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Palaeontological age and correlations of the Tertiary deposits of the NW Iberian Peninsula: the tectonic evolution of a broken foreland basin

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Ages of Cenozoic sedimentary basins yield information that can be used to infer detailed spatial and temporal evolution in the Alpine foreland. The Tertiary deposits of the NW Iberian Peninsula comprise the remains of a broken foreland basin (the West Duero Basin). This work constrains the timing of tectonic fragmentation and the evolution of the western termination of the Alpine Pyrenean–Cantabrian Orogen (NW Iberian Peninsula). The discovery of *Issiodoromys* cf. *minor* 1 and *Pseudocricetodon* in the lower formation of the Tertiary depression of Sarria (the Toral Formation) constrains its age to the late Early Oligocene (MP23–MP25), similar to its age in the El Bierzo depression (MP24–MP25). Sedimentation initiated in the NE of the study area at Oviedo during the Middle Eocene (Bartonian–Early Priabonian MP16–MP17) and migrated towards the west and south during the Early Oligocene. The Toral Formation was deposited in a foreland basin that connected the present day outcrops of the El Bierzo, Sarria and As Pontes Tertiary depressions. The basin was segmented during the westward migration of structural deformation associated with the Orogen, and the subsequent uplift of the Galaico–Leoneses Mountains. The present-day height above reference level of the base of the Toral Formation has been used to quantify Alpine segmentation that took place after Early Oligocene times. Minimum tectonic uplift assessed is 960 m in the Cantabrian Mountains and 1050 m in the Galaico–Leoneses Mountains. Copyright © 2013 John Wiley & Sons, Ltd.

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1. INTRODUCTION

The ages of Cenozoic sedimentary basins yield information that can be used to infer detailed spatial and temporal denudation patterns, tectonic and topographic evolution in the Alpine Foreland (Allen and Allen, 1990; Cloetingh *et al*., 2006; 2007; De Vicente *et al*., 2007b; Martín-González and Heredia, 2011a). The northern part of the Duero and Ebro Basins comprise the southern foreland basins of the Alpine Pyrenean–Cantabrian Orogen (Cordillera Cantábrico–Pirenaica) (Alonso *et al*., 1996; Gallastegui *et al*., 2002; Muñoz, 2002; Martín-González and Heredia, 2011a) (Fig. 1a). Towards the west there are few exposures of Tertiary-aged sections, and the Duero Basin terminates abruptly against the Galaico–Leoneses Mountains region (Fig. 1a).

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The age of the Tertiary deposits in the NW Iberian Peninsula has not been established with certainty to date, and therefore the understanding of the tectonic evolution of the region remains imprecise and controversial (Martin-Serrano *et al*., 1996; Alonso and Pulgar, 2004; Barnolas and Pujalte, 2004; De Vicente and Vegas, 2009; Martín-González and Heredia, 2011b). The difficulty in dating these deposits is due to their limited exposure and the fact that they were deposited as terrigenous continental sediments, in oxidized arid or semiarid environments. Differences in the preserved record of the deposits also make lithostratigraphic correlation difficult (Martín Serrano *et al*., 1996; Pagés *et al*., 2001). As a result, a number of different and contradictory interpretations for these deposits exist, based on local palaeogeographical, tectonic, geomorphological, or complex stratigraphic criteria (Martín-Serrano *et al*., 1996). Recent studies demonstrate the need to better constrain the age of the Tertiary deposits in order to understand the tectonic evolution of the western termination of the Orogen and its associated foreland basin

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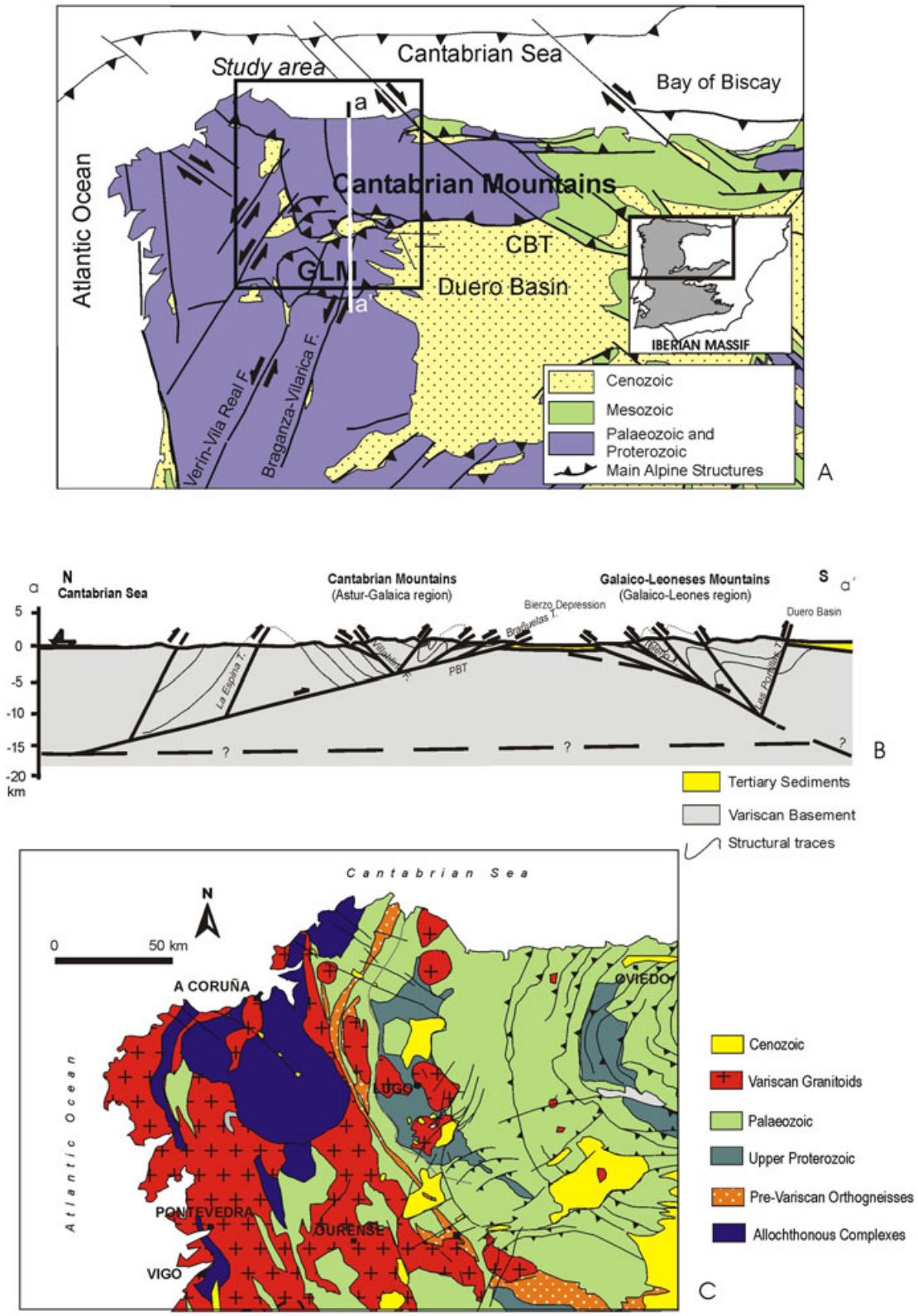


Figure 1. (A) Generalized geological map of the Alpine–Pyrenean Orogen showing the main Alpine structures and foreland basins (CBT = Cantabrian Basal Thrust; GLM = Galaico Leoneses Mountains). (B) N–S cross sections (Modified from Martín-González and Heredia, 2011b). Location provided in Fig. 1a. (C) Geological map of the NW Iberian Peninsula (Modified from Martín-González, 2009).

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(Freudenthal *et al*., 2010; Martín-González and Heredia, 2011a; De Vicente *et al*., 2011). The Tertiary deposits crop out in small sub-basins or depressions that comprise the remains of a broken foreland basin, related to the southward propagation of Alpine tectonic activity (Martín-González and Heredia, 2011a, b). However, this model was only based on tectonostratigraphic correlations as no accurate age information was available.

The aim of this study is to constrain the chronology and quantify the tectonic evolution of this broken foreland basin and the western termination of the Alpine Pyrenean–Cantabrian Orogen (NW Iberian Peninsula). It presents an interdisciplinary study of new palaeontological data with the tectonic deformation history of the Cenozoic deposits, quantifying the segmentation and deformation of the Alpine Foreland Basin.

2. GEOLOGICAL SETTING

The NW Iberian Peninsula is mainly composed of Precambrian and Palaeozoic rocks (Fig. 1c), deformed during Devonian–Carboniferous times in the Variscan Orogeny. These sediments were intruded by granites during Carboniferous and Permian times forming the Iberian Massif (Fig. 1a). The Variscan structure has an arch-like plan (called the Asturian Arch) with the external parts facing eastward (Fig. 1a and c).

The Alpine Pyrenean–Cantabrian Orogen extends from the Pyrenees in the east to the Cantabrian Mountains in the west. The Orogen was the result of the collision between the Iberian Microplate and Eurasia in Late Cretaceous–Cenozoic times. The Pyrenees trend ESE–WNW and represent a doubly vergent continental collision zone (Choukroune *et al*., 1990; Muñoz, 2002; Teixell, 1998). This double vergence generated two continental foreland basins: the Ebro Basin in the south and Aquitaine Basin in the north. The western extension of the Pyrenees are the Cantabrian Mountains (Gallastegui *et al*., 2002; Muñoz, 2002; Pedreira *et al*., 2007; Martin-González and Heredia, 2011b) which trend E–W. The structures of the southern Pyrenean Zone extend westward along the Cantabrian Mountains, and the structures of the north Pyrenean Zone continue offshore into the Bay of Biscay (Cámara, 1997; Gallastegui *et al*., 2002). Structures in the Ebro Foreland Basin extend into the Duero Basin (Fig. 1a).

The topography of the NW Iberian Peninsula is related to the Alpine structures that uplifted the Cantabrian Mountains (CM) and south of these, the Galaico–Leoneses Mountains (GLM) (Fig. 1a). These mountains represent the western termination of the Alpine Pyrenean–Cantabrian relief (Santanach, 1994; De Vicente and Vegas, 2009; Martín-González and Heredia, 2011a, b). The overall structure of the central Cantabrian Mountains consists of a regional monoclinal flexure related to the Cantabrian Basal Thrust (Alonso *et al*., 1996). However, in its westernmost part where the Alpine relief diminishes, this structure changes (Martín-González and Heredia, 2011b) as shortening is partially transferred toward the north into the As Pontes Fault by N–S trending arches (the Ibias–Ancares and Rúa–Vilalba structures). Subsequently in the south, the Galaico–Leoneses Mountains are mainly uplifted by north-verging thrusts (Fig. 1b). Shortening of the GLM north-verging thrusts is accommodated by the NNE–SSW strike–slip faults of the Iberian Massif. These faults were still active during Quaternary times (Martín-González *et al*., 2012a). The uplift of the GLM segmented the original foreland basin that surrounded the CM (Martín-González and Heredia, 2011a). The ages recorded by apatite fission track analysis (Martín-González *et al*., 2008, 2012b) point to an uplift of the CM that began during the Oligocene and continued into the Middle to Late Miocene times in the GLM.

The Tertiary synorogenic deposits of the NW Iberian Peninsula were affected and fragmented by Alpine structures that delimit their present outcrops. However, the amount of uplift associated with foreland basin fragmentation has not been assessed. The O Barco and El Bierzo depressions are orientated E–W because they are limited by E–W thrusts that generated a tectonic pop-down structure (Figs. 1b and 2; Santanach, 1994; Martín-González, 2009). The Monforte, Sarria and Vilalba depressions are orientated N-S as they are associated with N–S and NE–SW trending strike–slip faults with an important vertical component (Martín-González *et al*., 2003).

The preserved stratigraphic succession is similar in the Tertiary depressions (Fig. 2; El Bierzo, O Barco, Monforte, Sarria and Vilalba), displaying an upward-coarsening trend (Fig. 3). The deposits are mainly terrigenous with interbedded continental carbonates, deposited by alluvial fans located at mountain fronts under arid or semi-arid climatic conditions (Herail, 1981; Alonso *et al*., 1996; Alonso-Gavilán *et al*., 2004; Martín-González and Heredia, 2011a). In the El Bierzo depression, the main Tertiary outcrop of the NW Iberian Peninsula, three formations have been defined (Herail. 1981), in ascending order the Toral Fm., the Santalla Fm. and the Médulas Fm. (Fig. 3). The Toral Fm. comprises sands and clays deposited by ephemeral processes as a distal alluvial fan lithofacies, and clay and limestones deposited in a shallow lake environment that underwent periodic desiccation, subsequent calcrete formation and plant and animal colonization. The Santalla Fm. is composed of sands and conglomerates with polygenic pebbles (pebbles of quartzite, schist and sandstone), these deposits pointing to deposition in a more proximal alluvial fan setting. The Médulas Fm. is composed of conglomerate with pebbles and boulders of quartzite and sandstone, representing the most proximal lithofacies of the alluvial fans whose depositional geometries are preserved in some cases (e.g. Paradela de Muces in the south of the El Bierzo depression).

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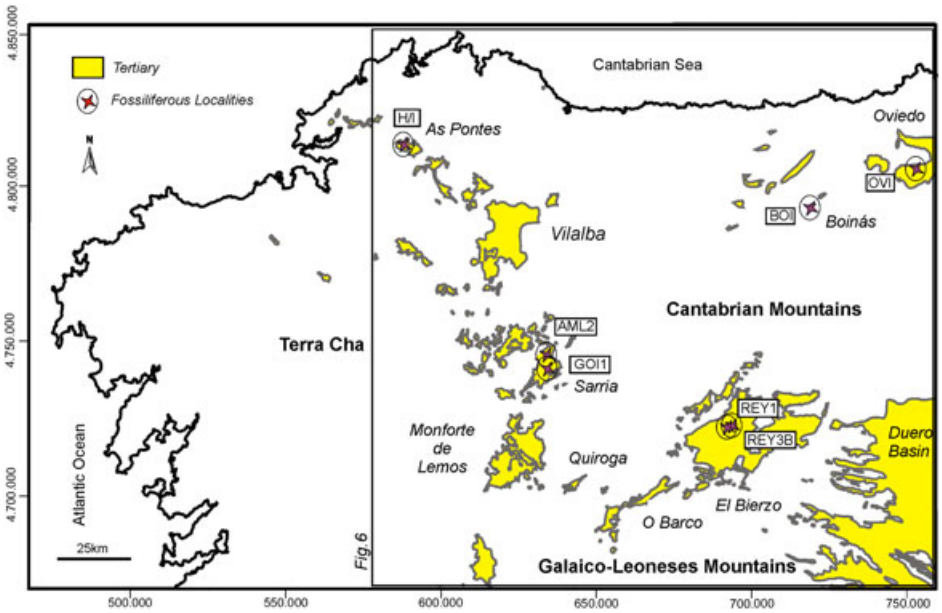


Figure 2. Distribution of the Tertiary deposits in the NW Iberian Peninsula, showing the location of the fossiliferous localities studied (UTM zone 29 N). This figure is available in colour online at wileyonlinelibrary.com/journal/gj

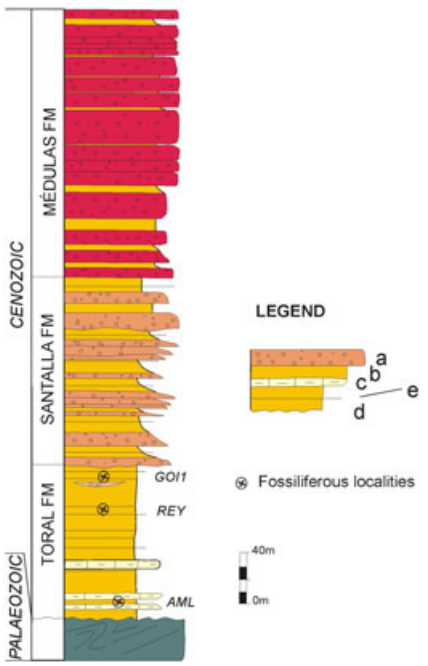


Figure 3. Synthetic stratigraphic column of the synorogenic Tertiary deposits of El Bierzo, O Barco, Monforte de Lemos, Sarria and Vilalba. Location of the fossiliferous localities is shown. Legend: (a) conglomerates, (b) sands, (c) calcretes and lacustrine limestones, (d) lutites, (e) palaeosoils. This figure is available in colour online at wileyonlinelibrary.com/journal/gj

The age and subsequent correlation of the Tertiary deposits have been determined on the basis of a wide range of criteria: lithological (Sluiter and Pannekoek, 1964; Brell, 1972; Brell and Doval, 1974; Martín-Serrano, 1982; Martín Serrano *et al.*, 1996; Hérail, 1981; Huerta *et al.*, 1997), palaeontological (Medús, 1965; Nonn, 1969; López Martínez *et al.*, 1993; Freudenthal *et al.*, 2010; this study), geomorphological (Birot and Solé Sabarís, 1954, De Groot, 1974) and tectonic (Olmo Sanz, 1981; Vergnolle, 1990; Bacelar *et al.*, 1988; Santanach, 1994; Martín-González and Heredia, 2011a). Palaeobotanical studies carried out to date of the Tertiary flora are contradictory, and more detailed studies are necessary (Barrón and Santos, 1998). Previous work has produced conflicting dates, with some studies proposing Palaeogene ages for the El Bierzo succession (Martín-Serrano, 1982; Pagés *et al.*, 2001; Gutiérrez-Marco, 2006), with others proposing Late Miocene–Pliocene (Brell and Doval, 1974), Oligocene–Pliocene (Herail, 1981; Vergnolle, 1990) or Early Oligocene ages (Freudenthal *et al.*, 2010). Table 1 presents a compilation of secondary source dates and our own data ages for the Toral Fm.

3. SEDIMENTARY RECORD

The sequence of the three formations defined in the El Bierzo depression (the Toral, Santalla and Médulas Fms.) can also be observed in other Tertiary depressions of the NW Iberian Peninsula, representing the deposits of synorogenic alluvial fan progradations (Alonso *et al.*, 1996; Martín-González and Heredia, 2011a; De Vicente *et al.*, 2011). The lower formations (e.g. Toral Fm.) are always deformed by Alpine faults, with drag folds being developed associated with faulting. Sedimentation clearly took place prior to the generation of the Alpine faults that delimit the present-day outcrops.

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Table 1. Compilation of dates for the Toral Formation from secondary source data (references highlighted) and those from this study

Sample	Tertiary outcrop	Location	Height above base of formation (m)	Lithology and formation	Age	References
OVI	Oviedo Basin (Llamaquique)	UTM 30T 0268708/ 4804878	≈10	Lacustrine limestones, mudstones and evaporites	Bartonian–Early Priabonian MP16–MP17	Truyols *et al.*, 1991
BOI	Boinás (El Valle Gold Mine)	UTM 29T 0719248/ 4796097	—	Limestones, clay and marls	Late Eocene–Early Oligocene MP17–MP22	Álvarez-Sierra and Daams, unpublished; De Vicente *et al.*, 2007a
REY1	El Bierzo	UTM 29T 0698946/ 4729738	>90	Clay, lacustrine limestones and sands (Toral Fm)	late Early Oligocene MP24	Freudenthal *et al.*, 2010
REY3B	El Bierzo	UTM 29T 0698928/ 4730079	>105	Clay, lacustrine limestones and sands (Toral Fm)	latest Early Oligocene age (MP25).	Freudenthal *et al.*, 2010
AML2	Sarria (Armea de Lancara)	UTM 29T 0633998/ 4745627	≈20	Clay, lutites, marls and lacustrine limestones (Toral Fm)	MP23–MP24	This study
GOI1	Sarria (Goian)	UTM 29T 0636151/ 4741688	≈130	Clay and lutites (Toral Fm)	MP25	This study
H/I	As Pontes (Coal mine)	UTM 29T 0589221/ 4813903	≈30	Clay and lutites (Toral Fm)	Early Late Oligocene MP25–MP26	López-Martínez *et al.*, 1993

The youngest Tertiary formations (e.g. the Santalla and Médulas Fms.) show onlap or syntectonic unconformities related to the Alpine faults that today limit their outcrops. Thus, the Toral Fm. is most likely the remains of an embryonic foreland basin fill deposited distal to the active orogenic front. Subsequently, it was deformed by the progressive foreland advancement of the orogenic front. The younger Santalla and

Figure 4. Palaeontological ages of the basal Tertiary formations of the NW Iberian Peninsula. Note the younger age progression to the west. (For locations, refer to Figure 2). This figure is available in colour online at wileyonlinelibrary.com/journal/gj

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Médulas Fms. reflect proximal deposition related to the later progradation of the orogenic front.

Palaeocurrent indicators in the Toral Fm. bear no relation to its present-day relief (Herail, 1981 and Martín-González and Heredia, 2011a), and indicate provenance from westerly and northerly sources. The presence of arkosic sandstones (with granitic clasts) in this formation, implies a granitic source area, which is located to the west of the present-day Tertiary outcrops (Fig. 1c). Moreover, this formation is believed to have formed a more extensive, laterally continuous lithosome (Herail, 1981; Vergnolle, 1990), and has been interpreted as the remains of an embryonic phase of foreland basin deposition (Martin-González and Heredia, 2011a).

The provenance of later formations (e.g. the Santalla Fm.) was controlled by the present-day topography, with palaeocurrent indicators reflecting both northerly and southerly sources. The distribution of the Médulas Fm. is closely linked to the present-day relief (e.g. Paradela de Muces in the south and Leitosa in the North of El Bierzo depression). The Santalla and Médulas Fms. are proximal lithofacies that developed adjacent to areas of positive relief, and represent the final intramontaine basin infill.

4. METHODS

The palaeontologically derived ages for various outcrops of the NW Iberian Peninsula (As Pontes, El Bierzo, Boinás and Oviedo Tertiary depressions) have been compiled (Figs. 2 and 4 and Table 1). Ages compiled from the lower formations (Toral Fm. in El Bierzo and related formations in other Tertiary depressions) and only ages with palaeontological criteria (Table 1). A spatial gap in this data is observed in the south-west of the study region (e.g. at Monforte de Lemos, Sarria; Fig. 2). The sampling strategy in this study was focused on obtaining ages from these Tertiary depressions in order to get a better understanding of the tectono-stratigraphic evolution of the basin. Twenty-three sites were sampled in total, with trial samples of 60 kg collected from each location (Table 2). These were transported to Granada, washed in a nearby lake, and the residues were processed in the laboratory with acetic acid, reduced with a magnetic separator, fractioned into six fractions with mesh between 2.5 and 0.5 mm and finally picked out under the binocular microscope. Only two samples yielded a positive result (Armea de Láncara 2 and Goián 1), both from the Sarria depression (Figs. 2 and 3; Table 2). These sites were revisited and a further 2000 kg sample was collected from each. These were washed in the field and then prepared in the same way as the trial samples.

To address the tectonic fragmentation of the embryonic foreland and its associated deformation, the present-day height in metres above sea-level (m a.s.l.) of the base of the Toral Fm. has been quantified (Fig. 6). This included direct field observations of the base of the Toral Fm. (where it unconformably overlies Palaeozoic basement), mapping

Table 2. Table showing the details of the palaeontological prospection for this study in the Tertiary depressions of Sarria and Monforte de Lemos

Trial samples	Code	UTM 29T	Lithology	Sample weight (kg)	Prospection result
Fuenteabuin	ABU1	0633849/4742629	Grey marls and lacustrine limestones	60	Negative
Fuenteabuin	ABU2	0633886/4742574	Grey marls and lacustrine limestones	60	Negative
Armea de Láncara	AML1A	0634157/4745372	Pink marls and lacustrine limestones	60	Positive
Armea de Láncara	AML1B	0634157/4745372	Pink marls and lacustrine limestones	60	Negative
Armea de Láncara	AML2	0633998/4745627	Marls and lacustrine limestones	60 (2000)	Positive
Armea de Láncara	AML3	0632740/4745447	Grey marls	60	Negative
O Barco	BRC1	0668744/4700917	Reddish grey clay	60	Negative
Forcadas	FOR1	0627285/4715698	Dark grey clay	60	Negative
Fornelas	FRN1	0628461/4713784	Dark grey clay	60	Negative
Goián	GOI1	0636151/4741688	Clay and lutites	60 (2000)	Positive
Monforte de Lemos	MOF3	0624081/4709647	Dark grey clay	100	Negative
Monforte de Lemos	MOF4	0623991/4709477	Dark grey clay	60	Negative
Penelas	PNL1A	0623481/4713093	Grey clay	60	Negative
Penelas	PNL1B	0623481/4713093	Grey clay	60	Negative
Penelas	PNL1C	0623481/4713093	Grey clay	60	Negative
Penelas	PNL1D	0623481/4713093	Grey clay	60	Negative
Penelas	PNL2A	0623481/4713093	Grey clay	60	Negative
Penelas	PNL2B	0623481/4713093	Grey clay	60	Negative
Penelas	PNL2C	0623481/4713093	Grey clay	60	Negative
Penelas	PNL3A	0623481/4713093	Grey clay	60	Negative
Penelas	PNL3B	0623481/4713093	Grey clay	60	Negative
Rebolleira	RBL1	0637464/4742384	Grey clay	60	Negative
Rua Uxío-Novoneira	UXI1	0622619/4712535	Sand and grey reddish clay	60	Negative

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analysis and data referenced from geophysical studies or boreholes located in the Tertiary depressions.

5. PALAEONTOLOGICAL DATA RESULTS

Armea de Láncara 2 (AML2, UTM 29T 0633998/4745627)
The sample was collected 20 m above base of Toral Fm. in the lower part of the Sarria succession. Armea Member of Brell, 1972, here is composed of clays, lutites, marls, calcareous soils and lacustrine limestones up to 1.5 m thick.

Goián 1 (GOI1, UTM 29T 0636151/4741688)
The sample was collected in the lower part of the Sarria succession, 110 m above the AML2 sample, the lower part of Fuenteabuin Member of Brell, 1972, in this area comprising clays and lutites.

5.1. Systematic Paleontology

Material and measurements (in units of 0.1 mm). The specimens are stored in the 'Instituto Geológico y Minero de España, in Madrid'.

Armea de Láncara 2

AML2 1, *Pseudocricetodon* aff. *montalbanensis*, m1 dext., 14.0 x 9.8, Figure 5b
AML2 2, *Issiodoromys* cf. *minor*, m1, 2 sin., full crown size: 16.5 x 15.7, height 16.5, Figure 5, a1, a2
AML2 3, *Issiodoromys* cf. *minor*, m3 dext., width 16.3;
AML2 4, *Issiodoromys* cf. *minor*, m1, 2 sin., width 14.9
AML2 5, *Issiodoromys* cf. *minor* ?, p4 dext., 20.7 x ?, occlusal 15.7 x ?
AML2 6, *Issiodoromys* cf. *minor* ?, m1, 2 dext., >16.5 x ?

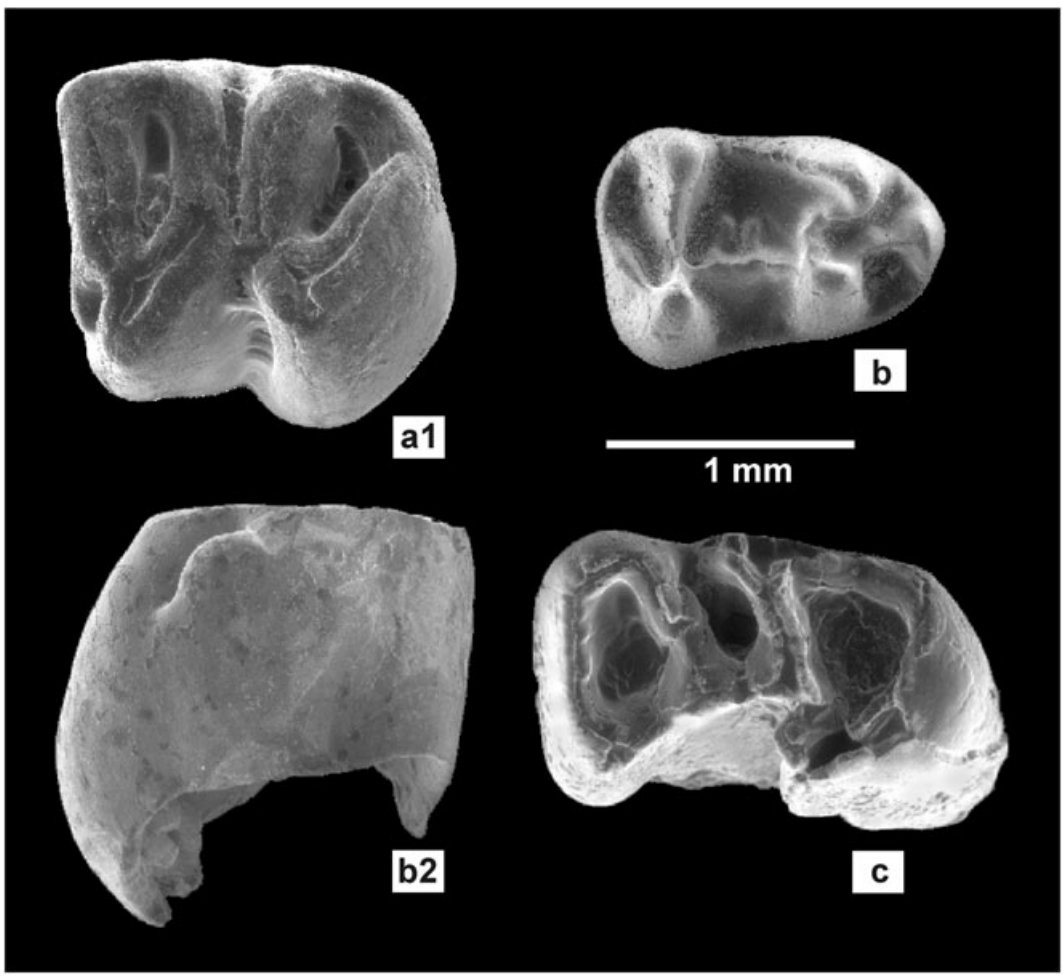


Figure 5. Armea de Láncara 2: (a) *Issiodoromys* cf. *minor*, m1, 2 sin., AML2 2, a1: occlusal view, a2: anterior view. (b) *Pseudocricetodon* aff. *montalbanensis*: m1 dext., AML2 1. Goián 1: (c) *Theridomys* sp. or *Issiodoromys minor* 3, m1, 2 sin., GOI1 1. Scale bar is 1 mm.

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Pseudocricetodon aff. *montalbanensis*

This well-preserved, unworn m1 has an anteroconid that is considerably lower than the protoconid, the lingual anterolophid is low, the labial anterolophid is absent; the anterolophulid is a curved ridge between protoconid and anteroconid. The (anterior) metalophulid is absent, the protoconid hind arm is high connected to the metaconid, forming a wide bend. The sinusid is transverse and open. The mesosinusid is closed by the ridge descending from the metaconid. The ectolophid is longitudinal, without a mesoconid. There are two low mesolophids of medium length and no ectomesolophid. The hypolophulid is anterior transverse, the posterosinusid is closed by the low posterolophid.

This specimen is close to *P. montalbanensis*, especially as indicated by the bend of the hypoconid hind arm and the double mesolophid, but it is somewhat larger. An unambiguous determination of this single specimen is not possible since most morphological features of *Pseudocricetodon* are shared with other species. The oldest record of the genus is *Pseudocricetodon* sp. from Montalbán 3C (MP22, Freudenthal *et al*., 1992); the youngest Oligocene record is *P. thaleri* from Coderet (MP30, Hugueney, 1969) and it is known from Estrepouy (Miocene, MN3; Hugueney and Bulot, 2011).

Issiodoromys cf. *minor*

The m1, 2 has exactly the same size as the mean values of *I. bergidensis* (Freudenthal *et al*., 2010), but a fundamental difference is the presence of an anteroconid, separated from the protoconid by a small antesinusid. Mödden (1994) stated that a population may be attributed to *Issiodoromys* when the antesinusid in little-worn specimens no longer reaches the occlusal surface. Our specimen is in one of the first wear stages and in a more advanced wear stage the anteroconid would certainly participate in the wear surface. The anterior half of an m3 and another fragmentary m1, 2 have exactly the same degree of development of anteroconid and antesinusid as the complete m1, 2 from AML2 1.

This morphology places our material at the very transition of *Elfomys medius* and *Issiodoromys*. The oldest occurrence of *I. minor* is from St.-Martin-de-Castillon eb (*Elfomys* aff. *medius* in Hugueney and Mödden, 1996). Schmidt-Kittler *et al*., (1997) named this *I. minor* 1, and considered it to be the first stage of transition between *Elfomys medius* and *Issiodoromys*. It occurs in MP24, in levels probably older than that at Heimersheim.

Two fragmentary specimens are provisionally classified as p4 and m1, 2. The mesolophid in both specimens is reduced to an isolated cusp in the centre of the tooth, a remarkable feature, unknown in other representatives of the Issiodoromyinae. The material is too fragmentary to permit conclusions, but it cannot be excluded that it belongs to a different species.

Goián 1

This locality has produced two unworn specimens:

GOI1 1, m1, 2 sin., total crown 19.5 x 14.2; occlusal 16.0 x 9.1; height 17.5, Figure 5c
GOI1 2, m3 dext., total crown 17.9 x15.2; occlusal 17.7 x 10.4; height 20.4

There is no trace of an anteroconid or antesinusid, and the anterior wall is completely smooth. This excludes its belonging to *I. bergidensis*. The longitudinal crest is not incised in the centre of the molar, and the teeth are much more slender than the specimen from AML2. They are attributed to *Issiodoromys minor* 3, sensu Schmidt-Kittler *et al*., (1997). Dr M. Hugueney, in her review of this paper, remarked that the slender outline and the oblique entolophid indicate they possibly belong to a *Theridomys* sp.

5.2. *Age of the fossiliferous localities*

On the basis of *Issiodoromys* cf. *minor* 1 we place locality AML2 in the lower part of MP24, although an MP23 age cannot be excluded. *Pseudocricetodon* does not provide more detailed age information, but it is not in conflict with this dating. GOI1, on the basis of *Issiodoromys*, is clearly younger than AML2 and may be similar in age to REY3B from El Bierzo (MP25 age, Freudenthal *et al*., 2010; Fig. 4). Identifying the specimens from GOI1 as *Theridomys* sp. does not fundamentally change the dating of this locality.

Adding these new data to the compilation of available published and unpublished ages from the lower Tertiary formations (for location see Figure 2) allows a more robust correlation of sections from the various sub-basins (Fig. 4 and Table 1). The basal formation of the Oviedo Basin (lacustrine limestones, mudstones and evaporites) is Bartonian–Early Priabonian MP16-MP17 (Truyols *et al*., 1991); the Boinás deposits (limestones, clay and marls) are late Eocene–Early Oligocene MP17–MP22 (Álvarez-Sierra and Daams, 1995; De Vicente *et al*., 2007a); the Toral Fm. of El Bierzo (clay, lacustrine limestones and sandstones of arkosic nature) is of late Early Oligocene MP24–MP25 age (Freudenthal *et al*., 2010). The same age is ascertained for the basal formation at Sarria (clays, lutites, marls, calcareous palaeosols and lacustrine limestones; this study) as the lower clay horizons at As Pontes (López-Martínez *et al*., 1993).

6. TECTONIC FRAGMENTATION

The similarities in ages, lithofacies and palaeocurrent orientations between the deposits of the El Bierzo, O Barco, Monforte de Lemos, Sarria, and Vilalba depressions (Fig. 2) suggest the existence of a connected and coeval basin located in the orogen foreland. We interpret such connectivity with

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the present-day Duero Basin during the deposition of the first synorogenic sediments of the Toral Fm. (Herail, 1981; Vergnolle, 1990; Martín González and Heredia, 2011a).

The base of the Toral Fm. is located at a variety of altitudes, from less than 300 m a.s.l. up to 1350 m a.s.l. The lowest altitudes are located at El Bierzo (<300 m a.s.l.), O Barco (<300 m a.s.l.) and Quiroga (260 m a.s.l.). These low altitudes are related to the tectonic pop-down generated between the south-verging thrusts of the CM and the north-verging thrusts of the GLM (Figs. 1b and 6b B–B′). The highest altitudes are located at El Teleno and the Cabrera Mountains in the GLM (e.g. 1350 m a.s.l. at Corporales) and at Ancares in the CM (1260 m a.s.l.). These localities are in the centre of the tectonic pop-up structure of the Ancares Mountains (Figs. 1b, 6b B–B′). However, altitudes of the Tertiary outcrops located to the west, in the Lugo and Terra Cha Plains (e.g. Sarria, Monforte de Lemos and Vilalba) are consistently between 420–460 m a.s.l. (Fig. 6b A–A′). This constant altitude in the less deformed foreland (Terra Cha Region, Martín-González *et al*., 2012b, Fig. 6) could indicate the original deposition altitude of the foreland deposits. This implies a slight inclination of the original foreland basin toward the east, which is consistent with the increase in thickness of preserved Cenozoic sediments toward El Bierzo and The Duero Basin (≈150 in Sarria; ≈200 m in El Bierzo; ≈1500 m in the Duero Basin). This inclination must be related to a thickening of the crustal orogenic wedge of the CM in the same direction (Pedreira, 2004; Pedreira *et al*., 2007) and it is also consistent with the predominantly westward palaeocurrents in the Toral Fm. of the O Barco depression and the western part of El Bierzo. It is also in agreement with the presence of a westerly granitic source area (probably from the Lugo Dome) for the Toral Fm. of El Bierzo and the equivalent of Monforte (Figs. 1c and 7; Capdevila and Floor, 1970). The southern provenance of the palaeocurrents in the upper formations (e.g. Médulas Fm.) is related with the subsequent uplifting of the GLM and the segmentation of the foreland basin (Fig. 7; Martín-González and Heredia, 2011a).

Collectively, this analysis suggests that the Toral Fm. represents distal terrigenous lithofacies, deposited in low gradient areas (Fig. 6b A–A′), with the conspicuous differences in height being related to the uplift of Alpine structures after its deposition (Early Oligocene; Fig. 6b B–B′). The Alpine tectonic uplift of the areas where sediments are preserved is estimated to be 960 m in the CM and 1050 m in the GLM. These are minimum estimates of uplift as Tertiary deposits have been eroded from higher altitude mountain summits.

7. DISCUSSION

The correlation of different Tertiary formations that have been age-dated using different techniques has generated confusion in the past. For this reason, in this study, we have only compared the ages of lower Tertiary formations using palaeontologically derived ages. The studied formations are always deformed and faulted by later Alpine faults. The present-day outcrops are likely to represent structurally isolated inliers that originally were deposited in a connected foreland basin that was subsequently segmented by the propagation of Alpine tectonic activity (Martín-González and Heredia, 2011a). Therefore, the Toral Fm. may be useful for correlation as it represents the basal deposit that represents the initiation of the foreland basin sedimentation.

A correlation displaying the spatial and temporal distribution of the Tertiary lower formations is displayed in Figures 2 and 4. The eastern Oviedo Basin is Bartonian (latest Middle Eocene) in age, while the westernmost As Pontes Basin is latest Early Oligocene. The other Tertiary deposits located in the basins that surround the Cantabrian Mountains (El Bierzo, Sarria and As Pontes) have very similar ages, and deposits in the Oviedo and Boinás Basins are the oldest (Figs. 2 and 4). This distribution can be explained by the westward migration of the tectonic uplift and the associated foreland basin development (Fig. 6). This is in broad agreement with the general migration of the Orogen with oldest preserved deposits being located to the east. In the Ebro Foreland Basin, deposits related to the initiation of Pyrenean uplift are Late Cretaceous–Paleocene in age (Vergés and Burbank, 1996; Anadón and Roca, 1996; Jurado and Riba, 1996; Friend *et al*., 1996; Pardo *et al*., 2004). In the Eocene, a paroxysmal phase of compression was responsible for the uplift of the Pyrenean Mountains and for thin-skinned deformation in its foreland basin (Curnelle *et al*., 1982; Biteau *et al*., 2006). It is important to recognize that during the initiation of sedimentation in the Ebro and Duero Basin, no deposits were recorded in the study area supporting the migration of the foreland basin toward the west.

In the Tertiary depression of Sarria, fossils recovered from the AML2 sample indicate an early MP24 age, though an MP23 age cannot be excluded. Dating of the GOI1 sample clearly indicates a younger age than that of AML2, and may be a similar MP25 age to that interpreted from REY3B the El Bierzo depression (REY3B; Freudenthal *et al*., 2010). It appears that deposits of the Toral Fm. that surround the CM are coeval at El Bierzo, O Barco, Monforte and Sarria (Herail, 1981; Vergnolle, 1990; Martín-González and Heredia, 2011a). Subsequent to deposition, the basin was uplifted, dissected and eroded during creation of the Cantabrian and Galaico–Leoneses Mountains.

The early stage of foreland basin development was located at Oviedo during the Middle Eocene and migrated towards the west and south by the Early Oligocene. At this time the El Bierzo, O Barco, Monforte and Sarria depressions were connected. Subsequent Alpine deformation, led to dissection and fragmentation of the basin and its depositional fill by

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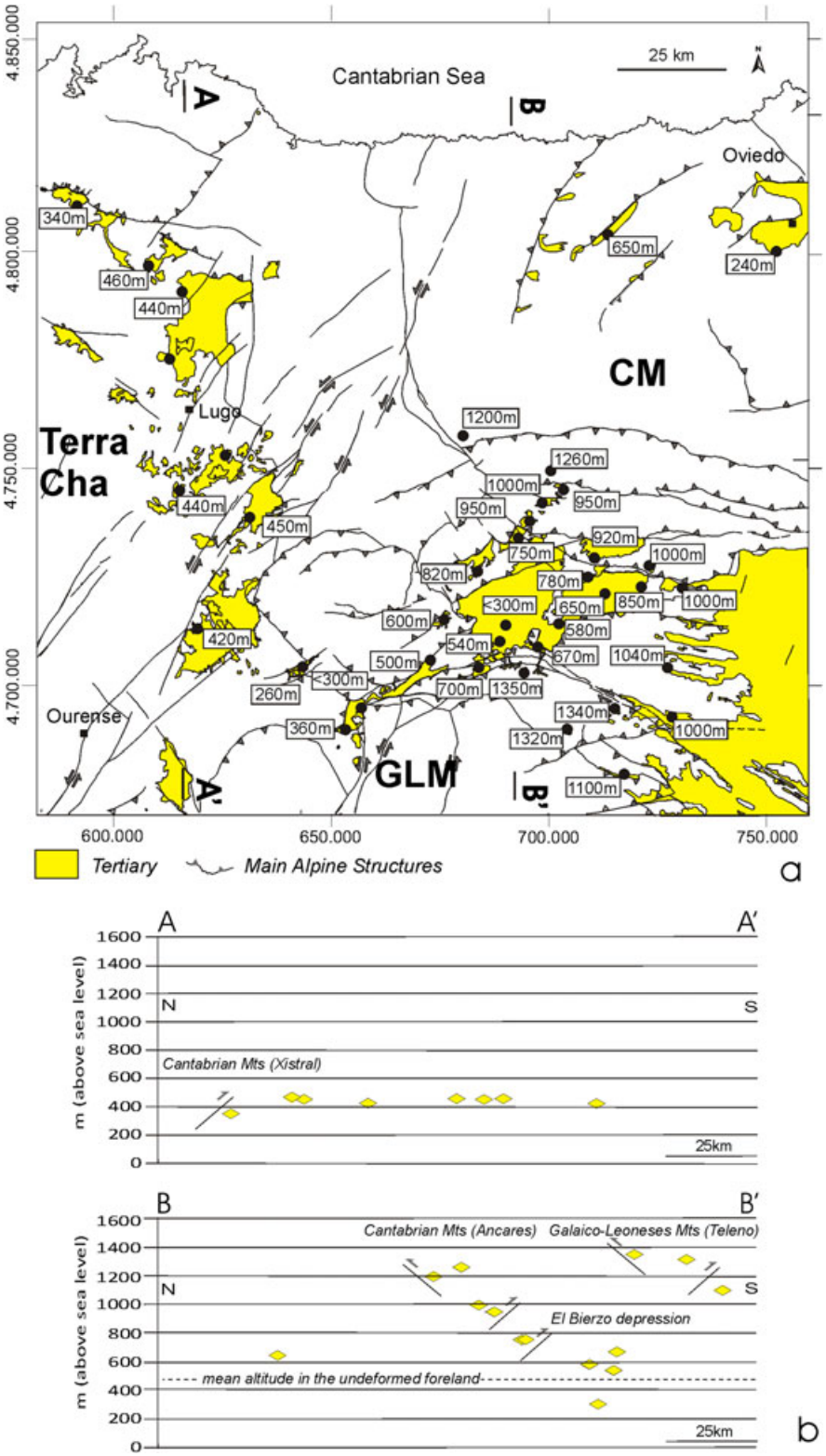


Figure 6. (a) Structural map of the NW Iberian Peninsula showing the altitudes of the base of the Tertiary basal Formation in metres above sea level (UTM zone 29 N) (CM = Cantabrian Mountains; GLM = Galaico–Leoneses Mountains) (b) N–S cross-sections showing the height of the base of the Toral Fm. A–A′ cross section over the sediments less affected by the Alpine structures, showing the original disposition of the foreland basin. B–B′ cross section over the sediments fragmented by later Alpine structures (parallel to the structural cross-section of Figure 1b). Main Alpine structures are also depicted. This figure is available in colour online at wileyonlinelibrary.com/journal/gj

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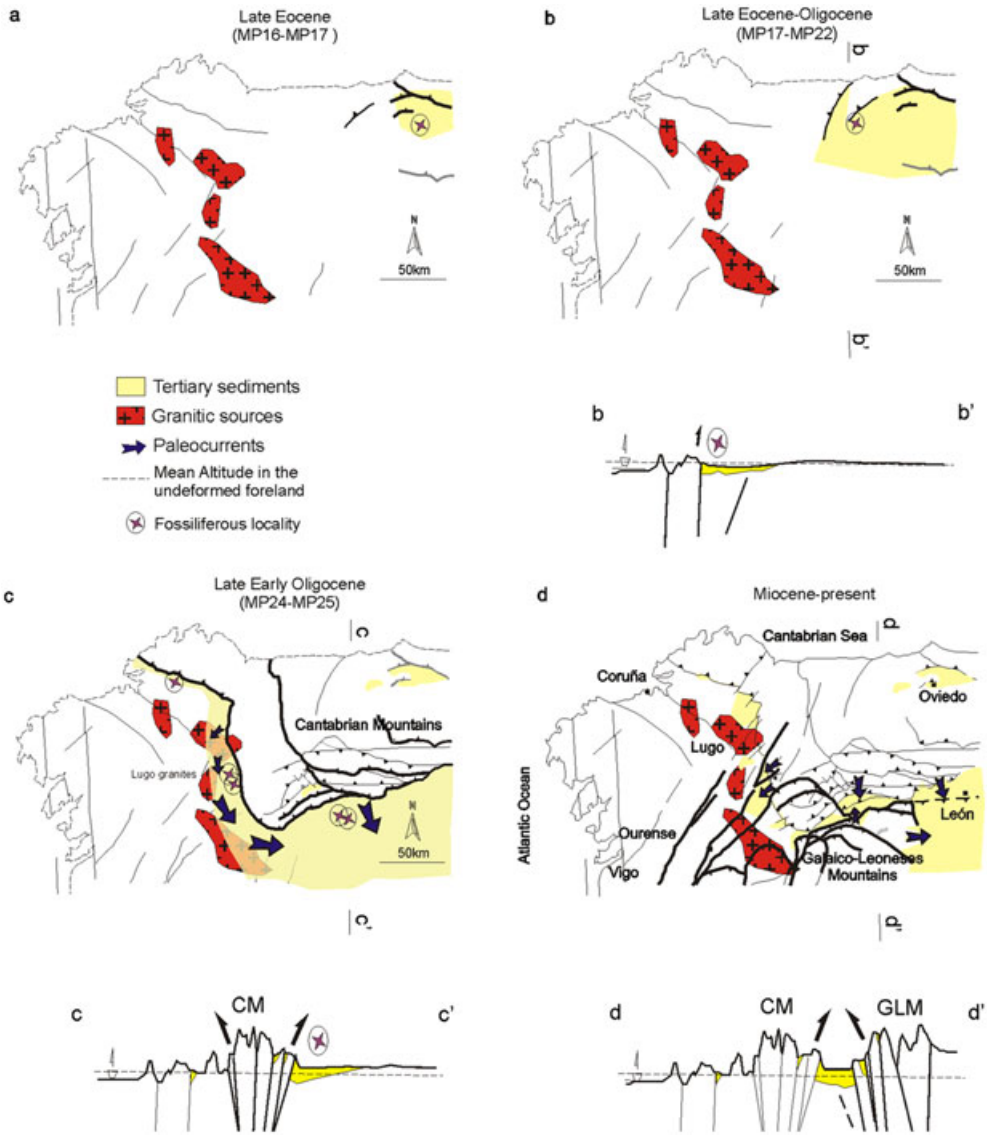


Figure 7. Tectonic and palaeogeographic evolution model for the Duero Foreland Basin, showing the development of the basin and the stepwise progressive migration of the Orogen. Bold lines indicate active structures during each time period. In (c) and (d) arrows indicate sediment transport direction inferred from palaeocurrents and clast provenance. This figure is available in colour online at wileyonlinelibrary.com/journal/gj

Miocene times (Figs. 6 and 7). Apatite fission track analysis (Martín-González *et al*., 2008, 2012b) indicate that uplift of the CM commenced during the Oligocene and continued into Middle to Late Miocene times in the GLM. This is in agreement with data presented in this study (Fig. 7).

Similar structurally segmented foreland basin deposits have been described in the Central Andes, where the foreland basin of the east verging Andes Mountains (Principal, Frontal and Precordillera) was deformed and segmented by uplift of the foreland basement comprising the west verging Sierras Pampeanas (Rodríguez Fernández *et al*., 1999; Ramos *et al*., 2002). Segmentation has also been described in the Ionian Sea region of the Apennine Mountain Belt, where the earlier foreland basin has been deformed and subsequently incorporated into the advancing accretionary wedge (Doglioni *et al*., 1999).

8. CONCLUSIONS

The lower formations (e.g. Toral Fm.) of the main Tertiary depressions in the NW Iberian Peninsula are similar, composed mainly of clay, lacustrine limestones and arkosic sands. They represent the distal lithofacies of ephemeral alluvial fans, alluvial plains and very shallow lakes that developed in front of the Alpine Mountains. The age of these formations in the

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NW Iberian Peninsula varies between latest Middle Eocene in Oviedo to latest Early Oligocene in As Pontes. The date of the lower Tertiary formation in the Sarria Basin is established as latest Early Oligocene on the basis of two fossiliferous localities (AML2 and GOI1). The identification of *Issiodoromys* cf. *minor* 1 and *Pseudocricetodon* places the lower part of the Toral Fm. at Sarria in MP23–MP25, being of similar in age at El Bierzo, MP24–MP25.

The basal Fm. of the Oviedo Basin is Bartonian–Early Priabonian in age (MP16–MP17), that at Boinas is late Eocene–Early Oligocene in age (MP17–MP22), whilst at El Bierzo, Sarria and As Pontes it is late Early Oligocene in age (MP24–MP25; Figs. 2 and 4 and Table 1). The basal Tertiary formations become progressively younger in a westward direction. This is likely a consequence of the westward migration of deformation and accommodation space development associated with the Alpine Pyrenean–Cantabrian Orogen.

The similarities in lithofacies, tectonic relationships, palaeocurrents and ages between the deposits that surround the CM suggest deposition in a linked, embryonic foreland basin. This basin was later segmented and uplifted during Alpine structure generation as the deformation front propagated to the west and south. In the less deformed areas of the Terra Cha Region and the El Bierzo depression (Fig. 6), the present-day altitude of the base of these deposits ranges from 420–460 m a.s.l. to 300 m a.s.l. However, in the areas deformed by the Alpine structures they can reach altitudes of 1350 m a.s.l. After Early Oligocene times, minimum tectonic uplift of 960 m occurred in the CM, with 1050 m in the GLM.

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