permian age [Lago *et al*., 1992]. A Neoproterozoic age is suggested for the Paracuellos Group, despite the scarcity of paleontological record composed of the ichnospecies *Torrowangea* aff. *rosei* WEBBY, 1970 [Liñán and Tejero, 1988], and *Cloudina*-like shelly fossils [Streng, 1996]. The uppermost part of the overlying Bámbola Formation contains the ichnogenera *Monomorphichnus*, *Phycodes*, *Arenicolites* and *Gordia*, belonging to the Cordubian stage (earliest Cambrian stage defined for the Iberian Peninsula) [Liñán *et al*., 1993]. The horizon of the Precambrian/Cambrian boundary has not been recognized in the Iberian Chains.

The stratigraphic character of the top of the Paracuellos Group has been a matter of controversy : (i) some authors envisaged this limit as an angular unconformity [Lotze, 1956; Aliaga, 1968; Schmidt-Thomé, 1973; Palacios and Vidal, 1992], whereas (ii) other authors proposed a conformable and gradual transition with the overlying Bámbola Formation [Bartsch, 1966; Teyssen, 1980, 1987], or (iii) as a cartographic disconformity developed after subaerial exposure and erosion [Liñán and Tejero, 1988].

The lithostratigraphic framework of the Paracuellos Group was first established by Liñán and Tejero [1988] in the Paracuellos antiform (fig. 3). This group was then divided into four formations, from bottom to top, the Sestrica, Saviñán, Frasno and Aluenda Formations. A bed (the smallest formal lithostratigraphic unit) is erected in this paper to characterize one distinct marker bed cropping out in the Codos area.

The Sestrica Formation

Several boreholes drilled in the western flank of the Paracuellos antiform encountered a new lithology not recognized in outcrop, which is here considered as the lower prolongation of the Sestrica Formation. The subsurface part of the latter is a monotonous unit, at least 100 m thick, composed of laminated black shales. The facies consists of dark grey to black, thinly laminated shales with common intercalations of either thin- to medium-bedded, very fine-

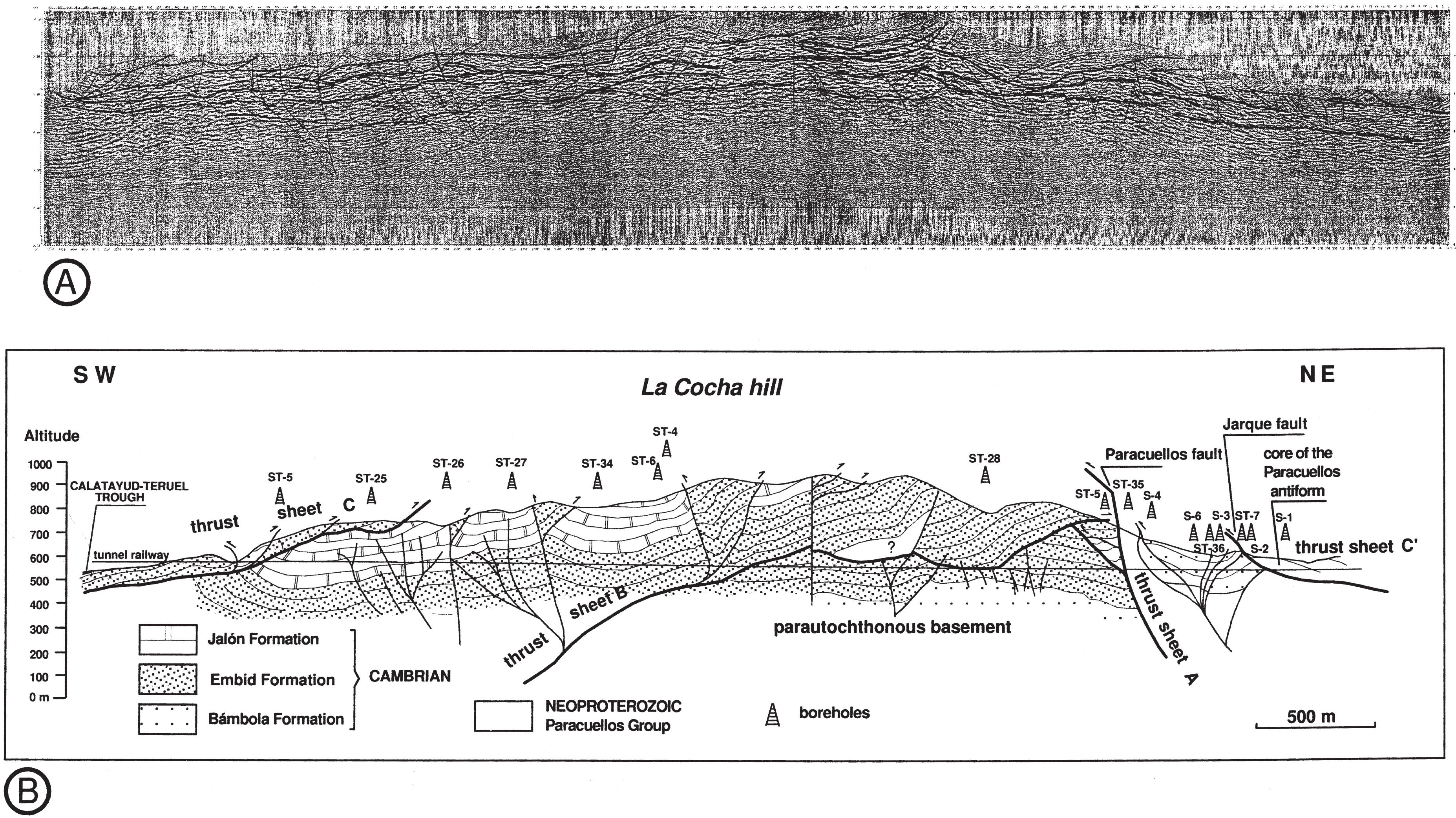

FIG. 2. – A. Explosive source reflection profile across the Paracuellos axial core (data processed by U.T.E. CALATAYUD). B. – Interpreted geological section based on seismic profiles, boreholes and surface mapping.

FIG. 2. – *A. – Profil de sismique réflexion à travers la zone axiale de Paracuellos (d'après les données U.T.E. CALATAYUD).* B. – *Section interprétative à partir des données des profils sismiques, des sondages et de la cartographie de surface.*

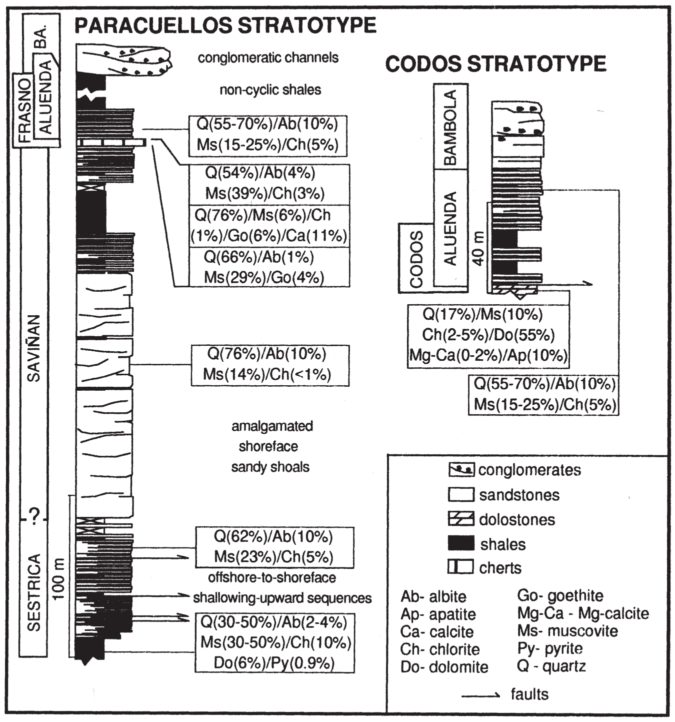

FIG. 3. – Sedimentary and petrographic features of the Paracuellos Group stratotypes. Mineralogical assemblages determined from X-ray diffraction data.

FIG. 3.– *Caractérisation sédimentaire et pétrographique des stratotypes du Groupe de Paracuellos ; composition minéralogique à partir des analyses par diffractométrie des rayons X.*

to medium-grained feldspathic greywackes, or laterally discontinuous beds of coarse-grained siltstone. The Sestrica black shales are fine-grained, dark-coloured sediments that show distinct lamination but contain very scarce amount or absence of organic matter. Dark colour is associated with the presence of finely dispersed iron sulfides (mainly pyrite) less than 1 %. Pyrite occurs as disseminated subhedral to anhedral grains (up to 30 μm in size), concordant to sedimentary bedding, and concentrated in the groundmass of greyish and blackish clayey laminae, reaching locally 5-10 % in volume (fig. 4A).

The upper part of the Sestrica Formation (up to 60 m thick), cropping out on the core of the Paracuellos antiform, consists of centimetric to decimetric alternances of dominant, grey to green shales and fine-grained sandstones. Sandstones are predominantly greywackes, which petrographically contain quartzofeldspathic grains set in a matrix rich in chlorite and fine-grained muscovite (sericite). Patches and veins of sparry dolomite are randomly distributed, generally in amounts of 0-10 % of the bulk rock. These alternances are grouped into 3-8 m thick, small-scale, coarsening-upward sequences. From bottom to top, they are structureless shales, coarse-grained siltstones and sandstones with parallel to low-angle laminations, and local hummocky structures and slumping features. The upper boundary of the Sestrica Formation is gradational, recognized by the increase in grain size and the sharp occurrence of cross-stratified sandstones.

The apparent absence of trace fossils, the preservation of fine parallel, even lamination and the abundance of pyrite in the clayey laminae of the lower Sestrica Formation suggest sedimentation in deep, quiet waters during a regional transgression. Laminae were preserved in low-energy bottom waters, due to likely low oxygen levels at the depositional surface, preventing bioturbation. By contrast, the sequences of the upper Sestrica Formation represent successive progradational trends, from offshore with shaly sedimentation to shoreface sedimentation episodically affected by storms.

According to Bauluz *et al.* [1998], the oldest Cambrian sediments of the Iberian Chains exhibit a very low-grade anchizone-anchizone/epizone boundary degree of metamorphism, which would correspond to the temperature attained by burial depth with a normal geothermal gradient. We have analysed the lowermost metapelites of the Sestrica Formation from drill holes using X-ray diffraction techniques. Their mineralogical assemblage comprises quartz, muscovite and chlorite; in addition, dolomite, albite and pyrite appear as accessory minerals (fig. 3). The Kübler index of illite crystallinity has modal values of 0.18^{o} 2 q displaying a very low-grade epizonal degree of metamorphism.

The Saviñán Formation

This formation consists of alternating grey to brownish, fine- to medium-grained sandstones and green shales, 200 to 300 m thick. The average overall sandstone content is more than 70 %. Sandstones are subfeldspathic greywackes, whose accessory minerals are zircon, sphene and staurolite. Clay minerals in the matrix and shaly intercalations are fine-grained muscovite (sericite) and chlorite.

The lower alternations are arranged into thickening- and coarsening-upward, small-scale sequences (0.8 to 2.6 m thick). From bottom to top, they display a vertical succession from shales to laminated and cross-stratified sandstone beds. The shale/sandstone transition includes subordinate massive and laminated argillite and siltite, displaying grading patterns (silty layers), composed of centimetric, upward-fining layers bearing very fine sand to silt-sized grains and erosive contacts. After the upward decrease of shaly intercalations, sandstones show tabular to lenticular features (0.2 to 0.8 m thick), with common erosive bases exhibiting locally tool marks and flute-casts. They consist of amalgamated planar and trough cross-bedded sandstones, intercalated with low-angle and parallel laminations, and wave-ripple laminations present on bed tops. The small-scale sequences represent shallowing-upward nearshore facies, in which fine-grained outer-platform deposits, recording episodic deposition from suspension by weak distal tempestites, are overlain by amalgamated shoal complexes on a prograding platform.

The Frasno Bed

The bed (up to 4 m thick) consists of an alternation of grey to black, bedded chert and grey to green shales, exhibiting a reduced geographical area of distribution to the east of the Jarque fault. The bedding is on the centimetric scale showing common parallel microlamination. Alternating silicified and shaly laminae, 1-2 cm thick, are abundant at the bottom of the bed, which change gradually to the underlying Saviñán Formation, whereas the top of the Frasno Bed is sharp. The chert is traceable along strike for several hundred metres, and is sharply underlain by Stephanian- Permian rhyolitic dykes. The mineralogy of these cherts,

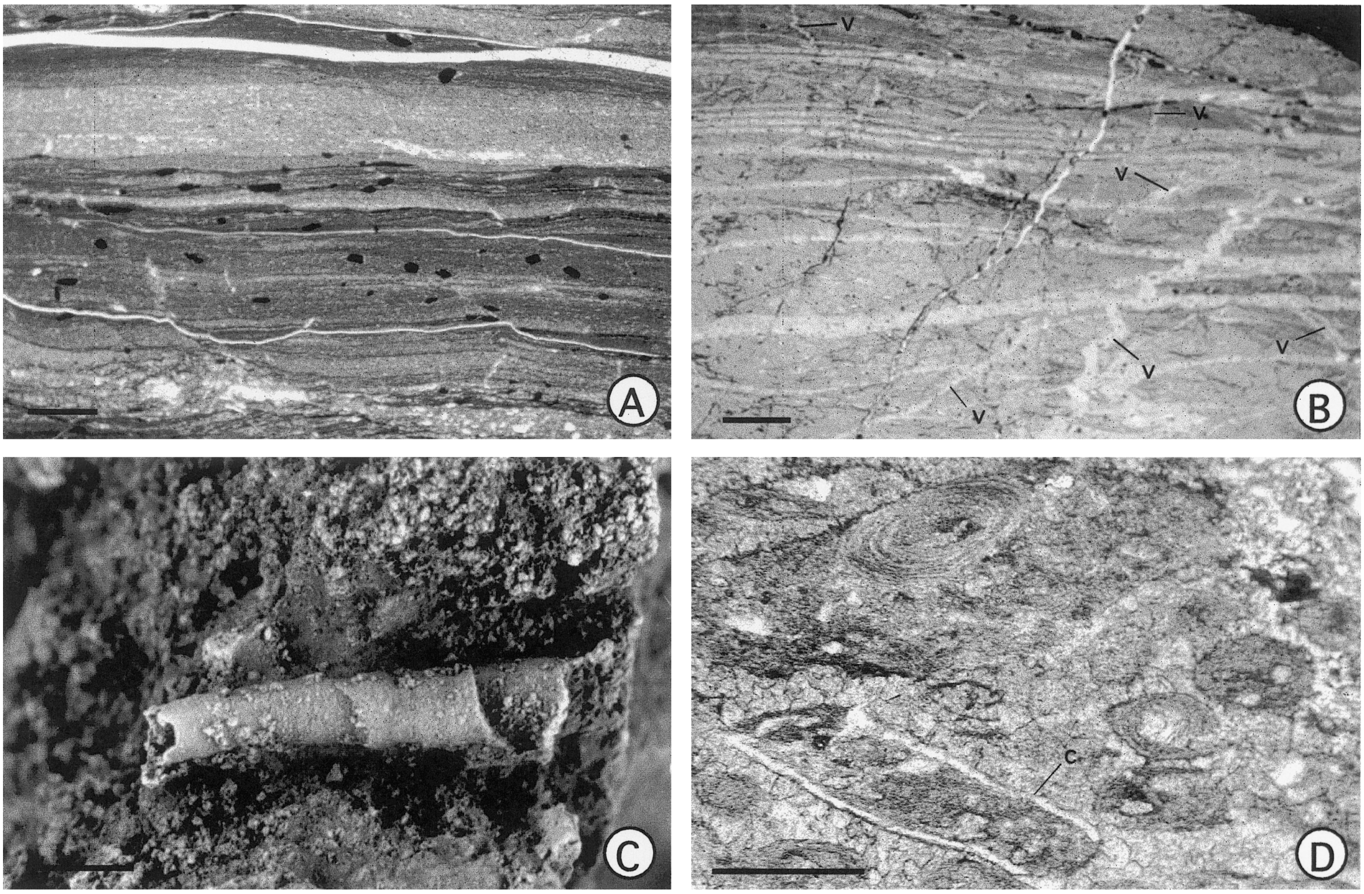

FIG. 4. – A. – Photomicrograph (plane light) showing rhythmites of silt-grade quartz and clay rich in subhedral to anhedral pyrite grains; lower part of the Sestrica Formation. B. – Photomicrograph (plane light) of bedded chert composed of layered microquartz exhibiting alternating, silicified or not, shaly laminae cut by subvertical veins of quartz (v); Frasno Bed (plane light). C. – Phosphate shell of a *Cloudina*-like microfossil with a suspected cone-in-cone structure (scale = 1.4 mm; courtesy of M. Streng). D. – Photomicrograph (plane light) showing ooids with strong concentric fabrics and tube-like microfossils (c) surrounded by dolomitized microsparite; Codos Bed. A, B and D scales : 0.8 mm.

FIG. 4. – A. – *Alternances de silts quartzeux et d'argiles riches en grains de pyrite subautomorphe à xénomorphe : partie inférieure de la formation Sestrica*. B. – *Chert lité montrant une alternance de lamines de microquartz et de lamines argileuses, silicifiées ou non, recoupées par des veines subverticales de quartz* (v) *: Couche de Frasno*. C. – *Coquille phosphatée, probablement à structure en cônes emboîtés, d'un microfossile de type Cloudina (échelle : 1,4 mm; courtoisie de M. Streng)*. D. – *Ooïds à structure concentrique marquée et microfossiles tubulaires* (c) *dans une microsparite dolomitisée; Couche de Codos*. A, B *et* D : *lames minces en lumière analysée, échelle : 0,8 mm*.

determined by X-ray diffraction and thin-section observations, is quartz, muscovite, albite and chlorite, in decreasing order of abundance. At least two generations of silica precipitation are recognisable in the Frasno cherts (fig. 4B).

(i) The first generation, better developed and volumetrically dominant, consists of a mosaic of quartz crystals showing highly irregular crystal boundaries. The size of individual crystals is mostly 5-20 μm. The crystals show undulatory up to incipient sweeping extinction in polarized light and coexist with finer crystalline varieties. This petrographic chert displays a bedded structure with layers ranging from 1 to 20 cm separated by mm-scale films of dark clay. A superimposed laminated structure is much thinner than the bedded one, and may be recognized as rhythmically alternating hairline crystals, parallel to bedding ; under the microscope, the alternation of microcrystalline quartz and clay-rich laminae is characteristic. Alternating, silicified or not, shaly laminae have little, if any, evidence of intergranular pressure solution or compactional grain breakage.

(ii) The second generation is represented by subvertical veins of quartz crystals (0.1 mm or more in size, displaying undulatory extinction), which can reach 40 % of the whole rock. The network of veins, up to 5 mm wide, cut the previous bedded and laminated chert. Several stages of vein formation can be identified based on their cross-cutting relationships.

Silica diagenesis was a multi-stage process as indicated by the variety of textures and crystal sizes. Possible silica precursor phases were wholly transformed to stable quartz erasing the primary structures excepting parallel microlamination. The occurrence of the bedded chert as centimetric to decimetric laminae with a sharp upper contact, the lack of nodular chert and the absence of ghosts of carbonate grains evidence a distinct facies control on diagenetic silicification processes. No evidence was found for an intraformational (biogenic ?) silica source, but there is a direct relationship between the thicker bedded chert and the presence of altered and fragmented rhyolitic dykes of Stephanian-Permian age in the Paracuellos stratotype. Therefore, silica was seemingly supplied through weathering or alteration of the associated rhyolitic dykes. Cherts probably originated through progressive diagenesis of abiogenically derived silica, combined with silica authigenesis and hydrothermal influences : veining, common in hydrothermal sediments, would be related to fluid channels that discharged into the previously silicified sediments [Renant and Owen, 1988; Zhou *et al.*, 1994; Krainer and Spötl, 1998].

The Codos Bed

This new unit is found in the core of the Codos antiform underlying the outcropping Aluenda Formation (fig. 3). The bed consists of a dark-grey phosphatic dolostone, up to 4 m thick. Sedimentary structures include dominant low-angle cross-beds, and rarer ripple cross-laminae, low-angle and parallel lamination.

The dolomitized ooidal packstones occur as bed and lenticular sets, less than 60 cm thick. They consist of moderate-sorted, fine to medium sand-size ooids and small amounts of skeletal debris (such as *Cloudina*-like microfossils; fig. 4C), commonly flattened and distorted by compaction. The nuclei of ooids are generally composed of sparite, quartz grains and fragmented bioclasts; cortices (up to 30 μm thick) have well-developed concentric fabrics (fig. 4D). Other minor components include a great variety of intraformational clasts, such as coated grains with one lamella, composite ooids and ooidal aggregates. The terrigenous component mainly consists of sand-sized, subrounded, monocrystalline quartz, mica flakes, and rock fragments of stylolitized polycrystalline quartz, phyllosilicate-rich schist, laminated shales and phosphate grains. Both phosphate grains and bioclasts, in the present form of fluorapatite, reach 10 % of the whole rock. Dolomitization of allochems and matrix (microsparite) is nearly complete (only 0-2 % Mg-calcite).

The abundance and diversity of grain types contrast with the low diversity of bioclasts. The diversity of allochems and the sorted character of ooids with concentric fabrics indicate relatively high-energy conditions. This bed was deposited in agitated, subtidal environments such as ooidal-bioclastic shoals : the most concentrically laminated ooids reflect the most agitated conditions.

The Aluenda Formation

The formation consists of alternating grey to white, feldspathic greywackes and brownish to green shales (90-200 m thick). The formation shows an upward increasing frequency of sandstone intercalations in the southern Codos area, and the opposite pattern in the northern Paracuellos antiform, where the sandstones disappear at the uppermost part. It contains the trace fossil *Torrowangea* aff. *rosei* WEBBY, 1970.

The petrographic patterns, sedimentary structures and small-scale sequences are very similar to those of the Saviñán Formation. The lower boundary of the Aluenda Formation is marked by the occurrence of the Codos and Frasno Beds. The southern Codos area represents inner parts of the Iberian platform, where a broad shallowing-upward trend is recognized across the Aluenda/Bámbola transition. In contrast, the offshore to hemipelagic shales of the uppermost Aluenda Formation in the northern (distal) Paracuellos antiform were diachronously covered by the progradation of the Bámbola alluvial fan ? and deltaic complexes [Gabaldón, 1990], whose lower boundary constitutes a channelled erosive contact.

NEOPROTEROZOIC EVOLUTION OF THE IBERIAN PLATFORM

The homogeneous lithologic features of the lowermost Sestrica Formation and the paucity of sandstones can be assigned to a low-average energy level. Its evolution ranges from transgressive, non-cyclic, offshore to hemipelagic, black shales (lacking trace fossils) to the progradational trends of the Saviñán Formation. This transition gradually records the influence of wave and storm actions, and the input of coarser grained siliciclastic material. The Saviñán Formation reflects an increase in clastic supply and the establishment of a prograding platform, presumably in response to a low standing sea-level. Coarse-grained sediment influx and higher wave and bottom current activity favoured the development of nearshore sandy shoals during the deposition of the Saviñán Formation. About half of the aggregate thickness of the Saviñán Formation is grouped into coarsening-upward sequences, 0.8-2.6 m thick. Shoaling during times of rapid sediment influx offers a simple and repeatable mechanism for creating these sequences. The vertical sequences begin with outer platform hemipelagites, with minor storm and slump influences, and grade upwards with an increasing sandstone content into trough cross-stratified beds.

The siliciclastic succession is punctuated by the deposition of ooidal-bioclastic carbonates, which represents a major shoaling event. The Codos Bed clearly reflects a sharp regional change of sedimentation separating two siliciclastic tendencies, lithologically comparable. This interval marks a shoaling interval in inner areas of the Iberian platform, recording high patterns of carbonate productivity. The Frasno Bed is a diagenetically induced, stratigraphic unit. The petrographic observations on the Frasno bedded cherts, in which no original carbonate relics are observed, are interpreted as being the product of at least two silicification episodes. No direct evidence for intraformational silica sources is present, which is related to the presence of altered rhyolitic dykes close to the thickest bedded chert. Finally, a return to deeper, shoreface to offshore conditions is recorded across the Aluenda Formation.

A sharp unconformity exists at the boundary of the Aluenda/Bámbola Formations in distal areas (Paracuellos antiform), whereas this transition is gradual in proximal areas (the southern Codos area). Therefore, this sedimentary discontinuity appears as a paraconformity at the scale of the entire Iberian Chains, which could be responsible for the erosive disappearance of a part of the Aluenda Formation in the northern outcrops. As Teyssen [1987] pointed out, neither Cadomian deformation nor weak folding nor cleavage have been recognized in the Iberian Chains.

CONCLUSIONS

The Paracuellos Group comprises the oldest sedimentary succession known in the Iberian Chains. It crops out in the core of two disconnected faulted blocks : the Paracuellos and Codos antiforms. Precise lithostratigraphic correlations between both areas are not possible due to the structural complexity and because marker beds (such as chert and carbonate beds) do not persist laterally.

A seismic cross-section across the Paracuellos axial core evidences a much more complex structural architecture than previously known. Its structural geometry is that of a parautochthonous Precambrian-Lower Cambrian basement and, at least, four distinct thrust systems arranged in imbricated fans. The western boundary of the Paracuellos antiform (named here the Paracuellos fault) is a NE-dipping, major thrust, which constitutes an axis of bivergent, lateral crustal elements. The seismic section shows a bivergent structural geometry for the reflecting elements with gently west-dipping reflectors in the west and moderate to steep east-dipping reflectors in the east. As a result, after analysing the Paracuellos antiform with seismic data and boreholes, thrusting is the predominant structural style of the axial core of the Iberian Chains, although these outcrops have been classically described in surface as 'antiforms'. Another further consequence is the structural and 'tectonostratigraphic' importance of the Jarque fault, a secondary SW-dipping thrust related to the major NE-dipping, Paracuellos fault.

The sedimentary evolution of the Neoproterozoic Iberian platform ranges from offshore to hemipelagic, black and green shales (epizonal metapelites of the Sestrica Formation) to progradational shoaling trends recorded during episodes of rapid sediment influx, presumably in response to a low standing sea-level. The siliciclastic succession is punctuated in the inner platform by deposition of phosphatic limestones (Codos Bed), rich in ooids and *Cloudina*-like shells, representing a major shoaling event and demarcating a sharp regional change of sedimentation separating two similar siliciclastic tendencies. This sharp increase in carbonate production favoured the development of carbonate shoal complexes forming a discontinuous high-energy belt in proximal areas. Diagenetically induced bedded cherts (Frasno Bed) occur in the outer platform, and are interpreted as being the product of at least two silicification episodes. Both the Codos and Frasno Beds are overlain by the Aluenda Formation, which exhibits nearshore to offshore features.

The upper limit of the Paracuellos Group is commonly tectonically disturbed, but some outcrops permit to recognize the original boundary with the Bámbola Formation as a conformable passage. The Cambrian(?) Bámbola Formation is paraconformable with the Aluenda Formation displaying a gradual transition in inner areas of the Iberian platform (Codos antiform), and a sharp and erosive contact in outer platform areas (Paracuellos antiform) marked by conglomeratic channel fills.

The correlation of the Precambrian-Cambrian transition in southwestern Europe is still a complex matter of discussion due to the lack of a confident biostratigraphic chart for its siliciclastic platforms. Significant ichnofossils are commonly absent in the lowermost Lower Cambrian coarse-grained, siliciclastic successions as their first appearances are constrained by paleogeographic flooding trends and not to evolutionary events. However, the terminal Neoproterozoic sediments of southwestern Europe exhibit relatively common, shelf to turbidite patterns : (i) the Narcea or Mora Formations of the Cantabrian and West Asturian-Leonese Zones contain a main turbidite succession [Pérez Estaún, 1973] unconformably overlain by Cambrian rocks, and (ii) a flyschoid or turbidite complex in the Ossa-Morena Zone displays deep-sea fan facies, and slope and shelf facies [Quesada *et al.*, 1990]. In contrast, the Upper Alcudian-Pusian of the Central-Iberian Zone contains a mixed (carbonate-siliciclastic) succession displaying a wide spectrum of sedimentary environments; its uppermost episode, which concludes with the progradation of Lower Cambrian shallow marine facies, is separated from the preceding ones by an important paraconformity or slight angular unconformity [San José *et al.*, 1990].

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