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Depositional style and tectonostratigraphic evolution of El Bierzo Tertiary sub-basin (Pyrenean orogen, NW Spain)

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ABSTRACT

El Bierzo Tertiary sub-basin (Oligocene–Miocene, NW Spain) is a small remnant of the western Duero Basin, a nonmarine broken foreland basin developed in front of the Cantabrian Mountains (Pyrenean orogen). The alluvial infill of El Bierzo Tertiary sub-basin consists of a coarsening-upward succession from fluvial (Toral Formation) to alluvial-fan deposits (Las Médulas Formation) and reflects the uplift of the Cantabrian Mountains, in the north, and then of the related Galaico-Leoneses Mountains, in the south. These alluvial deposits show signs of having been laid down mainly by catastrophic flows (flood-dominated systems) and consist of three main depositional elements, namely, flood-plain fines, and lobe and channel conglomerates and sandstones. The vertical stacking patterns of these deposits and their relationships to the Alpine structures permit to unravel the tectonosedimentary evolution of the basin. The alluvial-plain element is the main constituent of a wide unconfined alluvial plain (Toral Formation) during the early stages of basin evolution, whereas the channel and lobe elements form a set of relatively small, laterally confined alluvial fans (Las Médulas Formation) fed first from the north and then from the south. Las Médulas deposits form two superposed units, the lower unit, cut by the Alpine thrusts, shows a progradational character, and the upper unit, which postdates most of the thrusts but not the youngest ones, displays a composite retrogradational trend. This organisation reflects the interplay between thrust emplacement and alluvial-fan sedimentation and suggests that maximum progradation took place during the climax of Alpine deformation.

KEYWORDS **Cenozoic. Pyrenean orogen. El Bierzo. Alluvial fans. Foreland basin.**

INTRODUCTION

Nonmarine foreland basins and the late nonmarine stages of foreland basins are mainly filled by alluvial fans and associated fluvial and lacustrine systems (see examples in Allen and Homewood, 1988). The architecture and the vertical trends of the alluvial infill reflect a complex interplay between tectonics, denudation and climatic forcing (Blair, 1988; Heller, 1989; Massari *et al.*, 2009; amongst others) and may become extremely complex due to basin partitioning (*e.g.* DeCelles, 1986). In this work, we show a case study of the architecture of the alluvial infill in the nonmarine El Bierzo Tertiary sub-basin (BTS), a remnant of the Duero broken foreland basin (Martín-González and Heredia, 2011a, b; Martín-González *et al.*, 2014). The BTS is located in the NW Iberian Peninsula, between the western termination of the Alpine Pyrenean orogen in the Cantabrian Mountains and the related

Galaico-Leoneses Mountains (Fig. 1), where thrust timing from both basin margins resulted in a complex sedimentary evolution.

The alluvial deposits of the BTS were mainly sourced from Cambrian–Silurian and Stephanian rocks of the Variscan Iberian Massif, which also yielded detrital gold. Gold particles became concentrated as placers in the proximal alluvial facies (maximum gold grade of 3gr/t; Pérez García *et al*., 2000), which were intensively mined by the Romans between I BC and II AC (see Pérez García *et al*., 2000). Mining through gravity-driven hydraulic fracturing led to the collapse of hill flanks and resulted in badlands called médulas, whose rock towers and vertical cliffs provide large, good quality outcrops. Médulas are present in both the northern (médulas of La Leitosa) and southern (médulas of Santalla, Orellán, Carucedo, Yeres and Paradela) margins of the basin. Those of Orellán, Carucedo and Yeres form a large and well-preserved mining site collectively referred to as Las Médulas and declared World Heritage Site and Archaeological Site by UNESCO (2011) and National Monument by the Spanish Government.

As a result of its economic and archaeological relevance, the BTS has been extensively studied; however, contradictory conclusions have been reached about both the depositional style and the tectonic setting of this basin. The deposits have been interpreted as alluvial-fan sediments (Herail, 1981; Manjón *et al*., 1986; Pérez-García *et al*., 2000; Martín-González and Heredia, 2011a) or as terrace deposits recording the entrenchment of a large fluvial system (Hacar *et al*., 1999; Pagés *et al*., 2001; Matias *et al*., 2008; Gutiérrez-Marco, 2011). Moreover, different tectonic settings have been invoked, from compressive (Vergnolle, 1990; Santanach 1994; Heredia *et al*., 2004; Santanach *et al*., 2005; Martín-González, 2009), or transpressive (Olmo, 1985; Barrera *et al*. 1989; Yepes and Vidal Romaní, 2003; Vegas *et al*., 2004), to extensional (Sluiter y Pannekoek, 1964; Herail, 1981; González Lodeiro *et al*., 1982; Matías *et al*., 2008).

This paper aims at i) reconstructing the succession of the BTS, mainly based on the southern-basin-margin outcrops at Las Médulas and Santalla Roman mines; ii) reviewing the sedimentary evolution of the basin; iii) deciphering the relationship between the sedimentation and the Alpine tectonics to help unravel the last stages of Alpine evolution in this sector of the NW of the Iberian Peninsula.

To reach these objectives a classical fieldwork methodology was followed, involving mapping at the 1:25.000 scale, discriminating Alpine from Variscan tectonics, and detailed logging of stratigraphic sections. During logging, special attention was paid to define the facies of the deposits in terms of texture, sedimentary structures and bed geometry. The combination of mapping and logging allowed for establishing the geometry, spatial distribution and facies architecture of the stratigraphic units as well as studying their relationships to the Alpine structures. Outcrop photographs, included those linked to Google Earth, much helped in defining the medium-scale geometry and distribution of sedimentary bodies.

GEOLOGICAL SETTING

The Alpine Pyrenean orogen formed at the collisional boundary between the Iberian and Eurasian plates during the Cenozoic. This linear E–W-trending orogen stretches over 800km from Provence (France) to the western Iberian continental margin off the Galician coast (Fig. 1A). The Pyrenean orogen comprises two main mountain ranges, the Pyrenees in the east, forming the isthmus between France and Spain, and the Cantabrian Mountains in the west, running parallel to the Spanish coast of the Bay of Biscay (Pulgar *et al*., 1996; Gallastegui *et al*., 2002; Barnolas and Pujalte, 2004). In their western end, the Cantabrian Mountains are bound to the south by a related Alpine range, the Galaico-Leoneses Mountains (Martín-González and Heredia, 2008, 2011a, b), with the BTS lying in between (Fig. 1B).

The BTS is one of the remnants of the western part of the Duero Basin, a nonmarine foreland basin that lies to the south of the Cantabrian Mountains (Fig. 1B; Santanach, 1994; Alonso *et al*., 1996; Cámara, 1997; Gallastegui *et al*., 2002) that began to be filled in this area from the late early Oligocene (Freudenthal *et al*., 2010). During the Miocene, the uplift of the Galaico-Leoneses Mountains, south of the Cantabrian Mountains (Fig. 1A), compartmentalised the western part of the Duero Basin (broken foreland basin stage of Martín-González and Heredia 2011a; Martín-González *et al*., 2014) into smaller basins, the main of which are those of El Bierzo, O Barco, Sarria, Monforte de Lemos and Vilalba (Fig. 1B). The BTS is the largest and easternmost of them and maintains some degree of continuity with the remainder of the Duero Basin.

The BTS lies on a Variscan Palaeozoic substratum (Cambrian to Carboniferous), which belongs to the West-Asturian-Leonese Zone of the Iberian Massif (Fig. 1B), where the post-tectonic Carboniferous (Stephanian) sedimentary rocks rest unconformably on the Cambrian–Devonian ones (metasedimentary basement). All of these rocks were intruded by Permian postorogenic granitoids. The main Variscan structures are E–W trending, N-verging folds and thrusts, the latter of which were reactivated during the Pyrenean N–S compression. The BTS is strongly compartmentalised, mainly in its northern margin,

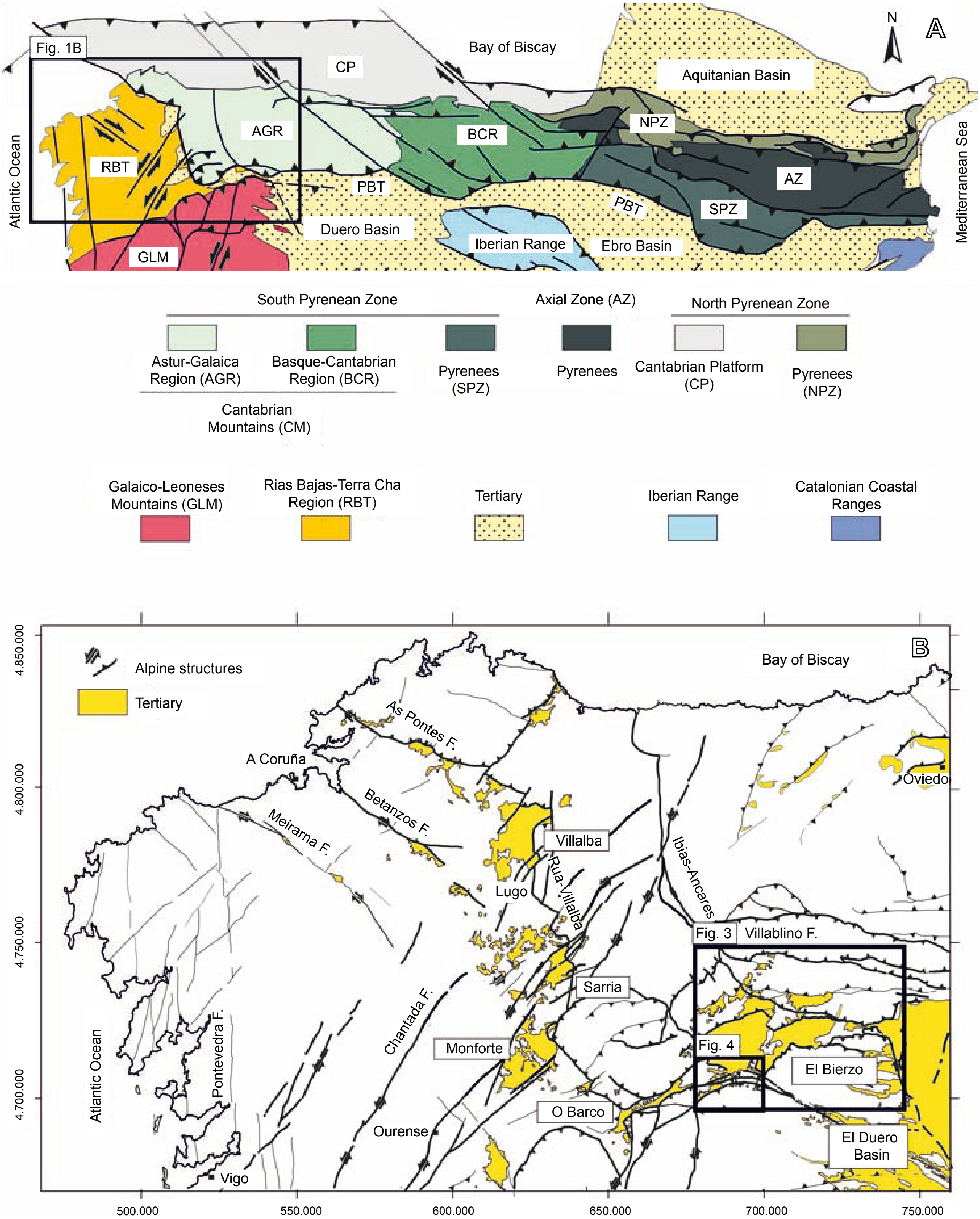


FIGURE 1. A) Schematic map showing the lateral extent of the Pyrenean orogen in the Iberian Peninsula and its related Tertiary basins (based on Martín-González and Heredia, 2011b). B) The broken foreland basin of the western Duero Basin, showing the location of El Bierzo and other minor basins and the main tectonic units discussed in the text (adapted from Martín-González and Heredia, 2011a).

and constitutes a pop-down structure located between the south-directed thrust of the Cantabrian Mountains in the north, and the north-directed thrusts (Fig. 1B) of the Galaico-Leoneses Mountains in the south (Martín-González and Heredia, 2008, 2011a, b). The north-directed thrusts are laterally constrained by WSW–ENE tear faults and both structures cut the Cantabrian Mountains front (Fig. 1B). The Alpine reliefs related of these structures, made of Palaeozoic rocks, provided the clastics that infilled the BTS.

Stratigraphic framework and structural imprints of the BTS

The alluvial synorogenic infill of the BTS spans from late early Oligocene (Freudenthal *et al.*, 2010) to late Miocene (Martín-González *et al.*, 2011, 2012), although the uppermost strata could be younger. It consists of a coarsening-upward siliciclastic succession several hundreds of metres in thickness, mainly made of pinkish to reddish siliciclastics. This succession was subdivided by Herail (1984) in three main formations, which are, from base to top, the Toral, Santalla and Las Médulas formations. A fourth unit, the Orellán Formation (Fm.), comprises the very coarse, disorganized deposits that form the proximal equivalents of both the Santalla and Las Médulas formations (Fig. 2).

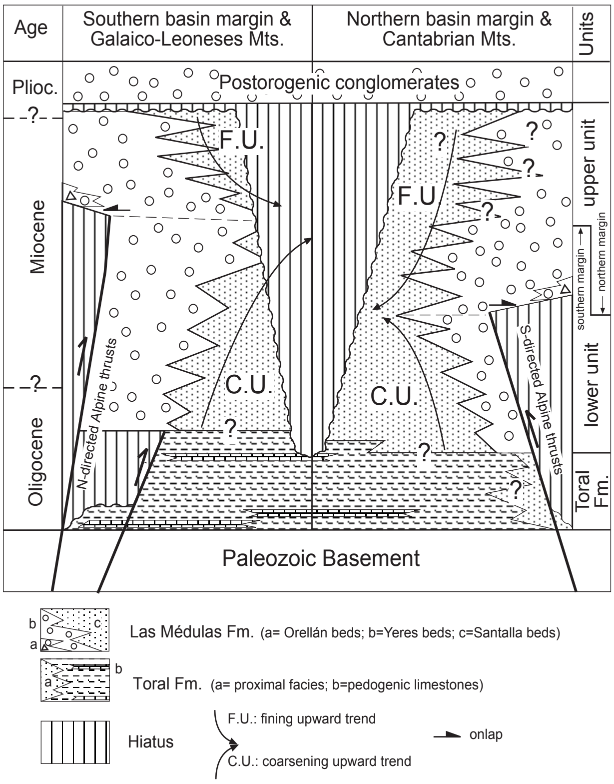


FIGURE 2. Schematic chronostratigraphic chart displaying the stratigraphic units distinguished in El Bierzo sub-basin in this work and their relationships with the timing of thrust emplacement.

The Tertiary succession of the BTS culminates with an uppermost unit, named "plateau conglomerates" by this author, which forms very discontinuous outcrops (Fig. 3) and records the post-orogenic sedimentation, before the present-day fluvial drainage system of the Sil River was established.

The Toral Formation is a dominantly pinkish-coloured succession of mudstone and sandstone alternations with thin and discontinuous conglomerate beds and with whitish pedogenic carbonate units in the lower part. The Santalla Formation is mainly greyish ochre and consists of conglomerates, sandstones and mudstones, with the conglomerates ranging from dominant to subordinate. Las Médulas Formation is made of orange to reddish conglomerate packages with subordinate sandstone and mudstone units.

The laterally discontinuous character of these alluvial deposits and their sharp lateral facies changes make the recognition of the Herail's (1984) units, especially of the Santalla and Las Médulas formations, difficult and controversial in many places. As a result, later authors have modified the Herail´s framework to a variable extent. Recently, Martín-González and Heredia (2011a) regarded the Santalla and Las Médulas formations as being partly laterally equivalent units, representing the mid–distal (Santalla) and proximal (Las Médulas) deposits of a presumed progradational alluvial-fan complex. Finally, Heredia *et al.* (2012) renamed them as the Santalla facies (Santalla Formation of Herail, 1981) and the Yeres facies (Las Médulas Formation of Herail, 1981) of their Las Médulas Formation (Fig. 2). In this work we will follow this nomenclature, although renaming them as the Yeres and Santalla beds, respectively, and including the Orellán beds (Orellán Formation of Herail, 1984) to refer to the most proximal deposits (Fig. 2).

The Toral Formation is evenly distributed in the central part of the basin, but only locally preserved in the basin margins, due to its removal from the uplifted fault blocks. On the contrary, Las Médulas Formation is only present in the northern and southern margins of the basin, where it overlies the Toral Formation or the Variscan substratum (Figs. 2, 3 and 4) whereas its distal deposits in the central part of the BTS are absent due to their removal during the Quaternary incision of the River Sil. The Yeres beds of Las Médulas Formation displays the maximum gold grade and focused the Roman mining works (Fig. 2 and 4).

The Alpine deformation did not affect severely the succession, which only dips gently in the vicinity of the Alpine reverse faults, lying horizontal elsewhere. The

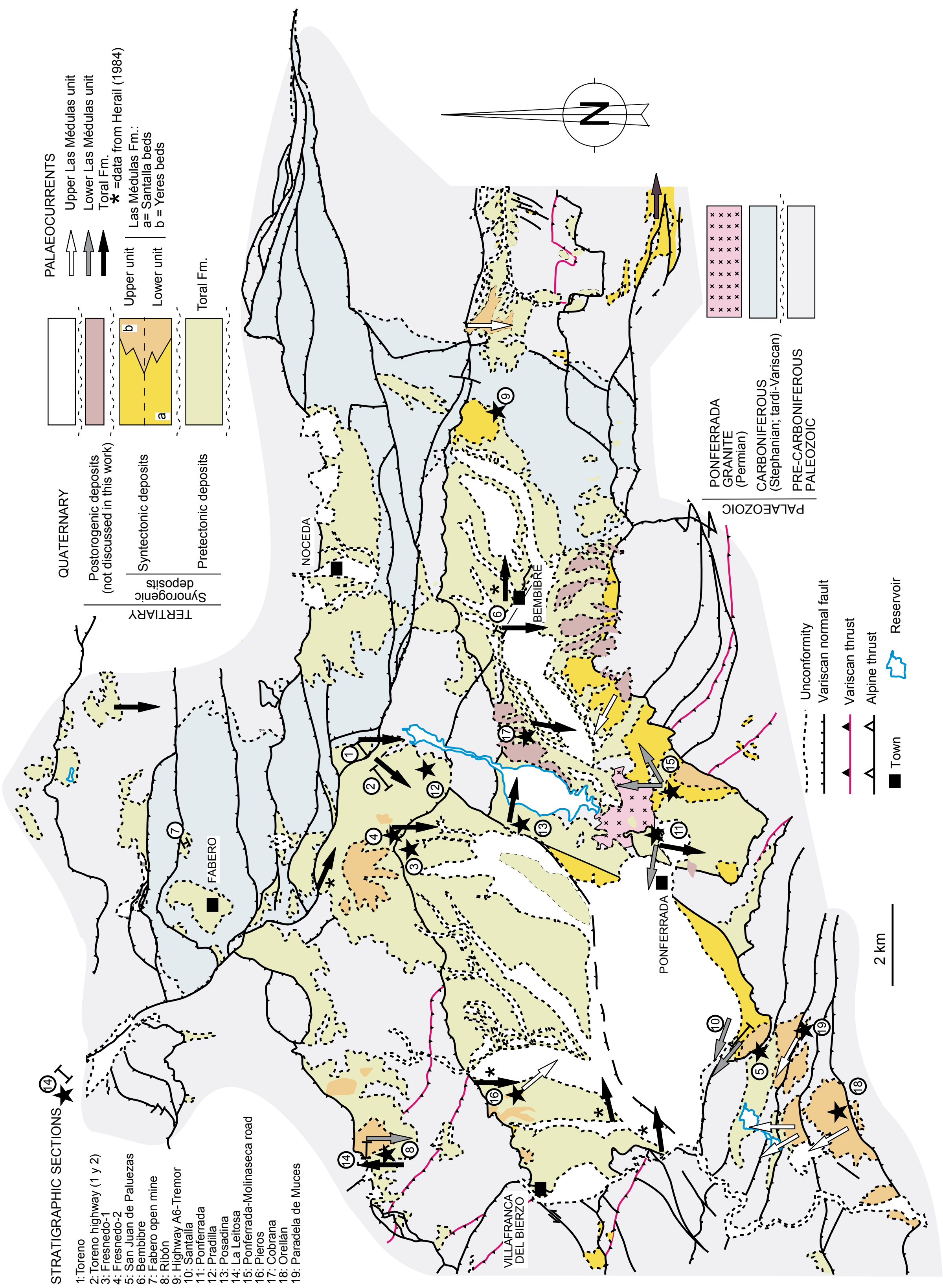


FIGURE 3. Simplified geological map of El Bierzo Sub-basin, showing the palaeocurrent distribution and the localities and sections discussed in the text.

most conspicuous effect of these faults is to displace the succession vertically. This can be seen across the several fault blocks of the southern margin area where the base of Las Médulas Formation lies 500m higher in the southernmost block with respect to the northernmost one (Figs. 4 and 5). Fault restoration in the southern margin permitted to reconstruct the original geometry of the deposits of Las Médulas Formation.

In Las Médulas-Santalla area, these deposits form three northwards-prograding, laterally coalescent sedimentary bodies (Fig. 4). On the basis of their shape, and facies and palaeocurrent distribution they are interpreted as alluvial fans (see also Heredia *et al.*, 2012). The largest fan (Yeres-Carrucedo fan) comprises the deposits exposed in the médulas of Carucedo, Orellán and Yeres, and buries a paleorelief developed on Ordovician limestones. The second-largest fan (Paradela-Santalla fan) crops out in the Paradela and Santalla médulas, and its feeder canyon is likely represented by an elongate outcrop of large-boulder breccias that cut deeply into the underlying Devonian limestones (Fig. 6D). Finally, the smallest fan crops out to the S of La Chana village. Overall, these three fans seem to have formed a confined fan system between the two palaeoreliefs that form the western and eastern margins of the Yeres-Carrucedo and Paradela-Santalla fans, respectively.

THE STRATIGRAPHY OF THE BTS: A SEQUENTIAL AND TECTONOSTRATIGRAPHIC APPROACH

In this work, we will follow an independent approach based on the vertical stacking patterns of the deposits and on their cross-cutting relationships with the Alpine structures. Using these criteria, mapping and logging data from the Santalla and Orellán sections (southern basin margin) and from La Leitosa section (northern basin margin), completed with additional data from other outcrops (Figs. 3, 4 and 6), permit to distinguish three superposed units below the postorogenic deposits ("plateau conglomerates" of Herail, 1984), which will not be dealt with in this work. The lower unit equals the Toral Formation whereas the middle and upper units form the lower and upper parts of Las Médulas Formation, and will be termed lower Las Médulas and upper Las Médulas units, respectively (Figs. 2 and 6A–D). As it can be seen in Figures 2 and 6C and D, the lower and upper Las Médulas units have similar lithological features, and both include the proximal (Yeres) and distal (Santalla) beds. They only differ in their different stacking patterns and relations to the structures. Also, as it will be detailed below, the upper Las Médulas unit comprises the very proximal deposits of the Orellán Formation of Herail (1981), here called the Orellán beds (Figs. 2 and 6E).

The Toral Formation

The Toral Formation is a dominantly fine-grained succession (Fig. 6A) that unconformably overlies the Variscan substratum and is affected by the Alpine structures. In the Santalla section, it is ~90m thick and consists of three intervals forming a package that coarsens and then fines upward (Fig. 7). The basal interval, ~20m in thickness, is made of amalgamated whitish nodular pedogenic limestones. The middle interval, ~30m thick, is formed of pinkish–reddish, rarely greenish, mudstone-rich packages alternating with pedogenic limestones, which are up to 2m in thickness each comprising several amalgamated calcretes. The mudstone-rich packages contain tabular, sharp-based bodies of sandstones and granulestones, some of which display rooting and pedogenic features. Finally, the upper interval, 40m thick, consists of pinkish/reddish mudstones with thin pedogenic limestones, which become thicker and more abundant upwards.

In the central part of the BTS, several partial sections (see Fig. 3 for location) permit to reconstruct the succession of the Toral Formation with the exception of the upper part, which does not crop out. This composite succession forms, at least, a large-scale coarsening-upward cycle, which is thicker than the whole formation in the Santalla section. It remains unclear whether this cycle is of the same order as the thinner coarsening-upward cycle of the Santalla section. In this case, the Santalla section would represent a relatively condensed section of the Toral Formation, possibly located towards the foreland-basin margin. Alternatively, this thicker coarsening-upward cycle could be of a lower order, being composed of higher-order cycles like those described in the Santalla section.

Las Médulas Formation

Two units have been distinguished in this formation: a lower unit with a coarsening-upward trend and an upper unit with a fining-upward trend. Their vertical trend and relationships to the Alpine structures indicate that they were deposited in different tectonostratigraphic scenarios (Fig. 2).

The lower unit of Las Médulas Formation (lower Las Médulas unit) unconformably overlies the Toral Formation, or more rarely, the Variscan substratum. In the Santalla section, the Toral Formation and the lower Las Médulas unit are bound by a progressive angular unconformity, involving a transitional interval, here called "transition beds" (Fig. 7). The lower Las Médulas unit displays a diagnostic coarsening-upward trend and is affected by the Alpine structures (Fig. 2), giving rise to progressive unconformities and growth strata not only affecting the basal strata, as in the Santalla section, but

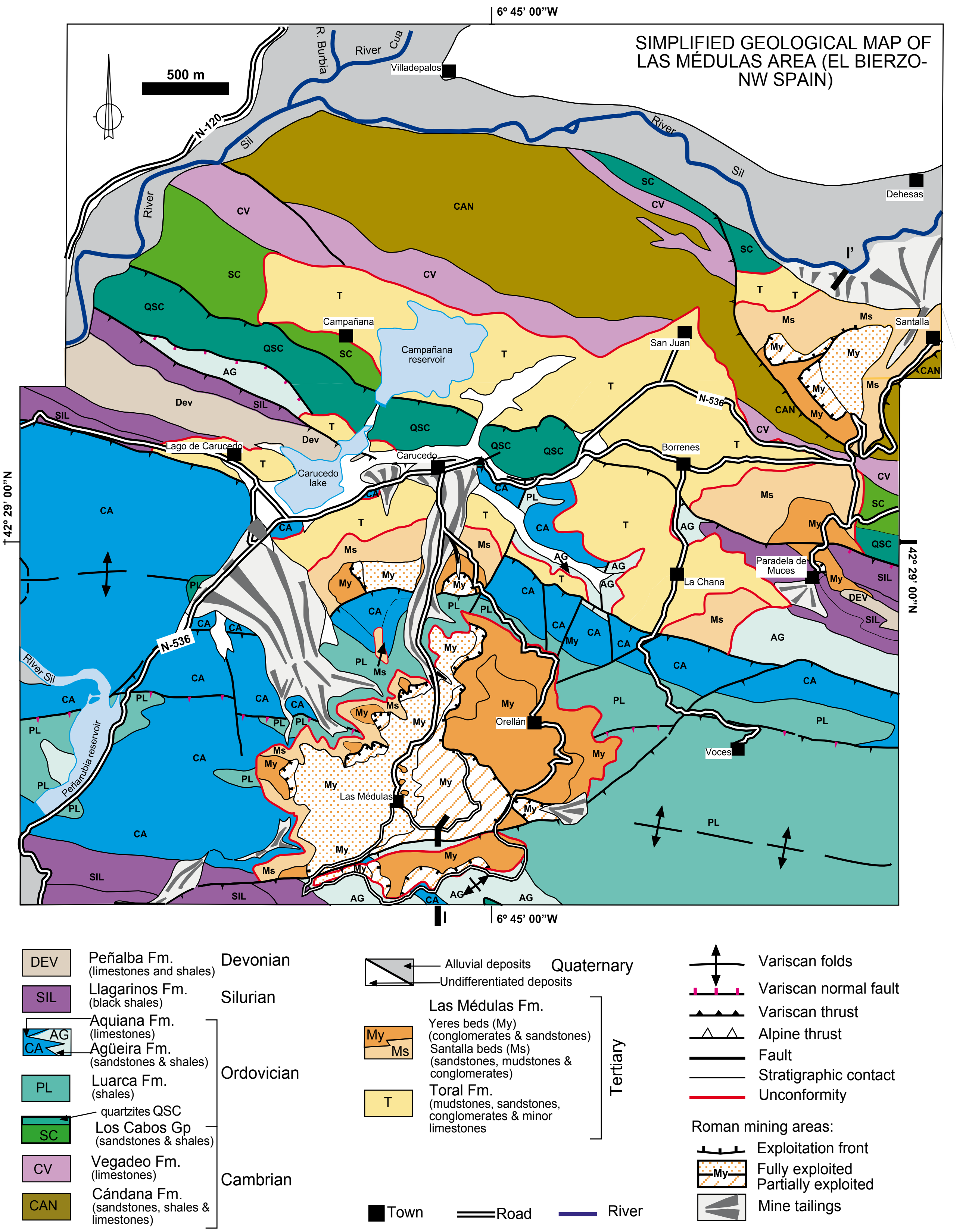


FIGURE 4. Geological map of the southern part of El Bierzo Sub-basin in Las Médulas area.

also the whole unit (médulas of La Leitosa; Fig 6C). In the latter section, growth-stratal patterns and cross-cutting relationships show that this unit is essentially coeval with the emplacement of thrusts, although its uppermost strata are post-tectonic as they lap onto the upper fault block.

In the Santalla section (Figs. 6B and 7), the lower Las Médulas unit comprises the Santalla beds. At its base, the transition beds are ~12–20m thick and form a composite fining upward package made of metre-scale fining upward cycles. The rocks also evolve upwards from pinkish to beige-brownish rocks. The base is marked by a ~0.5m-thick bed of conglomerates with pebbles and cobbles of quartzite and of dark slates. Clast imbrication indicates a paleoflow towards NW (290º–310º). The remainder of the unit is made of sandstones, and subordinate conglomerates, siltstones and mudstones. Sandstone beds are graded and laterally continuous, up to a few tens of centimetres in thickness. In each minor cycle, sandstone beds are amalgamated in the lower part and pass into a thin siltstone or even a mudstone cap in the upper part. Also, in the lower part of the minor cycles, sandstone beds display a basal lenticular division of granulestones to pebble conglomerates (mean clast size 1cm) with quartzite and dark slate clasts. These basal divisions have an erosional base with V-shaped scours a few centimetres deep, a sharp top and may consist of several amalgamated beds.

In the Santalla section, the remainder of the lower Las Médulas unit sharply overlies the transition beds by means of reddish, cobble-and-pebble conglomerate body, up to 10m in thickness (Figs. 6B and 7). This basal body consists at least of two fining-upward cycles of conglomerate beds with interleaved coarse-sandstone lenses. Conglomerates are similar to those in the base of the transition beds and clast imbrications indicate a palaeoflow towards W (270º). The remaining of the unit is a ~110m thick succession of mudstones with conglomerate and sandstone packages (Figs. 6B and 7). It displays a composite coarsening-upward trend with higher order cycles, up to several tens of metres thick each, that mainly fine upwards. The conglomerates at the base of these fining-upward cycles form metre-thick bodies, which are laterally continuous over several tens of metres and display erosional bases with a relief of up to 1m. They are pebble-and-cobble conglomerates with quartzite and dark-slate clasts. Clast imbrication indicates a palaeoflow towards W–NW (270°–310°). Sandstones range from fine- to very-coarse-grained and occur as graded or internally cross-bedded beds.

In La Leitosa section (Fig. 6C), the lower Las Médulas unit is more coarse-grained than in the Santalla section and attributable to the Yeres beds, being mainly made of conglomerates, mostly disorganized, with subordinate beds of massive or laminated sandstones and granulestones. The unit forms a coarsening upward package, some 100m thick, arranged into metre-scale fining upward bodies. These bodies are typically made of amalgamated conglomerate beds, and are laterally continuous at the scale of tens of metres, displaying erosional bases, up to 3m in depth. Some erosional scars suggest a main palaeoflow to the south.

The upper unit of Las Médulas Formation (upper Las Médulas unit) most commonly conformably overlies the lower Las Médulas unit. Nevertheless, in some places it unconformably overlies the Toral Formation or the Variscan substratum (*e.g.* Paradela de Muces and Orellán areas, Fig. 4). This upper unit is best developed in Las Médulas mining

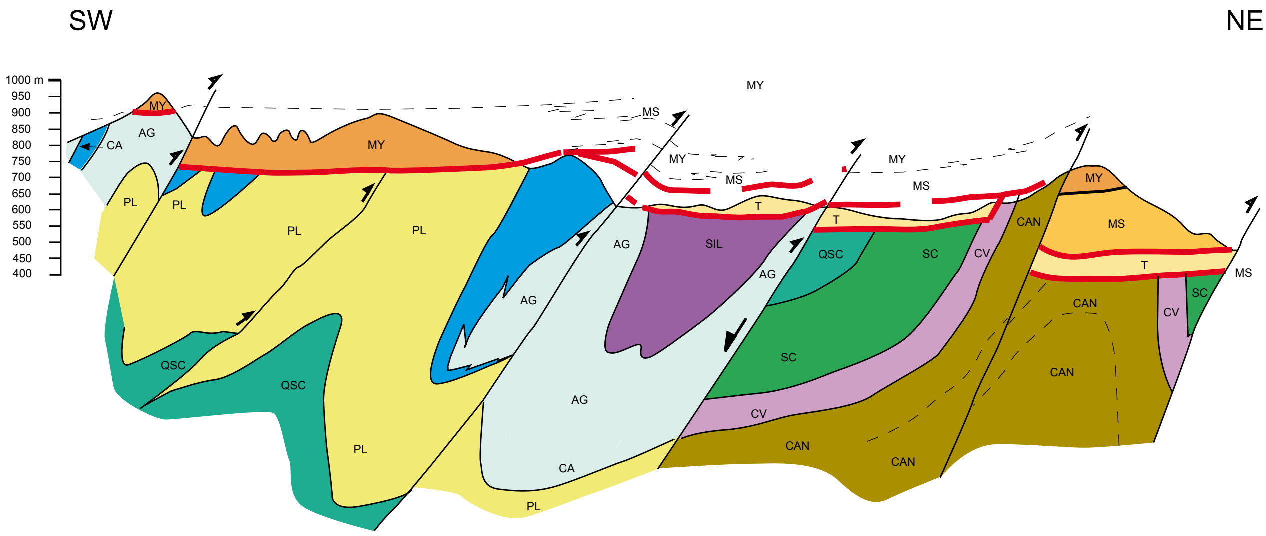


FIGURE 5. Geological cross section showing the structuring of the southern margin of El Bierzo Sub-basin and the northern end of the Galaico-Leoneses Mountains into thrust-bounded blocks. Note the resulting vertical offset of the succession. Same legend of Figure 4.

site, forming a ~230m-thick interval made of the Yeres beds (Fig. 6D). There, patchy exposures do not permit to examine its complete succession and it apparently does not display a clear vertical trend. Nevertheless, sandstone intercalations are thicker and more continuous in the upper part (see also Pérez-García *et al*. 2000; their Fig. 7). Also, according to the latter authors, both gold grade and conglomerate clast size decrease upwards. Overall, these features point to a complex, composite fining-upward trend (Figs. 2, 6D and 8).

This upper package shows a variable relationship to the Alpine structures. Both in the southern and northern margins of the basin (*e.g*. Paradela de Muces and médulas

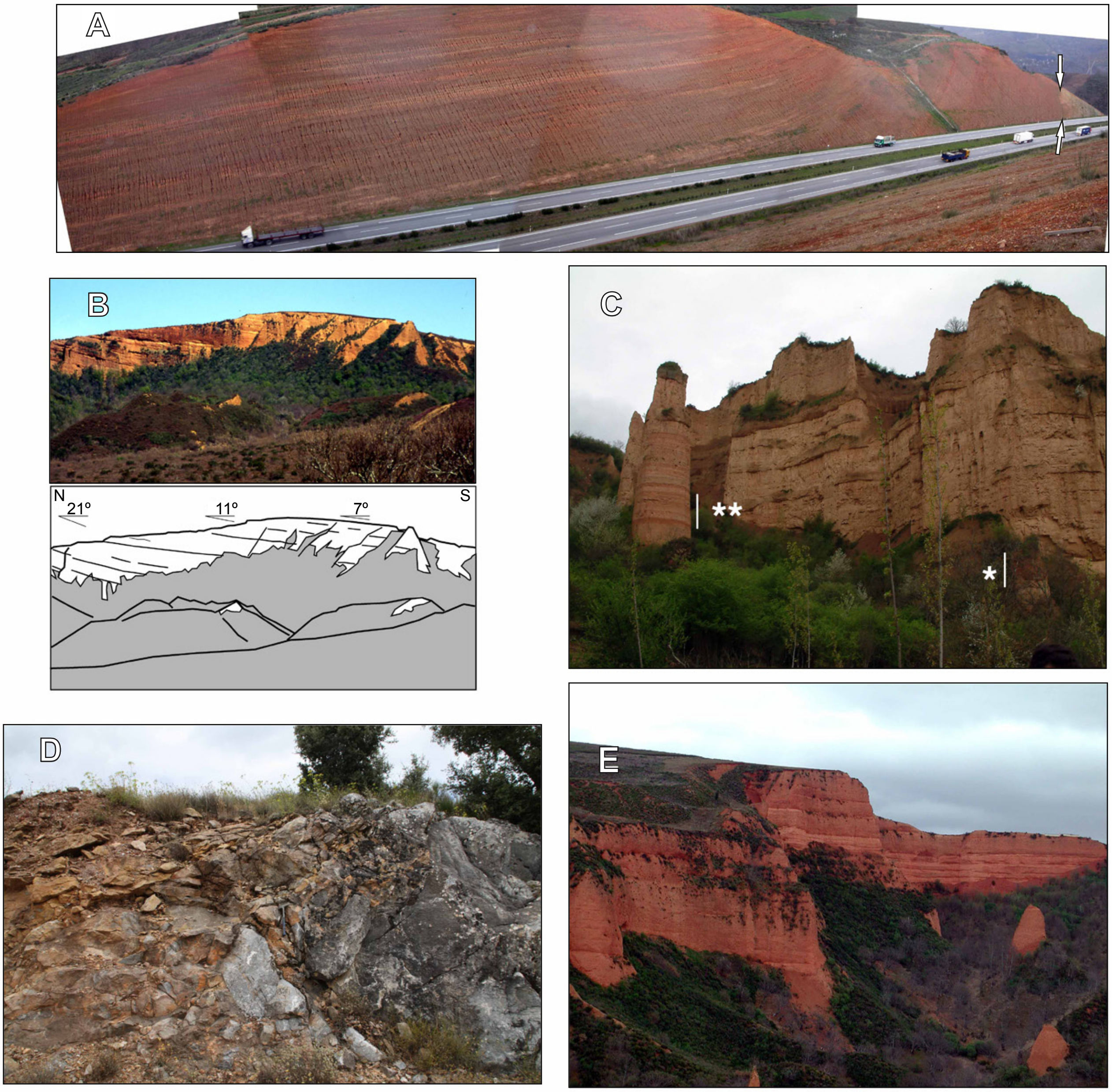


FIGURE 6. Field photographs showing the main features and bedding style, at outcrop-scale, of the stratigraphic units of El Bierzo Sub-basin. A) The Toral Formation.; light-grey rocks in the right (eastern) end of the road cut are the Stephanian substrate (arrows at unconformity) (section 9; see Fig. 3 for location). B) The lower Las Médulas unit (here equivalent to the Yeres beds of Las Médulas Formation) in the médulas of La Leitosa (section 10 in Figure 3). C) The lower Las Médulas unit (here equivalent to the Santalla beds of Las Médulas Formation) at Santalla section (section 10 in Figure 3). Vertical white bars and asterisks (* and **) mark the location of the intervals indicated in Figures 7 and 11. D) Orellán breccia beds filling the feeder canyon of the Paradela-Santalla fan. The canyon cuts into Devonian limestones, which provided the calcareous clasts of the breccia (Paradela de Muces; section 19 in Figure 3). E) The upper Las Médulas unit (Yeres beds of Las Médulas Formation) at the Orellán section (section 18 in Figure 3).

of La Leitosa outcrops, respectively), it seems to postdate the bounding thrusts as it laps onto the Variscan rocks of the upper fault block. Nevertheless, in the southern margin of the basin, it is affected by the youngest northward-directed thrusts of the Galaico-Leoneses Mountains (Figs. 3, 4 and 5).

In the Orellán section (Las Médulas mining site), the ~230m-thick upper Las Médulas unit is a reddish succession of alternations of conglomerates, subordinate sandstones, and rare mudstones. In the lower part, conglomerates form packages up to several tens of metres thick, with laterally

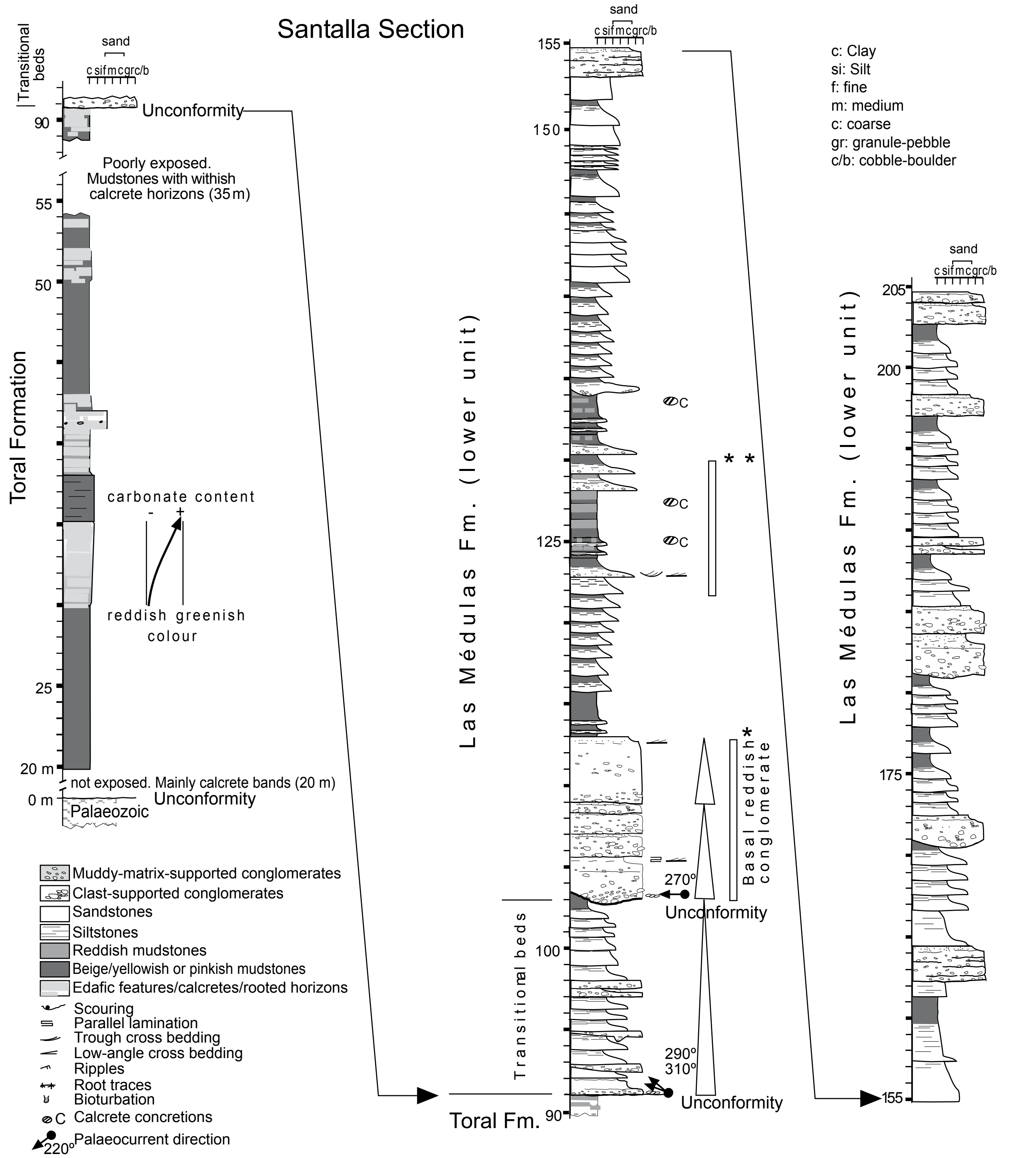


FIGURE 7. Stratigraphic log of the Santalla section (section 10 in Figure 3) showing the stratigraphy of the Toral Formation and of the lower Las Médulas unit (here represented by the Santalla beds of Las Médulas Formation). Vertical empty bars and asterisks (* and **) mark the location of the intervals depicted in Figures 6C and 11. See text for details.

discontinuous coarse-grained sandstone intercalations and basal and internal channelized surfaces. Upwards, the conglomerates form laterally continuous fining-upwards bodies, up to several metres in thickness, which pass upward into coarse- to fine-grained sandstones. These bodies show a remarkable lateral continuity, over hundreds of metres (Figs. 6D and 8), displaying essentially flat bases with local metre-deep scours. Conglomerate beds exhibit various types of fabric, including clast imbrication and cross bedding (see the facies section below). Palaeocurrent indicators from this area point to a sediment dispersal towards the northwest (Fig. 3).

As to the Orellán beds (Orellán Formation of Herail, 1981), defined in the southern and southeastern margins of the BTS, they form discontinuous patches that rest directly on elongate erosional lows cut into the Variscan substratum at the base of the upper Las Médulas unit (Yeres beds) in the southern part of the médulas of Orellán (Yeres-Carucedo fan) or are its updip equivalent (Paradela de Muces locality; Paradela-Santalla fan).

In the southern part of the médulas of Orellán (Yeres-Carucedo fan), the Orellán beds consist of very poorly sorted and disorganized breccias made up of cobbles and boulders of variable lithology set in a pebbly sandstone matrix. In the vicinity of Paradela de Muces (see Figs. 3 and 4 for location), they fill relatively deep and steep channels, incised into karstified Devonian carbonates and show a transport direction to the WNW (Fig. 6E). They are interpreted as the fill of the fan-feeder canyons.

Stratigraphic relationships between the units of Las Médulas Formation

Time relationships between the units of Las Médulas Formation cannot be well constrained at basin scale, but are assumed to be complex since, as Martín-González and Heredia (2011a) pointed out, thrust emplacement was highly diachronous from the northern to the southern margin of the basin. Nevertheless, at local scale, *i.e.* within a single depositional system, their opposing stacking patterns seem to rule out that they are, at least partly, time equivalent. Only if they had been deposited in laterally unconfined alluvial fans, the lateral shifting of the system could result in the coeval development of opposing stacking patterns between the areas from which the fan migrated, where a fining-upward trend is expected, and those to which the fan shifted, where a coarsening-upward would result. Nevertheless, regional evidence suggests that the alluvial fans were laterally confined (see above the section on the stratigraphic framework). In this scenario, it is interpreted that the lower Las Médulas unit, which coarsens upwards, is older than the upper unit with its overall fining upward (Fig. 2) and that both types of

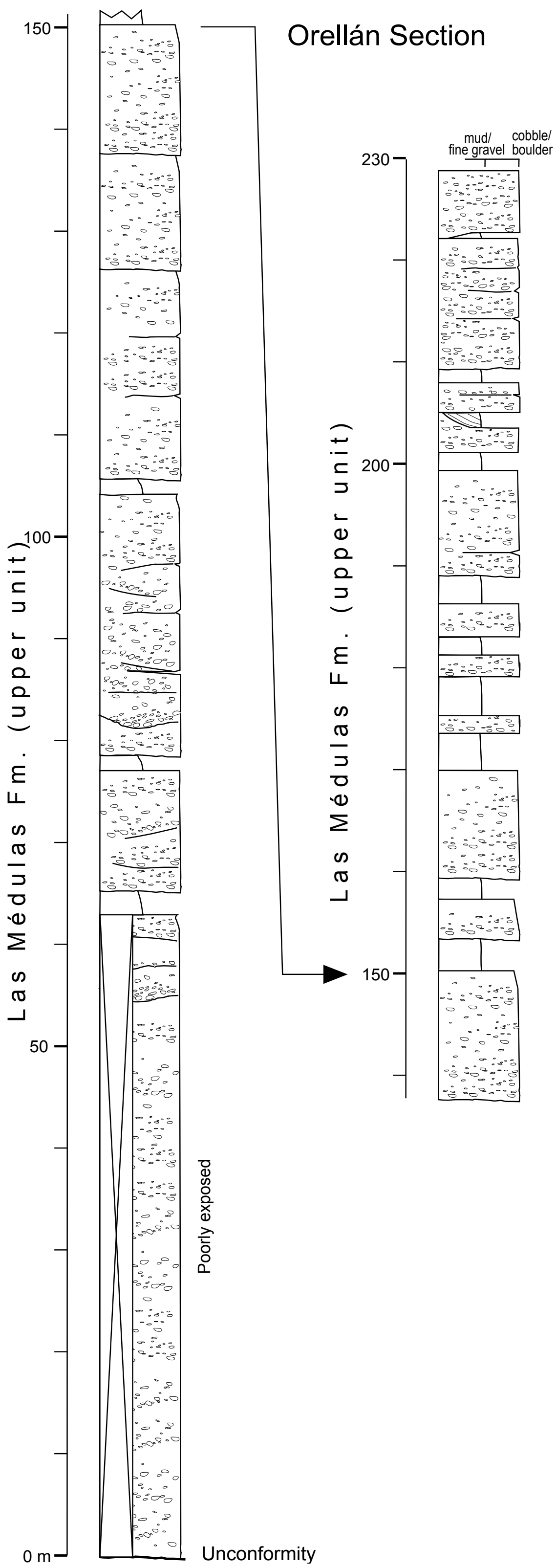


FIGURE 8. Stratigraphic log of the upper Las Médulas unit (here represented by the Yeres beds of Las Médulas Formation) in the Orellán section (Las Médulas mining site; section 18 in Figure 3). Symbols as in Figure 7.

stacking pattern are the response to external controlling factors, as it will be discussed below.

SEDIMENTOLOGY: FACIES AND DEPOSITIONAL ELEMENTS

Facies

The studied deposits can be described in terms of nine facies on the basis of bed features, texture and sedimentary structures: i) Disorganized breccias, ii) Poorly organised conglomerates and pebbly sandstones, iii) Clast-supported conglomerates with clasts parallel to bedding, iv) Stratified clast-supported conglomerates, v) Laminated granulestones and coarse-grained sandstones, vi) Massive to graded granulestones and coarse sandstones, vii) Fine-grained laminated sandstones, viii) Graded fine-grained sandstones, and ix) Mudstones. The main features of these nine facies are summarized in Table 1. Palaeosols have not been defined as a specific facies and they are regarded as a post-depositional feature that affects previous deposits, notably those of facies 9 (mudstones).

The operating processes: facies tracts and flow evolution

All the described facies have been seen to sharply or gradually pass into one another, both vertically and laterally, within single beds (see Figs. 9C-F and 11). Thus, they can be framed into a genetically-related system tract, *i.e.* a set of facies that pass into one another downcurrent as the flow evolves (see Mutti, 1992). These facies transitions, including the diagnostic vertical grading from sandstones into mudstones (see facies 7, 8 and 9), and the features of the facies suggest that this system tract can be mostly explained in terms of sedimentation from sediment gravity flows instead of fluid gravity flows (see Middleton and Hampton, 1986). Only in a few cases, sediment reworking by a fluid gravity flow, *i.e.* a mass of water flowing under the action of gravity, is envisaged.

A downcurrent evolution through flow transformations (Fisher, 1983) can be envisaged from a cohesive debris-flow, into a density-modified, cohesionless debris flow (or hyperconcentrated flow) (Nemec and Steel, 1984; Mutti, 1992), and then into a more dilute flow, comparable to a high-density and finally to a low-density turbidity current (see Lowe, 1982; Middleton and Hampton, 1986; Mutti, 1992; Mutti *et al.*, 1996, 1999).

Each facies records the rheological state of the flow at a given sedimentation stage. Cohesive debris flows (facies 1) and hyperconcentrated flows (facies 2) would evolve into high-density flows, through a hydraulic jump (see Mutti, 1992) recorded by the sedimentation of the coarsest sediment fraction forming a lag deposits (facies 3 and 4). The so-generated high-density flows would deposit through traction-plus-fallout or fallout processes (facies 5 and 6, respectively) leaving a final low-density flow that would deposit in the same way (facies 7 and 8, respectively) until the final exhaustion of the flow sediment load (facies 9).

The cases in which facies transitions take place over short distances point to relatively low-volume, low-momentum flows suffering a high rate of energy dissipation and thus not being able to transport their load far into the basin. The lesser-evolved flows would be those depositing the facies 1 and 2, which contain all the grain size populations, from gravels to clay and which would tend to be restricted to the more proximal parts of the systems. The remainder facies would record highly efficient flows, able to segregate the several grain size populations and to deposit them from the proximal parts (facies 3 and 4) to the distal (facies 7, 8 and, finally, 9) reaches of the system.

Summarising, these processes would have taken place in an alluvial setting dominated by catastrophic flows (flood-dominated system). Each of these single events would be responsible for a nearly instantaneous sedimentation stage punctuating longer periods of inactivity and reworking of the system surface. The interpretation of these deposits as alluvial sediments related to catastrophic events agrees with previous interpretations by Herail (1984), who proposed cohesive debris flows as the main flow type involved in the sedimentation of Las Médulas Formation.

Depositional elements

The facies described can be grouped into three types of depositional elements. Two of them are made of conglomerate and sandstone bodies, whereas the third one corresponds to the mudstone packages.

The two elements made of conglomerate and sandstone bodies are mainly tabular at outcrop scale (Figs. 6B–E and 12A–B). They are distinguished on the basis of their internal architecture. The first element is represented by bodies displaying a complex internal organization with different hierarchies of internal erosional surfaces of variable shape, flat or concave-up (Fig. 12A–B). In detail they comprise beds of varied geometry (Figs. 10 and 12C); see Miall, 1985). These bodies are overall coarser than those of the second depositional element and tend to display a fining-upward trend. They may appear amalgamated or encased within mudstone packages. This first element very likely represents the complex fill of wide and relatively shallow channels. The hierarchy of internal erosional surfaces can reflect the existence of macroforms within the channels, the scale of which would be of tens of metres at least (Fig. 10) and whose downcurrent accretion would record the sedimentation from a number of individual flows. The

TABLE 1. Main facies features

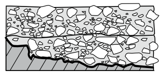
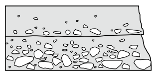
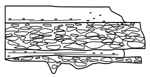
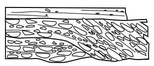
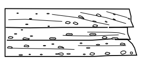
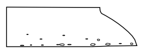
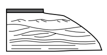
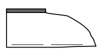
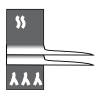
Facies (Clay Si f m c vc Gravel; Sand)	Texture & Composition	Bedding features	Sedimentary structures, grading & clast imbrication	Interpretation
1: Disorganized breccias  Fig. 6E and 9A	Matrix- to clast-supported. No sorting (m-size boulders to clay-grade particles).Clast composition varies with the type of Variscan substratum.	Metre-thick beds, laterally continuous to lenticular.	None. The largest clasts may lie at the bed top.	Cohesive debris-flow deposits (e.g. see Nemec & Steel, 1984 Mutti, 1992). Mostly found in the Orellán beds.
2: Poorly-organised conglomerates and pebbly sandstones  Fig. 9B	Matrix- to clast-supported. No sorting (m-size boulders to clay-grade particles). Includes clast-poor muddy sandstones.	Metre-thick beds, laterally continuous to lenticular.	Crude to well-developed normal grading. Clasts may be restricted to the lower parts of beds.	Deposited from density-modifiec debris flows. Clast segregatior due to turbulence (cohesionless debris flows of Nemec & Steel, 1984; hyperconcentrated flows of Mutti, 1992; Mutti et al., 1996, 1999, 2003).
3. Clast-supported conglomerates with clasts parallel to bedding  Figs. 9B-F and 10	Clast-supported, pebble and cobble conglomerates. Poorly sorted coarse-grained (granule- and sand-grade) clay-free matrix.	Laterally continuous or lenticular beds/divisions, isolated or amalgamated forming packages. Erosional base, may display V-shaped deep scours. Sharp lateral and vertical transitions into facies 4, 5 or 6.	Massive or graded (normal or inverse) beds. Clasts lie parallel to bedding or imbricated.	Frictional freezing of an inertial layer seggregated from a density-modified debris flow (see Lowe, 1988; Mutti, 1992; amongst others)
4. Stratified clast-supported conglomerates.  Figs. 9D-F and 10	Similar to facies 3.	Laterally continuous or lenticular beds/divisions, isolated or amalgamated forming packages. Erosional base. Sharp lateral and vertical transitions into facies 3 or 5 within single beds.	Clasts lie parallel to bedding or imbricated. Clast-size variations define internal parallel bedding (subfacies 4a) or cross-bedding (subfacies 4b). Planar or trough cross-bedding sets are up to a few metres thick.	Flat/ low-relief bars (4a) or 2D/3D bedforms (4b). Deposited from tractional flows (Rust, 1978; Miall, 1985), probably related to evolution (dilution) of denser flows (modified debris flows). Flow velocity variations could accoun for transitions from facies 3 (Fisher, 1983; Mutti, 1992; Mutti et al., 1996).
5. Laminated granulestones and coarse-grained sandstones.  Figs. 9E-F and 10	Moderately-sorted granulestones-conglomerates to coarse sandstones. Aligned fine gravels.	Laterally continuous or lenticular beds/divisions, isolated or amalgamated. May evolve from facies 3 or 4 and into facies 6 within single beds.	Variably developed lamination may be highlighted by aligned fine gravels. Diffuse horizontal lamination (subfacies 5a) or cross bedding (subfacies 5b).	Same processes as in facies 4, but from more evolved flows, with a lower velocity and carrying finer-grained particles. Relation to facies 6 suggests deposition by traction-plus-fallout from a gravity flow (see Lowe, 1982; Mutti, 1992).

TABLE 1 (continuation). Main facies features

Facies (Clay Si f m c vc Gravel; Sand)	Texture & Composition	Bedding features	Sedimentary structures, grading & clast imbrication	Interpretation
6. Massive to graded granulestones and coarse-grained sandstones.  Figs. 10 and 11	Same grain size populations as facies 5 down to fine sandstones.	Laterally continuous, tabular or lenticular beds/divisions. May overlie a facies 3 division. Flat to erosional base.	Massive or coarse-tail normal grading from granulestones to fine-grained sandstones.	Deposited from high-density flows carrying a sandy load. Sedimentation through hindered settling, en masse deposition and settling from suspension (see Lowe, 1982, Mutti, 1992). A lower flow power than for facies 6 would account for the lack of traction.
7. Fine-grained laminated sandstones 	Fine-, exceptionally medium-grained sandstone that fines upwards into very fine sandstone to siltstone. Some beds grade into a final mudstone division.	Laterally continuous to tabular divisions up to several tens of cm in thickness, forming entire beds or overlying other facies within beds.	Two structurings: parallel lamination to low-angle cross-bedding or wavy lamination (subfacies 7a) and ripple cross-lamination (subfacies 7b).	Deposited by traction-plus-fallout from waning turbulent suspensions, either in a supercritical to upper subcritical regime (7a) with combined flow conditions (HCS), or in a lower subcritical regime (7b). Normal grading into mud suggests deposition from low-density turbidity currents (see Middleton and Hampton, 1976; Mutti et al., 1996).
8. Fine-grained graded sandstones 	Fine-grained sandstone that fines upwards into very fine sandstone to siltstone, and finally into a mudstone division.	20-30 cm-thick divisions that form entire beds with a sharp base and a gradational top to F.9.	Normal grading. Some beds display a subtle parallel lamination.	Deposition by fallout from a turbulent suspension (low-density gravity flow). Cases with parallel lamination suggest a transition between this facies and facies 7 (eg, see Mutti, 1992)
9. Mudstones  Figs. 6B and 11	Mudstone, may contain a minor amount of sand particles. Variable colour from pinkish to orange or reddish.	Several metre-thick intervals or forming thin divisions that gradually cap sandstone beds of facies 7 and 8.	Massive of bedded. Root or animal bioturbation.Rooting often results in a mottled appearance.	Background, low-energy sedimentation in sheltered/distal reaches of the basin. Mudstone caps of sandstone beds represent settling from residual low-density flows. Poorly sorted mudstone beds may derive from high-density (muddy) gravity flows or from mixing by bioturbation.

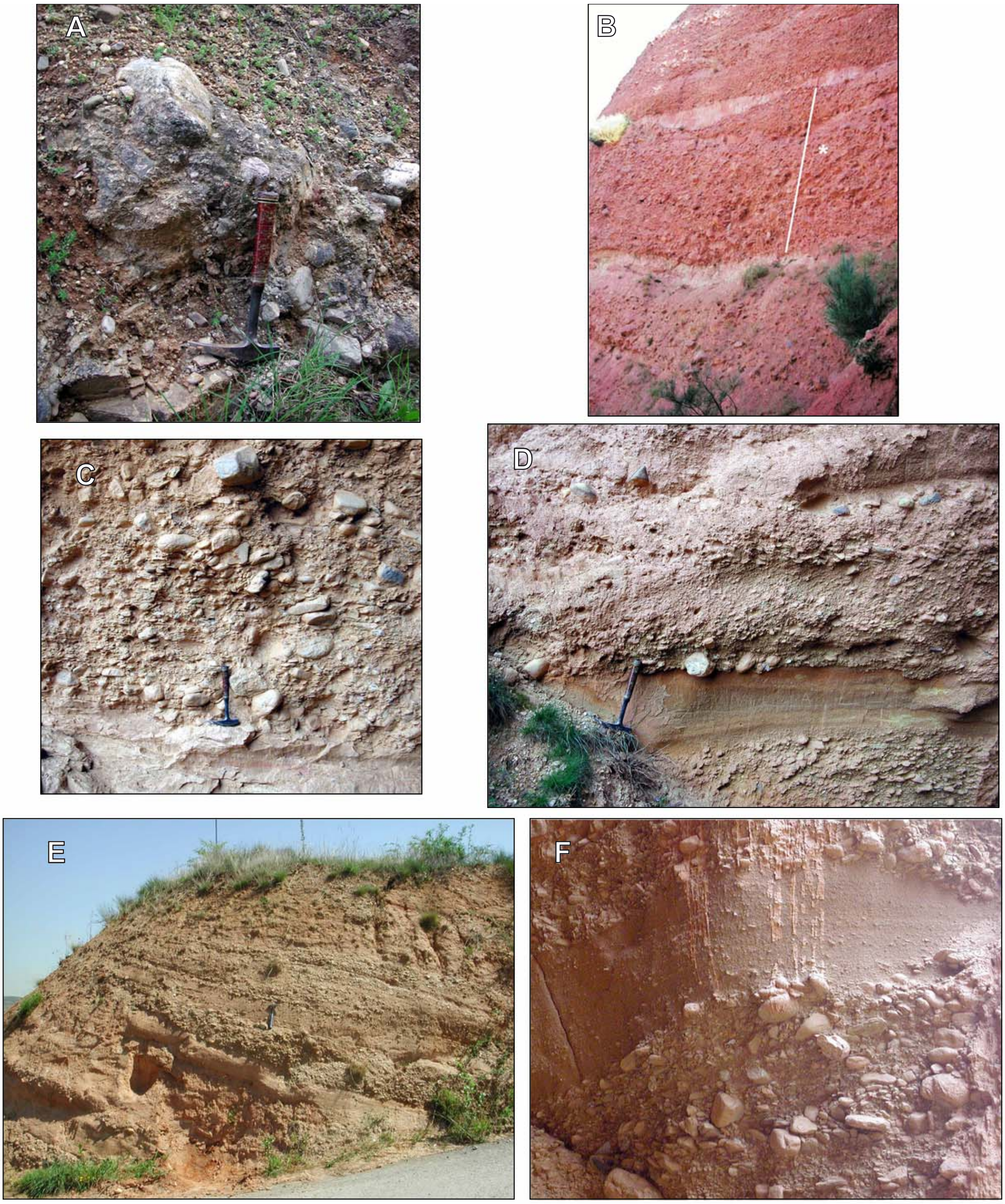


FIGURE 9. Field photographs showing the main features of the facies distinguished in El Bierzo Tertiary succession (see Figure 3 for location of the sections). A) Facies 1 (cohesive debris-flow deposits) (Orellán beds, Paradela de Muces section). B) Facies 2 (poorly organised conglomerates and pebbly sandstones) and 3 (clast-supported conglomerates with clasts parallel to bedding) (lower Las Médulas unit, La Leitosa section). Conglomerate unit in the middle of the photograph (asterisk) is 3.5m thick. C) Facies 3 (clast-supported conglomerates) displaying clast imbrications (upper Las Médulas unit, Orellán section). D) Stacked conglomerate beds, composed of several divisions each. The lowermost bed comprises a thin lenticular basal division of clast-supported conglomerates (facies 3) overlain by a division of cross-bedded clast-supported conglomerates (subfacies 4a), which evolves downcurrent (to the left) into cross-bedded coarse sandstones to granulestones (subfacies 5b). The overlying beds mainly comprise facies 3 and 4 divisions capped by graded-to-massive coarse sandstones to granulestones (facies 6) (upper Las Médulas unit, Orellán section). E) Stacked beds of conglomerates and coarse sandstones to granulestones. Beds mostly display a basal division of clast-supported conglomerates with clasts parallel to bedding (facies 3) or with cross-bedding (subfacies 4b), overlain by a thicker division of laminated (facies 5) or massive (facies 6) granulestones and coarse-grained sandstones. Note the thick division of cross-bedded granulestones (subfacies 5b) some 70cm above the hammer (lower Las Médulas unit, Ponferrada-Molinaseca road section). F) Close up of a bed composed of a lower division of clast supported conglomerates with cross bedding (subfacies 4b) overlain by laminated granulestones and coarse sandstones (facies 5). Note the lateral passage from the facies 4 to facies 5 (upper Las Médulas unit, Orellán section).

instances of metre-scale cross-bedded units (facies 3) are interpreted as bars, possibly of transverse type, with a well-developed lee side (Fig. 12C). Nevertheless, these deposits are rather rare and most of conglomerate bodies display a low angle to flat internal bedding suggesting that macroforms had a low relief, being probably similar to longitudinal bars (*cf.* Rust, 1978).

The second depositional element consists of metre-thick bodies that are mainly made of sandstone facies and appear amalgamated or, more commonly, encased in mudstone packages (Figs. 6B and 12B). These bodies comprise a few (tabular to laterally continuous beds) and they may coarsen upwards, fine upwards or show no trend. This depositional element is interpreted to

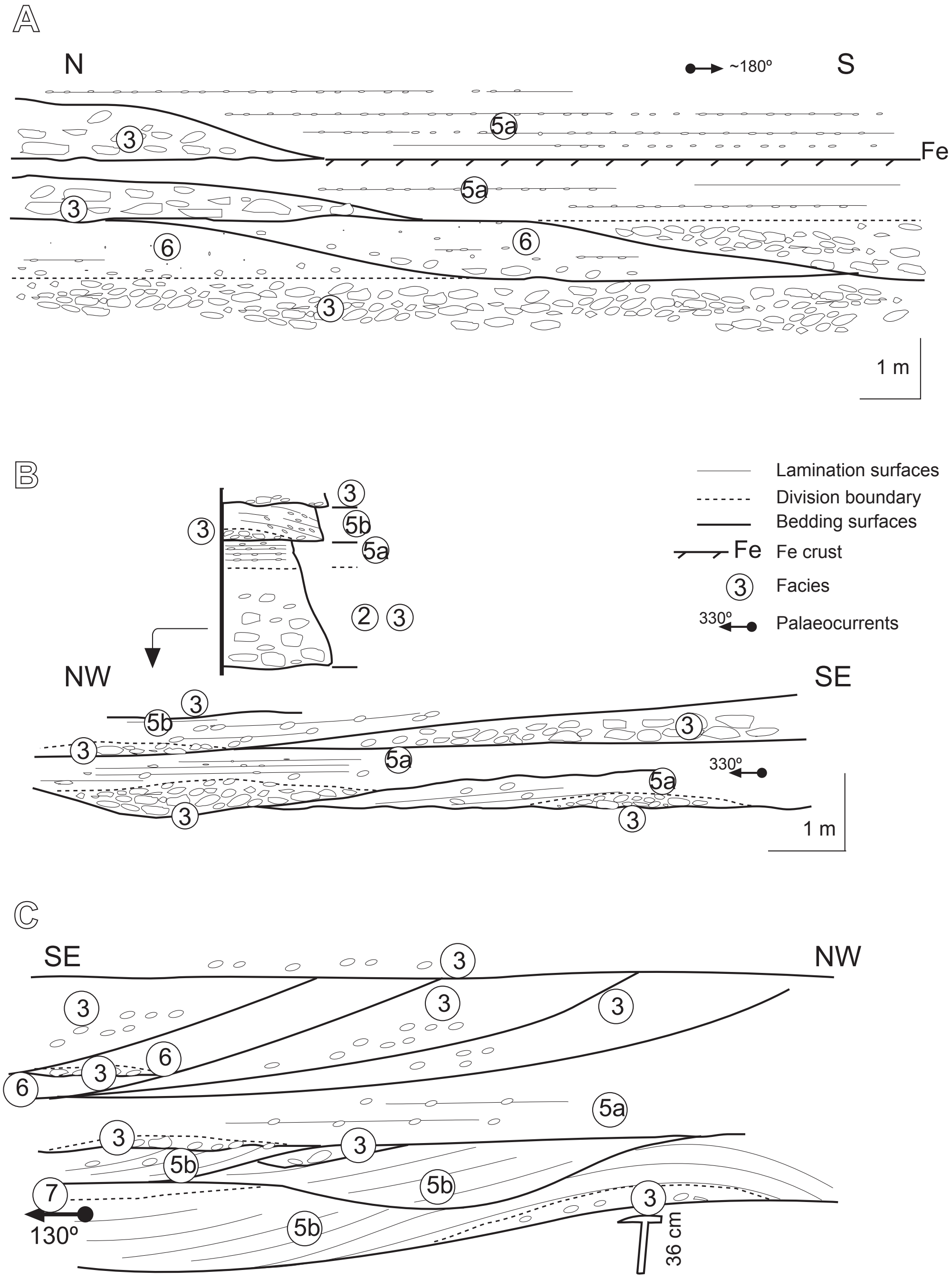


FIGURE 10. Sketches based on field photographs showing the internal bed organisation and the small-scale architecture of the alluvial deposits of El Bierzo Tertiary sub-basin. A) lower Las Médulas unit, La Leitosa section. B and C) upper Las Médulas unit, Orellán section. Facies are labelled as in text (see text for details). Sections located in Figure 3.

correspond to lobes deposited by unconfined flows in front of, or laterally to the channels. Some examples of these lobes in the Toral Formation display an inclined internal bedding (clinoformal geometry), a coarsening upward trend capped by channel deposits and a sharp lateral (downcurrent?) transition over short distances from cross-bedded coarse grained sandstones and granulestones (facies 5) to laminated fine-grained sandstones, siltstones and mudstones (facies 6, 7 and 8, Fig. 13). This architectural style suggests that these bodies represent minor deltaic lobes prograding into shallow bodies of water in front of, or laterally to the channels.

The third element consists of the mudstone packages that contain discrete bodies of the lobe and channel elements (Figs. 6B, 7 and 11). It is interpreted to represent a muddy alluvial plain, located laterally to the channels. The features of the alluvial plain, such as the bedded, not massive, nature of the mudstone intervals, the concentration of rooting traces at discrete horizons and the paucity of well-developed palaeosols point to relatively high sedimentation rates, probably related to mud-rich flows (see above the interpretation of facies 9). Also, as pointed out in the previous paragraph, the depositional surface could have been in places permanently submerged forming shallow ponds into which minor deltaic lobes prograded.

Sediment dispersal patterns

Palaeocurrent indicators are scarce in the BTS (Fig. 3), preventing a statistical treatment of the data. Paleocurrent data for the Toral Fm. are uniform across the basin, pointing to a sediment dispersal pattern towards south and east, from a source area located to the north and west–northwest, as regional data indicate (see also Herail, 1984).

This dispersal pattern changes completely in the overlying strata of the lower and upper Las Médulas units, with palaeocurrents indicating a southern provenance in the southern border of the basin, and a northern provenance in the northern margin. At the scale of the southern margin of the basin, a divergent (fan-shaped) dispersal pattern (Fig. 3) permits to distinguish several depositional systems. One of these systems, would be constituted by the outcrops of Santalla and Paradela de Muces (Paradela-Santalla fan). This system prograded towards west and northwest, as palaeocurrents suggest, and was later fragmented by the Alpine deformation. To the east, in the vicinity of Ponferrada, palaeocurrents markedly spread in two sets, one directed towards northeast and north, the other towards west and southwest, suggesting the existence of one or two systems fed from the south–southeast. In contrast, to the north and northwest (Cobrana, Posadina, Pieros and La Leitosa localities; see Fig. 3), palaeocurrents are directed towards the south, southeast and east and point to a set of systems fed from the northern margin of the basin.

FIGURE 11. Flood-plain element consisting in mudstone beds with some red palaeosoil horizons and intercalated beds of graded granulestones to coarse sandstones (facies 6). Santalla section (see Figure 3 for location). The interval depicted corresponds to that marked with a vertical bar and two asterisks in Figures 6C and 7.

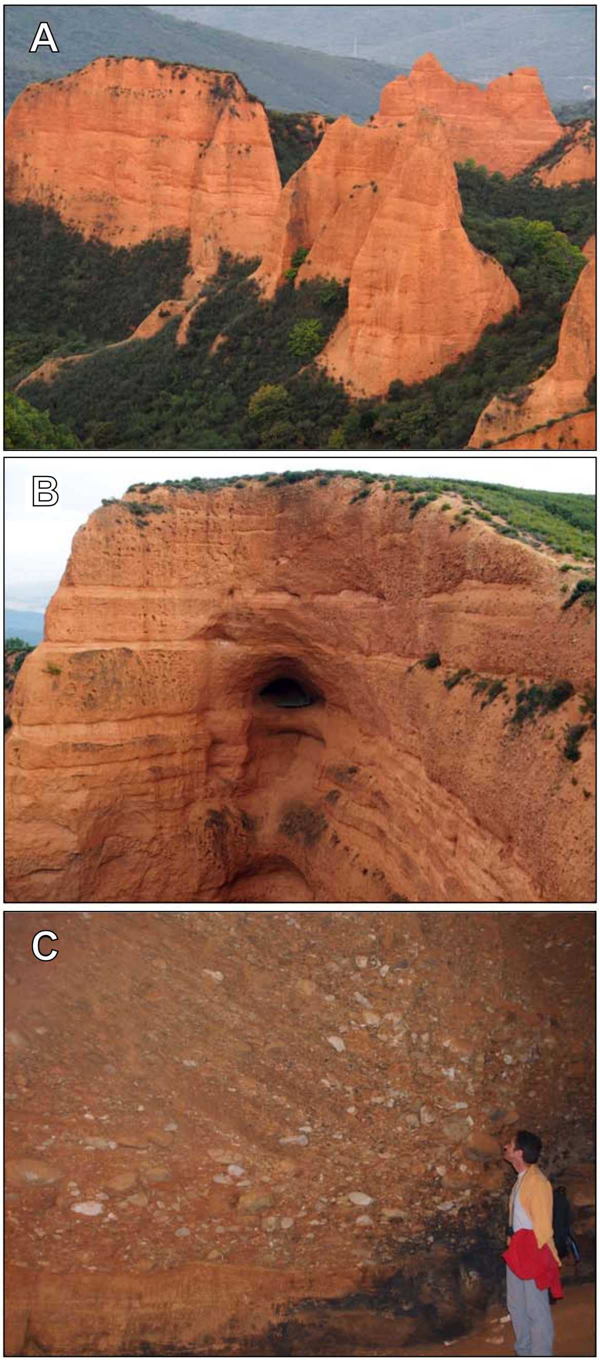


FIGURE 12. Field appearance of the alluvial elements described in text. All the photographs are from the upper Las Médulas unit at the Orellán section (see Figure 3 for location of the section and Figure 8 for location of photographs in the section). A) Cliff face showing a stacking of channel-fill units. Notice the concave-upwards master surfaces leaving a complex internal organisation with discontinuous intervals of finer-grained deposits (lower-middle part of the upper Las Médulas unit, between metres 70–110). B) Lobe and channel-fill elements. Note the different appearance of both elements (upper part of the upper Las Médulas unit, between metres 160–230). C) Detail of an example of the channel-fill element showing a large-scale cross-bedded unit with leftwards dipping strata, interpreted as the downcurrent (roughly northwards) migration of a macroform with a steep stoss side (lower-middle part of the upper Las Médulas unit, around metres 50–60).

DISCUSSION: DEPOSITIONAL STYLE AND TECTONOSEDIMENTARY EVOLUTION

Depositional style

In the studied area, the Toral Formation is formed mainly of facies 6, 7 and 9, which build alluvial plain elements with encased lobe and channel elements (Fig. 6A). These deposits would form the medial and distal facies belts of an extensive alluvial system in a wide basin. The coarse-grained proximal facies would have lain beyond the present-day margins of the BTS. According to the sediment composition and palaeocurrents, the Toral alluvial system would have been fed from the northwest and north. Herail (1984) postulated that the westernmost Toral outcrops, rich in granite clasts and arkosic sandstones, would have been fed from a granitic source area located to the west, whereas the outcrops in the east of the basin, with a lower percentage of arkosic sandstones, would reflect a sediment input from the north, where granites are rare. According to Martín-González and Heredia (2011a), these two distant source areas could correspond to the Lugo Dome granites (Martínez-Catalán, 1985) of the Mondoñedo Nappe Domain, and to the metasedimentary rocks of the Navia-Alto Sil Domain, respectively, both forming part of the West-Asturian-Leonese Zone (Iberian Massif). During Toral time, the wide basin would have been connected to the Duero Basin in the east (Martín-González *et al.*, 2014).

The progradational lower Las Médulas unit is mainly formed of a medial facies belt comprising an alternation of fine-grained alluvial plain elements with lobe and channel packages, evolving upwards into coarse-grained proximal facies mainly made of stacked, channel and lobe elements (Figs. 6B–C and 7). The latter two elements are the main constituent of the retrogradational upper Las Médulas unit (Figs 6D and 8). The stratigraphic relationships and the radial palaeocurrent patterns described above (Figs. 3 and 4) and the meaning of the Orellán beds, interpreted as the infill of feeder canyons (Figs. 2 and 6E), suggest that the deposits of the lower and upper Las Médulas units (Las Médulas Formation plus the Orellán beds) constituted a set of alluvial fan that entered the basin from its northern (*e.g.* La Leitosa fan; Fig. 6C) and southern (*e.g.* Yeres-Carrucedo and Paradela-Santalla fans; Figs. 3 and 4) margins, as the Alpine deformation proceeded first from the north (Cantabrian Mountains) and then from the south (Galaico-Leoneses Mountains) transforming the basin in a broken foreland basin (Martín-González and Heredia, 2011a; Martin-González *et al.*, 2014).

Contrasting to the alluvial-fan interpretation here supported, some authors (Hacar *et al.*, 1998, 1999; Pagés *et al.*, 2001; Gutiérrez-Marco, 2006; Matías, 2008) interpreted the middle and upper units as the deposits of four fluvial terraces of a braided-river system that flowed from a distant mountainous area located in the southeast. Two main reasons were invoked to back this hypothesis. First, the vertical offset of the deposits, which led these authors to interpret that they represent terraces witnessing the progressive entrenchment of a fluvial system. Second, the finding of a clast in Las Médulas Formation that contains a fossil bearing affinities with the Silurian fauna of the Alcañices–Moncorvo syncline, located 100km to the south of the study area, in the Central Iberian Zone of the Iberian Massif. Gutiérrez-Marco (2006) concluded that this proves that there was a fluvial system that flowed from that area into El Bierzo.

In our opinion, the two criteria above described are not conclusive and have alternative and simpler explanations. As it was discussed above, mapping data indicate that the vertical offset of El Bierzo deposits is due to Alpine faulting, (Fig. 5; see Martín-González y Heredia, 2011a, b). On the other side, the Gutiérrez Marco (2006) interpretation of a southeastern source area for the fossiliferous clast would mean that a large fluvial drainage system existed during the Neogene and flowing from SE to NW. This pattern would be completely different from the modern drainage system, which resulted from the evolution of the pre-existing Tertiary drainage pattern, and is at odds with the Alpine structural grain of the area and its inferred resulting palaeorelief. It would imply that an Alpine range grew in the south–southeast and that it was later completely levelled by erosion, since no evidence of it exists nowadays. Instead, the presence of a clast with such a fossil in Las Médulas Formation can be better explained by the more likely hypothesis of a polycyclic nature of the clast. It would have been recycled into El Bierzo during the Alpine orogeny from a late Variscan (Stephanian) conglomerate. These conglomerates are fairly common in the Stephanian outcrops across the Cantabrian and the West-Asturian-Leonese Zone, and they form the substratum of a significant portion of the BTS (see Fig. 3).

The timing of deformation

The different vertical stacking patterns of the lower and upper Las Médulas units, coarsening upwards for the lower one and fining upwards for the upper one, are interpreted to reflect different time relationships with the deformation.

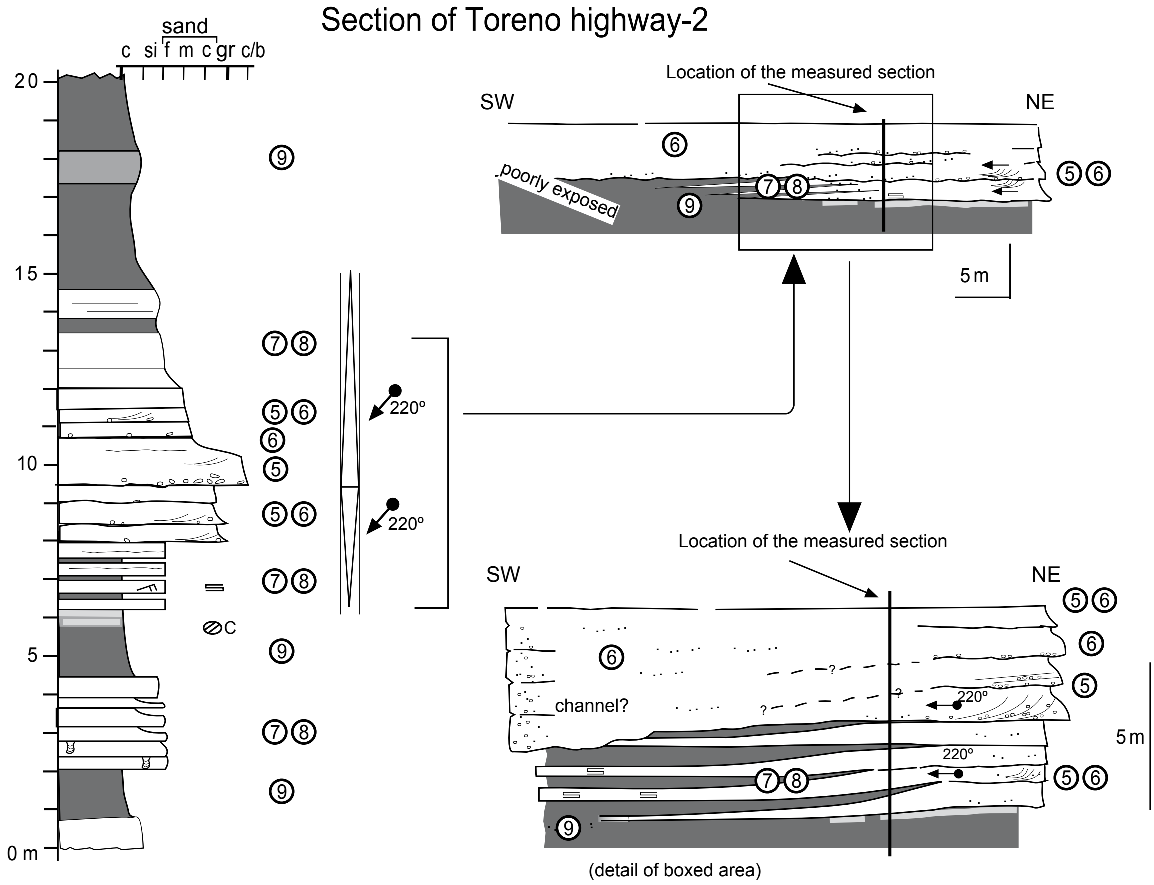


FIGURE 13. Log and field sketches of a sandstone body interpreted as a small-scale delta-like lobe (crevasse-splay lobe?) prograding into a flood plain environment (Toral Formation; Toreno highway-2 section; see Figure 3 for location). Encircled numbers denote facies. Symbols are as in Figure 7.

According to the crosscutting relationships that can be observed in the field between these sediment packages and the Alpine structures, we postulate that the coarsening-upward lower unit was deposited in progradational systems that were coeval with the emplacement of thrusts. Conversely, the upper unit with and overall fining-upward trend was deposited in later systems that were active after the climax of thrust emplacement. These relationships represent an alternative to the two published scenarios of gravel shedding in syntectonic basins. Based on the Cordilleran basins, Heller *et al.* (1988), amongst others, concluded that maximum gravel progradation takes place after periods of active thrusting, once the erosion of the allochtonous units leads to an isostatic rebound and to a concomitant lessened accommodation space in the proximal reaches of the basin. Conversely, Burbank *et al.* (1988), based on the study of Himalayan deposits concluded that maximum gravel shedding takes place during the phase of active thrusting. The latter authors emphasized that either model can be valid for a given basin depending on the balance between subsidence and sediment supply rates, which would be ultimately controlled by the type of drainage systems, the lithosferic rigidity and the type of rocks in the source area. In the BTS, data suggest that maximum gravel dispersal would take place at the end of the climax of thrust propagation and that then the progressive erosion of the created reliefs would result in a backstepping of the system. That would mean that the coarsening-and-then-fining-upward cycles would conform to the Davisian uplift-denudation cycles.

Although no solid field evidence exists, we postulate that the proximal Orellán beds, which occur as the infill of the feeder canyons (Fig. 6E), must represent mainly the last stage of evolution of these retrogradational systems, during which the backstepping of the system led to the choking of these previously active – and mostly empty – feeding conduits. That means that, if mapping could be done at sufficient detail, the strata of the upper unit would onlap the basin margin and the updip termination of the onlapping strata would be represented by the Orellán beds (Fig. 2).

Evolution model

The Toral deposits would record the mainly axial infill of a continental foreland basin bound by a rising orogen in the north (Cantabrian Mountains) and a foreland to the south. The proximal reaches, poorly preserved, comprised very likely a set of alluvial fans fringing the northern reliefs and evolving downcurrent into an axial, trunk river system flowing eastwards within an elongate foreland basin that continued in the Duero Basin.

Later, the continued uplift of the Cantabrian Mountains led to the erosion of the proximal facies of the Toral Formation to the north of BTS, and the forestepping of the alluvial systems towards the basin centre. Similarly, the uplift of the southern Alpine front (Galaico-Leoneses Mountains of Martín-González and Heredia, 2011a, b) completely removed the Toral sediments to the south of the BTS and forced the sedimentary systems to jump northwards (Fig. 14A). The Alpine deformation uplifted the deposits in the basin margins, where they lie at a higher position than in more internal parts of the basin. Uplift in the south (Galaico-Leoneses Mountains) resulted in the disruption and vertical offset of the Paradela–Santalla and Yeres–Carucedo fans (Fig. 14B) and in the individualization of the BTS from the southern O Barco Tertiary sub-basin. This stage of basin evolution resulted in an endorheic basin, which displays no evidence of connection with the Duero Basin, whose uplifted western edge, begun to provide sediments to El Bierzo. Finally, the erosion of the distal deposits of the lower and upper Las Médulas units (Las Médulas Formation) in the basin centre is interpreted to be due to erosion during the Quaternary fluvial capture of the Sil River. These fluvial-capture processes would have lead to the final opening of the basin to the Atlantic Ocean, and to the strong incision of the Sil River due to the resulting base-level fall.

CONCLUSIONS

The Toral and Las Médulas formations (Martín-González and Heredia, 2011a, b; Heredia *et al.*, 2012, after Herail, 1984) form the synorogenic sedimentary infill of the Cenozoic nonmarine BTS, recording the basin evolution and compartmentalization during the uplift of the Cantabrian Mountains and of the Galaico-Leoneses Mountains, in the western part of the Pyrenean orogen (Martín-González and Heredia, 2008, 2011a y b).

The Toral and Las Médulas formations comprise a range of alluvial deposits, from alluvial channels and lobes to flood plain deposits, laid down predominantly from catastrophic flows (flood-dominated systems). Three main elements can be distinguished, i) channel-fill units forming several types of gravelly and sandy macroforms in wide channels, ii) tabular, mostly sandy elements, constituting depositional lobes in front of or laterally to the channels, and iii) mudstone-dominated packages with carbonate-rich palaeosoils forming flood plain deposits.

The Toral Formation consists of flood plain elements with encased lobe and channel elements, whereas Las Médulas Formation comprises mainly lobe elements (Santalla beds) channel and lobe elements (Yeres beds) or fan-feeder canyon elements (Orellán beds).

Vertical stacking patterns and geometrical relationships to the tectonic structures permit to separate three units in the succession, i) the Toral Formation, affected by the Alpine tectonics and likely with a large scale coarsening upwards trend, ii) the unconformable lower Las Médulas unit, affected by the Alpine faults and showing a coarsening upward trend, and iii) the upper Las Médulas unit, resting on a variable substratum, affected only by the youngest structures and displaying an overall composite retrogradational (fining upward) trend.

The sedimentary architecture and palaeocurrent dispersal patterns of the Toral Formation suggest that this unit was deposited during an early evolutionary stage in a wide basin, connected with the Duero Basin, and fed from distant source areas of the Cantabrian Mountains, located to the west (mainly igneous) and north (mainly metamorphic) as it has been observed since Herail´s (1984) pioneering work. In contrast, the lower Las Médulas and upper Las Médulas units record a more advanced evolutionary stage and were sourced from the Cantabrian Mountains in the north, and then from the Galaico-Leoneses Mountains in the south, as these two ranges were uplifted and the El Bierzo became progressively isolated from the Duero Basin and finally from the O Barco Tertiay sub-basin. Palaeocurrents from these two units (Las Médulas Formation) indicate that they record a series of north- and south-derived small- to medium-scale alluvial fans that were laterally bound by palaeoreliefs and prograded towards the centre of the basin.

Maximum progradation of the Las Médulas alluvial fans is inferred to have taking place at the boundary

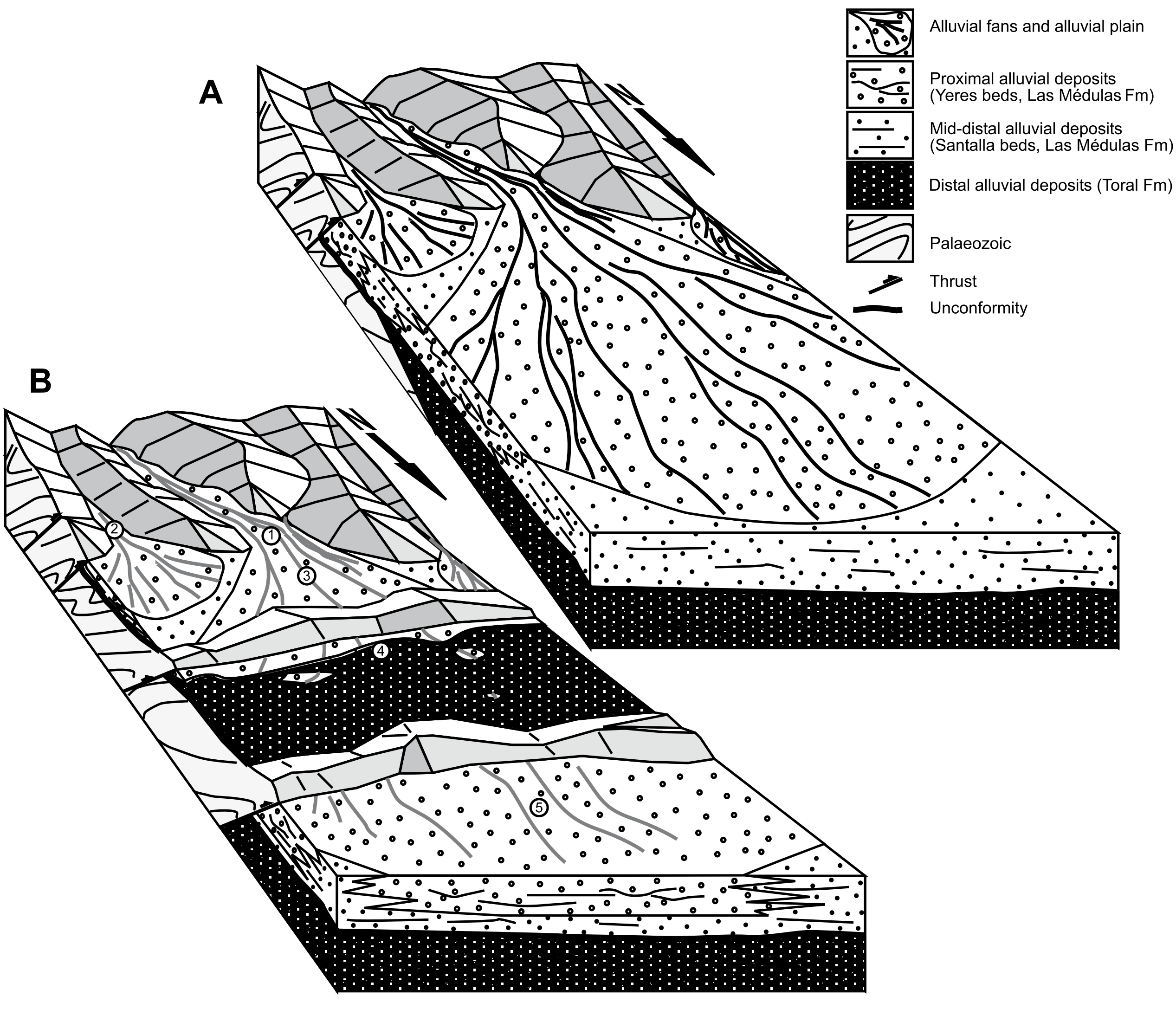


FIGURE 14. Schematic cartoon showing the palaeogeographic setup of El Bierzo sub-basin. A) During the time of sedimentation of Las Médulas Formation. The alluvial fans entering the basin seem to have been partially confined by the structural features and by the adjacent fans (see texts for details). B) Fan dismembering during later stages of the Alpine thrust emplacement, which led to the vertical displacement of the sedimentary units among fault blocks (see text for details). Numbers in (B) show the approximate location of the Roman mines ("médulas") in the proposed model: 1) Médulas de Yeres, 2) Médulas de Paradela, 3) Médulas de Orellán, 4) Médulas de Carucedo, 5) Médulas de Santalla (see also Figure 4).

between the lower Las Médulas and upper Las Médulas units, and this moment is correlated with the climax of Alpine deformation.

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