

# Geologic map of the Basque-Cantabrian Basin and a new tectonic interpretation of the Basque Arc

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**Abstract** A new printable 1/200.000 bedrock geological map of the onshore Basque-Cantabrian Basin is presented, aimed to contribute to future geologic developments in the central segment of the Pyrenean–Cantabrian Alpine orogenic system. It is accompanied in separate appendixes by a historic report on the precedent geological maps and by a compilation above 350 bibliographic citations of maps and academic reports (usually overlooked or ignored) that are central to this contribution. Structural scrutiny of the map permits to propose a new tectonic interpretation of the Basque Arc, implementing previously published partial reconstructions. It is presented as a printable 1/400.000 tectonic map. The Basque Arc consists of various thrust slices that can expose at the surface basement rocks (Palaeozoic to Lower Triassic) and their sedimentary cover (uppermost Triassic to Tertiary), from which they are detached by intervening (Upper Triassic) evaporites and associated rocks. The slice-bounding thrusts are in most cases reactivated normal faults active during Meso-Cenozoic sedimentation that can be readily related to basement discontinuities generated during the Hercynian orogeny.

**Keywords** Basque-Cantabrian Basin · Basque Arc · Pyrenees · Cantabrian Mountains · Spain · France

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## Introduction

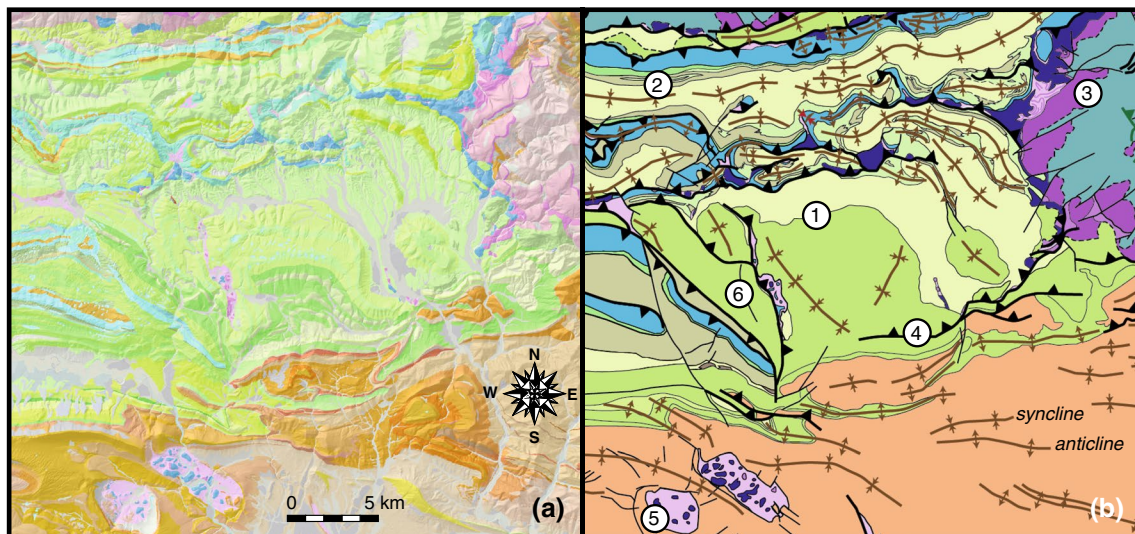
Geology emerged as an independent scientific discipline in the early nineteenth century after the complex relationships of continuity and superposition between rock strata and formations were gathered and represented graphically in internally consistent geological maps (Álvarez 2004). It was William Smith who published in 1815 the first geological map in a modern sense. The map gathered in a single document countless local and regional observations (Smith 1815; Winchester 2002) and expressed correctly the regular order in which the rock strata of southwest England and Wales appear, including their fossil content and topographic expression. It represented as well an essential tool for both geological interpretation and prediction, as the geometrical relationships between distinguishable rock formations were “readable” and permitted to reconstruct cross sections depicting the superposition order of formations, their current disposition, their overprinting by faults, folds, intrusions, unconformities, etc.

Construction of a geological map is a complex process that involves analysis and synthesis. A geological map records and represents a selection of lithostratigraphic units and contacts based upon their continuity and cross-cutting relationships. Its study and interpretation following some basic rules permit to unravel geometrical and historical (a sequence of geological events in chronological order) derivatives, thus being capable of representing in a sheet the four-dimensional space-time. A geological map is inherently an unfinished or incomplete document. It can be continuously implemented or revised in the light of new theories or complementary data. Because of this, it is often a matter of debate and scientific controversy. Additionally, geological maps can be drawn at several scales, from the most detailed (1 cm in the map to 1 m in the real world,

or 1/100) to the most synthetic (e.g. 1 cm to 100 km, or 1/10.000.000). The latter permit the observer to acquire a general idea of the principal elements that constitute a given crustal sector (representing a geographical area, a microplate or even a continent), while the former permit to decipher the fine geological structure and make reasonable predictions on the distribution of rock units in the subsurface or even above the earth's surface (in spite of currently being eroded rocks).

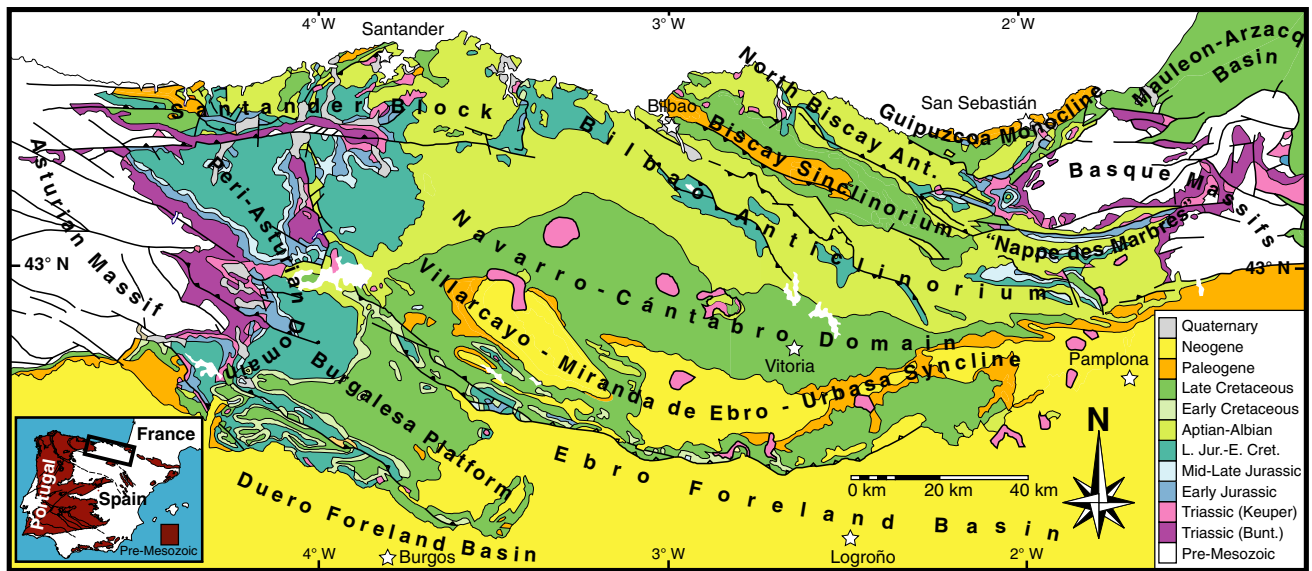
Drawing a synthetic geological map of any major crustal domain tens to a few hundreds of km in horizontal dimension, such a sedimentary basin or an orogen, commits several decisions either related to the use of the base maps available, the geological aspects that the author aims to emphasize, the units that would be mapped (and omitted), or the colours and patterns with which they should be identified (Reed 2007). A basic must is to represent as accurately as possible the extension (areal distribution) and mutual relationships of the rock units by fixation of their contacts. The subsequent interpretation of the nature and attitude of those contacts may not be unique (e.g. Fig. 1) but, in any case, can lead to more or less successful predictions of rock distributions to certain depths in the subsurface.

The geological map of the Basque-Cantabrian Basin (BCB) presented in this study (supplementary file 1) relies massively in previously published maps and geological research. In the first part of the manuscript, this background is described as a due tribute for two reasons. First, because so far such a compilation (Appendices 1 to 9) has never been made available to the scientific community in a scientific journal and cannot be gathered from any single bibliographic database. Second, because, following the analogy drawn by the philosopher Bernard of Chartres (Bernardus Carnotensis, died after 1124) recorded by John of Salisbury in his “Metalogicon” (1159): we can see further than our predecessors because we are lifted on their gigantic stature, as dwarfs perched on their shoulders (“Dicebat Bernardus Carnotensis nos esse quasi nanos, gigantium humeris insidentes, ut posimus plura eis et remotiora videre, non utique proprii visus acumine, aut eminentia corporis, sed quia in altum subvenimur et extollimur magnitudine gigantea”). In the second part of this contribution, the map characteristics represented are explained, together with the criteria supporting that election. As a corollary, it is presented in the third part a new proposal for the tectonic organization of the “Basque Arc” (Feuillée and Rat 1971), the most prominent geological feature of the northern BCB (Fig. 2).



**Fig. 1** Two contrasting versions of the geological map of the same area (approximately between 1°32′–1°58′ longitude W, and 42°52′–43°08′ latitude N). **a** Graphical representation of the outcrop distribution of various geological units in this digital map shows accurately the extension of the units and fixes their mutual contacts. A conventional colour code (*pink tones*: Triassic; *blue tones*: Jurassic, *green tones*: Cretaceous; *orange and earth tones*: Tertiary) is used to map those units on a *grey-shaded* relief base map. The represented quadrangle corresponds to the western area of the BCB, essentially in Navarre (source: [www.geologia.navarra.es](http://www.geologia.navarra.es)). **b** Conventional geo-

logical map of the same area that uses a similar colour code for a simplified categorization of the geological units represented (source: supplementary file 1 from this study) and adds further information on the nature of their contacts using six types of lines (numbered 1–6) to differentiate them (1 conformable lithological contact; 2 lateral facies change; 3 unconformity; 4 thrust; 5 diapiric mechanical contact; 6 normal/wrench fault). The second representation mode facilitates substantially the map interpretation in terms of stratigraphic and structural relationships



**Fig. 2** Geological sketch map of the BCB. The curved structures labelled in the top-right map corner conform the so-called Basque Arc. See text for further details

## The geological mapping background of the Basque-Cantabrian Basin

### The Basque-Cantabrian Basin

The Basque-Cantabrian Basin (BCB) is a geological constituent of the Bay of Biscay-Pyrenean realm (see Barnolas and Pujalte 2004, for further details on this realm's organization and terminology). Its precise definition can be a matter of debate because, in detail, it comprises various minor ranges and subbasins, and its palaeogeographical context exceeded during various geological periods its current limits. As a result, several terms have been used before to name it, such as “Cantabrian”, “Basque Pyrenees”, “Western Pyrenees”, “region”, “ranges”, “mountains”, “margin”, “passive margin”, “basin”, “domain”, “realm”, and their more or less accurate translations in French, German, Spanish and Basque languages. The name adopted here (Basque-Cantabrian Basin, acronym “BCB”) is the most frequent in the regional bibliography and can be readily found in document titles and figure captions. It is customarily assumed that the BCB is a major geological entity that was initiated as a peri-cratonic rift related to Mesozoic opening of the North Atlantic/Gulf of Biscay. It experienced extensive faulting and high subsidence rates during the Cretaceous and was inverted during Tertiary compression related to the Alpine orogeny (Mangin and Rat 1962; Rat 1988; García-Mondéjar et al. 1996; Cámara 1997; Gómez et al. 2002).

Currently, the BCB is considered a segment of the Pyrenean system (e.g. Tugend et al. 2014), which extends with a

E–W trend from the Mediterranean border between France and Spain (meridian 3°E) to the western end of the North Iberian margin (meridian 11°W). This segment connects two major geographical features: the Pyrenees and the Cantabrian Mountains.

From a geological viewpoint, it presents an ample onshore domain and a smaller domain offshore, currently under the Cantabrian Sea (the Atlantic Ocean in the inner corner of the Bay of Biscay). Complementary to its northern geographical boundary, the BCB southern boundary corresponds to a thrust equivalent to the south Pyrenean thrust (e.g. Choukroune 1992) along most of its central segment. However, towards the E and the W this structure is obscured and complicated by syn-sedimentary tectonism and by interactions with salt and wrench tectonism (e.g.: Larrasoña et al. 2003; Serrano and Martínez del Olmo 2004; Tavani et al. 2013; Carola et al. 2015). The BCB western boundary is geologically well defined and marked by the outcrops of pre-Mesozoic rocks from the so-called Asturian Massif (actually the Cantabrian Zone of the Iberian Hercynian Massif; Ábalos et al. 2002). On its hand, the BCB eastern boundary is more complicated and is loosely related to the long-debated geographical termination of the Western Pyrenees (cf. Olagüe 1951; Lamare 1952). At first sight, the outcrops of the pre-Mesozoic Basque Massifs might represent a geological limit equivalent to the western one. However, to the north and south of those massifs the Mesozoic and Cenozoic units of the BCB extend as a continuum into the allochthon North Pyrenean (Mauléon Basin) and South Pyrenean (Pamplona-Jaca Basin) zones.

In a wider tectonic scenario, the BCB has a southern foreland along the corridor connecting the Ebro and Duero Tertiary basins and a northern (Aquitaine) foreland. This comprises onshore and offshore segments of the Arzacq-Parentis rift systems (Jammes et al. 2009, 2010; Masini et al. 2015) and, westwards, the Cantabrian submerged margin of the Iberian microplate. This ensemble is currently considered as made of hyper-extended rifted domains, thinned lower continental crust, exhumed subcontinental mantle and oceanic crust (Boillot and Malod 1988; Fernández Viejo et al. 2011; Roca et al. 2011; Tugend et al. 2014).

Published geological syntheses of the BCB include classic papers such as Ciry et al. (1967), Feuillée and Rat (1971), Rat (1988) or Cámara (1997), state-of-the-art compendiums gathering significant research results, such as Aurell et al. (2002), Martín Chivelet et al. (2002), Barnolas and Pujalte (2004) and Robles (2014), and, from a divulgating perspective, the handbooks of Debouche and Deloffre (1976), Baceta et al. (2012) and Bodego et al. (2014a, b). Any of these reports might serve as a qualified source of scientific information and a perfect companion for the BCB geological map presented herein.

### Historical background: previous geological maps of the BCB

Leaving apart the countless sketches of the BCB that illustrate most scientific papers or reports, the latest geological map of the BCB with a size large enough as to be considered a map sheet (usually with a side length of several dm) was published more than two decades ago (Martínez-Torres 1993a) at the scale 1/300.000. Two similar precedents, though actually none of them accommodated the full extension of the BCB, are the 1/200.000 maps published by Lotze (1958, who completed his field work between 1930 and 1934; cf. Schroeder and Perejón 2006) and Rat (1959, who begun his field work in 1949; cf. Rat 1998). The 1/500.000 maps of Rat and Mangin (1962) and Rat et al. (1967), covering the whole BCB from the western Pyrenees to Asturias and synthesizing the previous work of the Dijon school, can be considered as something intermediate between a genuine map sheet and a geological sketch map. The same can be said of Ramírez del Pozo's (1973a) map of the BCB between the meridians of San Sebastián (ca. 2°00'W) and Unquera (ca. 4°30'W), where the author synthesized the mapping efforts previously completed for various petroleum exploration companies and the Instituto Geológico y Minero de España.

Martínez-Torres (1998) published an exhibition catalogue with a full description of the extant BCB maps, which were displayed (between September 15, 1997 and February 7, 1998) in Vitoria and Bilbao (Spain). Most of

those maps (several originals and some copies) are permanently exposed since 2003 in the Geodynamics Department wing of the Faculty of Science and Technology of the Universidad del País Vasco.

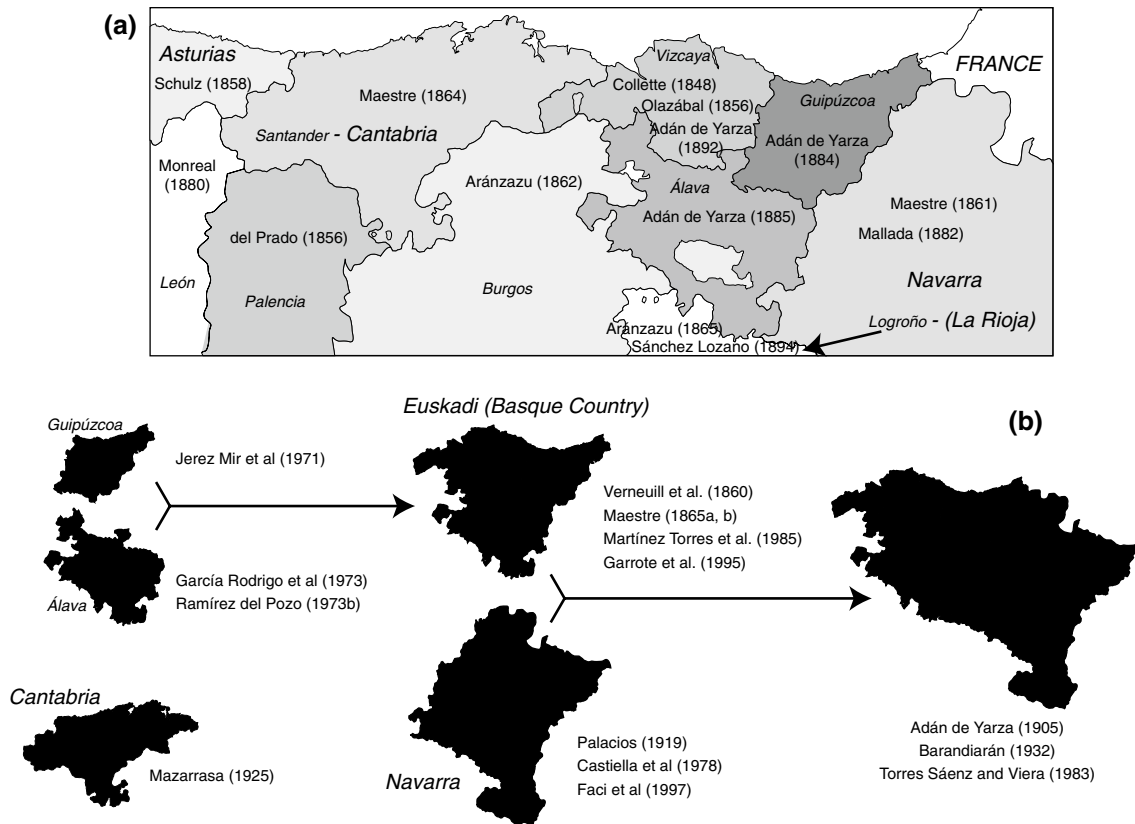
Geological knowledge and sheet maps in which appears the BCB or parts of it can be traced back to 1848, three decades after publication of William Smith's 1815 map (Smith 1815; Winchester 2002) and 14 years after the earliest known geological map of any Spanish region (Boixereu-Vila 2008). These maps have been subdivided here for descriptive purposes into three groups: (1) geological maps of the administrative domains that conform the BCB; (2) maps of the BCB included in very small-scale geological maps of Europe, France and Spain; and (3) geological maps of physically meaningful areas such as quadrangles of various scales and tectono-stratigraphic units.

### *Geological maps of administrative entities within the BCB*

The BCB spreads mostly in northern Spain, a small portion of it cropping out in south-western France. The Spanish portion of the BCB fully contains four of the Spanish provinces established in 1833 by the “Secretario de Estado de Fomento” Javier de Burgos. Those provinces depict intricate boundaries and have historically formed part of higher-rank administrative aggregations (regions or autonomous communities). 1/200.000 scale maps (84 × 111 cm in size) of most of those provinces were compiled and published sequentially between 1848 and 1870 by Francisco Coello, assisted by Pascual Madoz, in the “Atlas de España y sus Posesiones de Ultramar”.

The four provinces mentioned above are Álava, Guipúzcoa and Vizcaya, which integrate the so-called Comunidad Autónoma del País Vasco (also Euskadi or Basque Country), and Cantabria (capital Santander, conforming currently the “Comunidad Autónoma de Cantabria”, though “Provincia de Santander” has usually been used before). Additionally, the BCB spreads in part through another six provinces: Asturias (capital Oviedo), Burgos, Navarra (capital Pamplona), León, Palencia and La Rioja (capital Logroño, “Provincia de Logroño” sometimes being used, too). The BCB in south-western France is included in a single, equivalent administrative entity, the Département des Pyrénées Atlantiques (capital Pau, with “sous-préfectures” in Bayonne and Oloron), created in 1790 after the French Revolution (until 1969 with the name “Basses-Pyrénées”) by inclusion of the former provinces of Béarn, Basse-Navarre and the territories of Labourd, Soule and, in part, Soubestre.

In the mid-nineteenth century, the first Spanish provincial geological maps published include, chronologically (see also Fig. 3), those of Vizcaya (Colette 1848; later re-issued in one tint by Olazábal 1856), Palencia (del Prado



**Fig. 3** **a** Administrative organization of the area occupied by the BCB. Province names (*italicized*) are accompanied by bibliographic references of nineteenth century provincial geological maps. **b** Graph showing the outlines (*filled in black*) of various provinces (names

*italicized*), and of higher-rank administrative combinations of them, for which the geological maps referenced were published (principally along the twentieth century). See text for further details

1856), Asturias (Schulz 1858), Navarra (Maestre 1861), Burgos (Aránzazu 1862), Santander/Cantabria (Maestre 1864a) and Logroño/La Rioja (Aránzazu 1865). Well in the second half of the nineteenth century, new and revised 1/400.000 scale provincial maps were published as constituent parts of the geological map of Spain at that scale, planned in 1870 by the Commission for the Geological Map of Spain. These included Palencia (Monreal 1880), Navarra (Mallada 1882), Guipúzcoa (Adán de Yarza 1884), Álava (Adán de Yarza 1885), Vizcaya (Adán de Yarza 1892) and Logroño (Sánchez Lozano 1894). To my knowledge, no equivalent of these maps was published in France during this epoch.

In the early decades of the twentieth century, some new provincial maps were published, such as those of Palacios (1919) and Mazarrasa (1925). As regards the latter, it was actually unpublished, and it was through Ríos (1949a) that has been acknowledged the existence of a 1/100.000 map of the Santander province (drawn by the aforementioned author), accompanied by seriated cross sections as well as by stratigraphic and tectonic descriptions.

Several decades later, still in the twentieth century, the Spanish provincial subdivision was the basis for publication of various modern geological maps in Álava (García-Rodrigo et al. 1973 at the 1/50.000 scale; Ramírez del Pozo 1973b at the 1/200.000 scale) and Guipúzcoa (Jerez Mir et al. 1971, at the 1/50.000 scale). Navarra, which is at the same time a province and an administrative entity of higher rank (“Comunidad Foral”), has also published 1/200.000 geological maps of its territory as syntheses of previous mapping projects accomplished at the 1/50.000 (Castiella et al. 1978) and 1/25.000 scales (Faci et al. 1997).

The Basque Country (also a “Comunidad Foral”) has also produced a 1/100.000 geological map of its territory (Garrote Ruiz et al. 1995) after completion of a mapping project comprising 73 sheets at the scale 1/25.000. Antecedents of this map are the 1/740.000 map of Verneuil et al. (1860) the 1/400.000 and 1/500.000 maps of Maestre (1865a, b, respectively), and the 1/200.000 map of Martínez-Torres et al. (1985).

Geological maps of “Euskalerrria” (which would include Navarra, the three Basque provinces and parts of southwestern France, Logroño and Burgos) were published since

the early twentieth century. These include Adán de Yarza (1905) at the scale 1/200.000, Barandiarán (1932) at the 1/800.000 scale and Torres-Sáenz and Viera (1983) at the scale 1/200.000.

Currently, 1/25.000 geological maps of Navarra and the Basque Country can be accessed from administrative web-sites: <http://geologia.navarra.es/> and <http://www.eve.es/Aula-didactica/Publicaciones/Geologia/Mapa-Geologico-del-Pais-Vasco-a-escala-1-25-000/Mapa-Geologico.aspx>, respectively.

#### *The BCB in small-scale geological maps of Europe, France and Spain*

The oldest maps that allow identification of the BCB are general geological maps of Europe (Murchinson et al. 1856; Dumont 1857). It is presented there as an area dominated by Cretaceous rocks, located between the westernmost Palaeozoic outcrops of the Pyrenees and the northernmost outcrops of the Iberian Massif in the central segment of the mountains that face the Cantabrian Sea. These maps actually include versions of Verneuil's geological sketches of Spain drawn in 1850, 1853 (second sketch, included in Murchinson's et al. 1856 map) and 1855 (third sketch, included in Dumont's 1857 map). Improved versions were published along the forthcoming years (Verneuil and Collob 1864), together with an independent map by Maestre (1864b). Solé-Sabarís (1983), Aragonés-Valls (2013) and Julivert (2014) provide further details on these maps. Reproductions were compiled by Gutiérrez-Gárate and Rubio-Andrés (2007).

In the late nineteenth century, further progress in geological and cartographic knowledge of the BCB was accomplished, on one hand, by the Spanish "Comisión del Mapa Geológico de España" (after 1870) and, on the other hand, by the French "Service de la Carte Géologique de France" (after 1868).

Spain projected to map its territory at the 1/400.000 scale, and the actual map was presented in the "Exposición Nacional de Geología" (Julivert 2014), actually "Exposición Nacional de Minería, Artes Metalúrgicas, Cerámica, Cristalería y Aguas Minerales", held in Madrid between May and November, 1883. That map was slightly younger than the 1/2.000.000 geological map of Spain and Portugal published by de Botella (1879). Later, Cortázar (1892) and Fernández de Castro (1893) published geological syntheses at the scale 1/1.500.000. The 1893 map shows in a continuum the geology of southern France (south of parallel 44°N) and the Iberian Peninsula (including Spain and Portugal). The map description was presented by Lucas Mallada in seven volumes, between 1895 and 1911 (Mallada, 1895-1911). In this map, the BCB can be recognized as a separate geological entity. Its constituent Palaeozoic,

Jurassic, Cretaceous and Tertiary units are presented with unprecedented detail, though some of its specific geological features, such as the presence of Triassic salt diapirs (Ríos 1948a; Brinkmann and Lötgers 1968), are still absent.

France has a tradition of geological map publications longer than Spain. Actually, it can be traced back to the mid-eighteenth century (Ellenberger 1982). Dufrénoy and Élie de Beaumont published in 1840 a 1/500.000 geological map of France (in six sheets), prepared between 1830 and 1835. Later versions at this scale were published by Carez and Vasseur (1885–1886) and Vasseur and Carez (1889). The geological map of metropolitan France planned in 1868 by the "Service de la Carte Géologique de France" constitutes the first detailed map of that territory, as it was programmed at the 1/80.000 scale in 268 sheets. It was initiated in 1870. However, it was not fully performed until 1925. Renowned French geologists of that time contributed to this project, mapping parts of the Basque Pyrenees and the Cantabrian Mountains during the transition between the nineteenth and twentieth centuries (Stuart-Menteth 1881, 1891; Bertrand 1902, 1907, 1911, 1919; Maury et al. 1905; Termier 1905, 1907; Fournier 1908, 1911, 1913; Termier and Bertrand 1911). While the first geological synthesis of the Pyrenees was being published (Carez et al. 1903–1909), they met in the legendary 1906 "Réunion Extraordinaire de la Société Géologique de France" at Luz-Gavarnie-Les Eaux Chaudes, together with other illustrious Alpine and Pyrenean geologists (Bayley 1935). The aim was to discuss on the possible existence of thrust nappes there (and farther to the west; as would be dealt with in the following years by Bertrand and Mengaud 1912a, b, c; Mengaud 1912) similar to those discovered in the Helvetic Alps at Glarus (Suess 1909, pp. 119–120; Bayley 1935, pp. 45–56; Merle 1994, pp. 15–21). Some of them (A. Bresson, M. Casteras, H. Douvillé, Ch. Jacob and A. de Lapparent) were the mentors or examiners of the forthcoming generations of geologists that would contribute to survey the BCB and the western Pyrenees during the first half of the twentieth century.

The Spanish and French contributions itemized to this point supported Suess' (1909, pp. 243–246) geological descriptions of the Basque Pyrenees. These relate to the composition of the Palaeozoic massifs, to their relationships with the surrounding Meso-Cenozoic sedimentary rocks, and to the structural attitude of those units in relation to Pyrenean trends and the Bay of Biscay coastline. These topics resulted of the ideas and tectonic concepts already put forward by Suess (1875). Refined stratigraphic and structural observations enabled this author to introduce the role of tangential displacements and the concept of structural vergence. From this viewpoint, the eastern portion of the BCB was considered in that epoch as a constituent part of a mountain range or "orogen", and as such appeared explicitly in the 1/800.000 scale map of the Pyrenees

published by de Margerie and Schrader (1892). Note that this map was coeval with Cortázar's (1892) and Fernández de Castro's (1893) 1/1.500.000 geological syntheses reported above, in which the presence of orogens of various ages was not explicitly realized.

The last, and most important, small-scale geological map that can be included in this section is the 1/400.000 map that was exhibited (Truyols 2006) to the 722 attendees to the XIV International Geological Congress, held in Madrid in 1926 (Ayala-Carcedo et al. 2005). This map reoriented to Spain the research projects of various German, French and Dutch geological schools. It appears that it did not occur so as regards Anglo-Saxon schools, attending to the number of publications induced by the congress and published in German, French and Spanish, on the one hand, and to the countries receiving the greatest impact, on the other hand (Ayala-Carcedo et al. 2005; Ribera i Faig 1988). The Congress revolutionized the Spanish geological progress. In the case of the Pyrenees and the Cantabrian Mountains, several disciples and graduate students of the influential German geologist Hans Stille (then at the University of Göttingen) made seminal contributions. Similarly did L. Bertrand, Ch. Jacob and L. Mengaud's students, first from the Universities of Paris and Toulouse and latter from Dijon, Bordeaux, and other universities.

#### *Geological maps of quadrangles and geologically meaningful areas of the BCB*

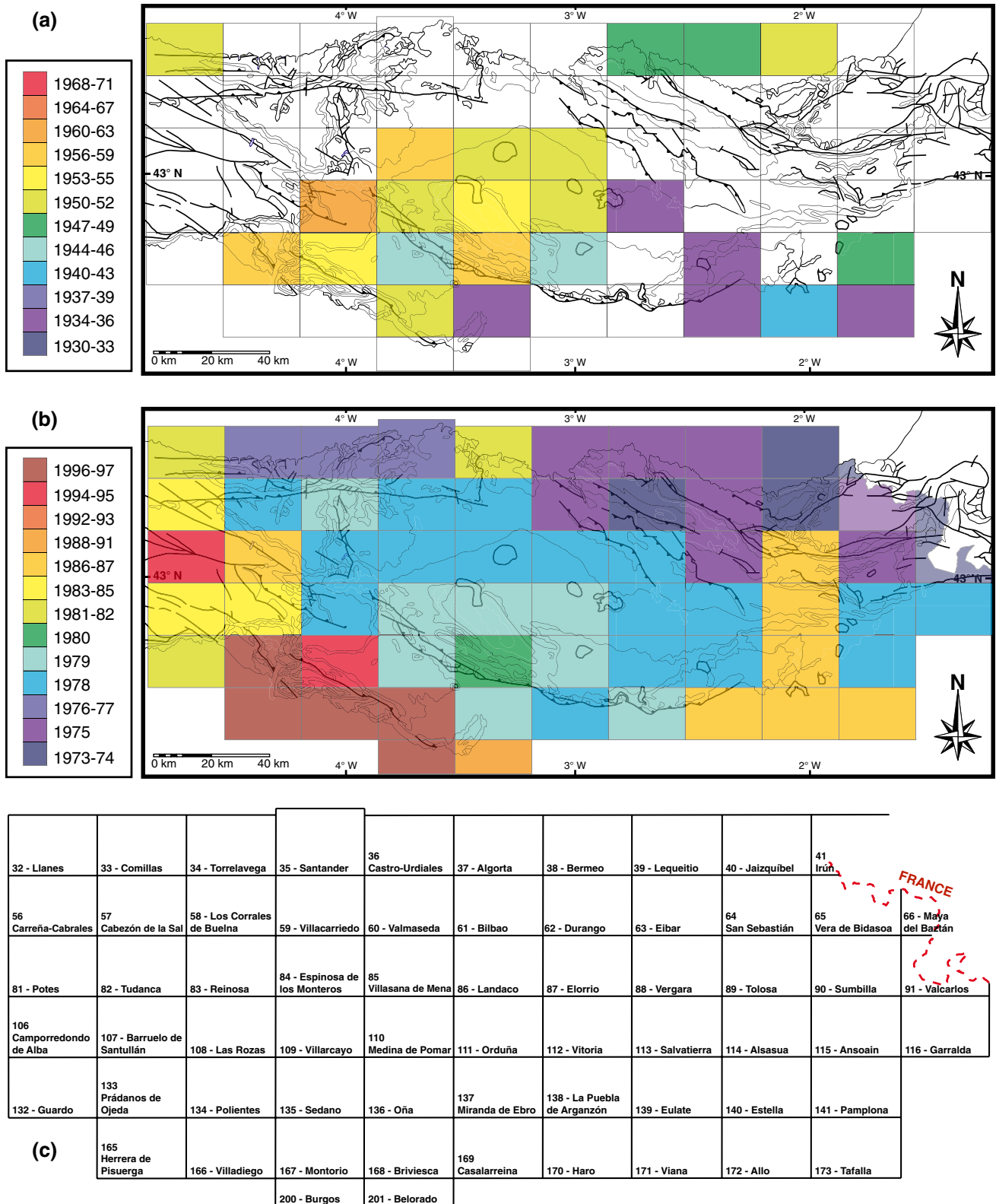
The first map that represents specifically a significant portion of the BCB transcending administrative or political boundaries was published by Verneuil et al. (1860), preceding publication of the Verneuil and Collomb's (1864) map. This is the unique contribution of this type dated in the nineteenth century. The geological maps of the twentieth century that most profoundly reshaped the geology of the BCB were published essentially after the 1926 XIV International Geological Congress. These can be categorized in three groups: (1) quadrangle maps that cover systematically the full national territories of Spain and France and the syntheses resulting from them (performed by Government-dependent, non-academic institutions), (2) maps resulting essentially from academic research projects that concentrate on specific geological units and (3) maps related to, or derived from the two previous categories, resulting from ongoing research or special events.

*Official national territory geological maps* The Spanish "Instituto Geológico y Minero" planned in 1927 the project of mapping Spain's conterminous territory (plus the Balearic and Canary Islands) at the scale 1/50.000. It would consist of 1130 sheets, and the first of them was actually published in 1928 (Rodríguez-Fernández 2005). As shown

in Fig. 4a, some sheets of this project belonged to different areas of the BCB (24 sheets, notably from Álava, the North of Burgos and the South of Navarra) and were published intermittently between 1928 and 1963 (see Appendix 1 for a full reference description of these maps). However, when the project was shut down in 1971, only 442 sheets had been published (ca. 40 %). The forthcoming 1/50.000 mapping project is known as the "Plan MAGNA" (after "MA"pa "G"eológico "NA"cional). It was formally planned between 1968 and 1970, and, as a first commitment, it accomplished a 1:200.000 geological mapping synthesis fully deployed between 1971 and 1972 with publication of the 86 sheets covering the territory. Those documents summarized as homogeneously as possible the geological cartographic knowledge gathered at that time in order to highlight the flaws and shortages. The full set of MAGNA sheets (1130) was deployed between 1972 and 2003. Their history, scientific and economic impact were analysed by García-Cortés et al. (2005), Pérez-Estaún (2005) and Rodríguez-Fernández (2005). In Fig. 4b and c, the publication date progression and numbering/labelling organization of the MAGNA sheets covering the BCB are shown, respectively. Appendix 2 contains the full reference list of the maps of this series (and their accompanying reports) that were used for preparation of the BCB 1/200.000 map presented here. These maps can be readily accessed in the site: <http://info.igme.es/cartografia/magna50.asp>.

In France, the first 1/50.000 mapping project begun in 1913, comprising 1060 sheets in metropolitan France. From them, 148 were edited between 1925 and 1967. At the same time, several of the 1/80.000 maps from the precedent series were repeatedly edited and improved until 1971. That was the case, as regards the BCB area, of the Bayonne (Maury et al. 1905; Viennot 1922–1923, 1923–1924; Lamare 1929; Lamare et al. 1935) and Saint-Jean-Pied-de-Port sheets (Termier 1907; Viennot 1921–1922, 1922–1923, 1923–1924; Lamare et al. 1954). In 1967, the Bureau de Recherches Géologiques et Minières (BRGM, created in 1959 and grouped with the Service de la Carte Géologique in 1968) was commanded to deploy the current 1/50.000 geological map, which comprises a heterogeneous, so far unfinished ensemble of ca. 1100 sheets often not well harmonized and assembled (since in several cases they are separated by decades). Appendix 3 contains the full reference list of the maps of this series that cover the French sector of the BCB and their accompanying reports (see also Fig. 5a, b), published between 1974 and 2005. These maps can be accessed in the sites: <http://editions.brgm.fr/pre-Carte50.do>, <http://infoterre.brgm.fr/cartes-geologiques> and <http://infoterre.brgm.fr/viewer>.

After 1978, some Spanish Autonomous Communities such as Navarra and Euskadi (Basque Country) created geological surveys. These completed 1/25.000 map

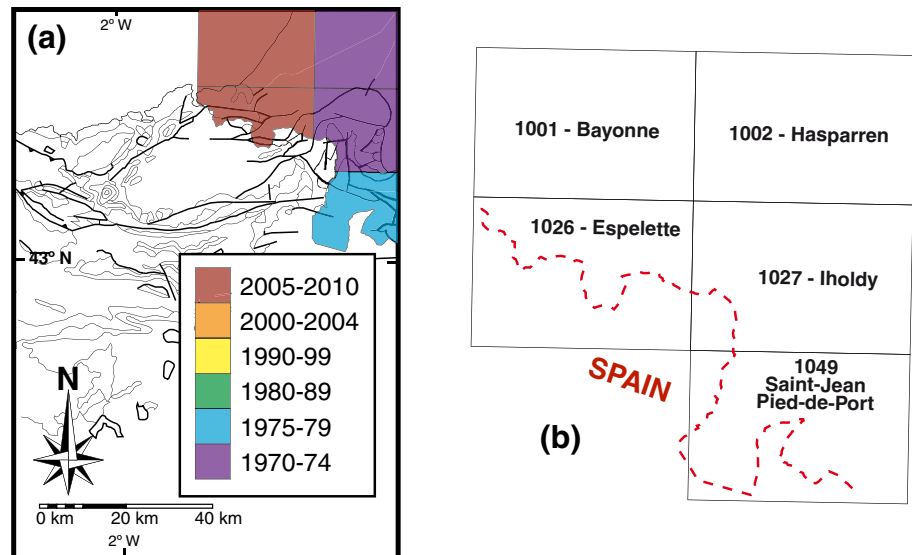


**Fig. 4** **a** Sketch map of the BCB with a superimposed grid showing the 1/50,000 sheet distribution used by the Spanish “Instituto Geológico y Minero” in its 1927 project of mapping Spain’s conterminous territory. The sheets completed before the project was shut down in 1971 are presented with a colour code according to their

publication date. **b** Idem as **a** for the MAGNA project, fully deployed between 1972 and 2003. **c** Reference chart presenting the numeration and names of the MAGNA 1/50,000 sheets. See text for further details



**Fig. 5** **a** Sketch map of the French portion of the BCB with a superimposed grid showing distribution of the 1/50.000 sheets used in this study (source: “Bureau de Recherches Géologiques et Minières”). The sheets are shaded with a colour code according to their publication date. **b** Reference chart presenting the numeration and labelling of the 1/50.000 sheets. See text for further details



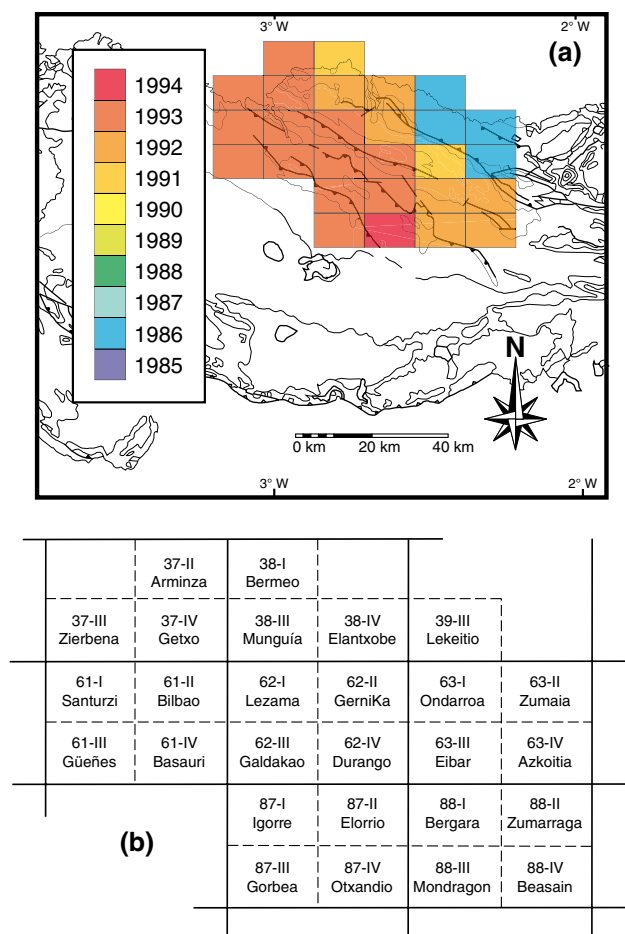
series of their territories that were already mentioned in Sect. 2.2.1. In several cases, the same geologists involved in the MAGNA 1/50.000 project completed them. Appendix 4 contains the list of the maps used here as a complement or in substitution of obsolete 1/50.000 MAGNA sheets. Figure 6a and b depicts the progression in their publication date and numbering/labelling organization.

*Academic geological maps* So far, above two hundred dissertations and doctoral theses devoted to the geology of the BCB have been completed, in its greater number from French, German and Spanish Universities. These contributions usually contain cartographic documents that improve the knowledge of specific geological units. Their number has grown exponentially along the last four decades, together with their degree of insight, focus and detail. The hundreds of scientific articles that have resulted from these original academic reports have been published in various languages in regional, national and international journals. Their number also exhibits an exponential growth in the last decades. They are relatively easy to search for, to trace and usually to access in scientific digital databases, as they irradiate from the original academic report author's name. In general, they will not be cited in this contribution unless they imply a specific important appointment.

The earliest of this type of contribution is committed to Carez (1881), whose “Thèse” was defended at the University of Paris and contained a map where he represented geological observations gathered in several places of the southern Pyrenees from Barcelona to Bilbao. Before 1950, most of the French “Thèses” pertained to the University of Paris and a few to Lille and Toulouse Universities (e.g.: Larrazet 1896; Mengaud 1920; Viennot 1927; Lamare 1936; Ciry 1940). After 1950, other French universities (summing up ten) were involved. Appendix 5 presents a list

of seventy contributions of French authors, dated between 1881 and 2014. The seminal stratigraphical work of Ciry (1940) and his disciples from the Université de Dijon (Rat 1957; Mangin 1958; Feuillée 1967), who launched a second pulse of academic contributions between 1970 and 1991 (Duvernois et al. 1972; Floquet and Rat 1975) were remarkable as regards the Cretaceous and Palaeogene rocks of the BCB. The schools of Toulouse and Paris, on their side, had a profound influence on the stratigraphy, palaeontology and structural geology of the western Pyrenean Palaeozoic massifs and their Mesozoic cover/aureoles (e.g.: Muller and Roger 1977, and references therein). For the sake of graphic simplicity, Fig. 7 presents the areas covered by the most relevant contributions before 1977.

The contribution of German Universities begun after the XIV International Geological Congress of Madrid, held in 1926. Appendix 6 presents the seventy-five contributions I have managed to gather, issued between 1930 and 2003. Figure 8 presents the areas covered by the most relevant contributions before the early 1980s. In several cases, this is unpublished material and, possibly, other similar contributions exist that I have failed to identify. The oldest dissertations are those of Hans Stille's students in Göttingen, whose works (coeval though independent of the ones of the French school) were intended to test Stille's (1927) hypothesis (his Fig. 1e, p. 23) on oroclinal bending and connection (thereafter discarded) between the Pyrenees and the Iberian Ranges in Spain. Two of those dissertations deal specifically with significant parts of the BCB (Schriel 1930; Karrenberg 1934). Several geological contributions of Lotze (also a Stille's disciple) to the geology of the BCB are also of this epoch and were aimed similarly. A most remarkable cartographic contribution was Lotze's (1958) map of the BCB (25.000 km<sup>2</sup>). It was mapped between 1930 and



**Fig. 6** **a** Sketch map of the north-central portion of the BCB with a superimposed grid showing the distribution of the 1/25,000 sheets used in this study (source: “Ente Vasco de la Energía” mapping project of the Basque Country). The sheets are shaded with a colour code according to their publication date. **b** Reference chart presenting the numeration and labelling of the relevant 1/25,000 sheets. Their organization is based upon the Spanish 1/50,000 sheet distribution (see Fig. 4). See text for further details

1934, before the Spanish Civil War (1936–1939), but it was published in 1958, long after the World War II ended. The cause of this delay was that he lost the map and most of the related explanations (except his original field notes and cross sections) as the Allies of the Soviet 3rd Ukrainian Front captured Vienna (2–13 April 1945), where he had been appointed Director of the Austrian Geological Survey (cf. Schroeder and Perejón 2006). Among the contributions that have not been cited previously, there are remarkable Lotze’s (1931a, b) papers on the geology of the aureole of the Basque Palaeozoic massifs, which were being also surveyed independently by Lamare (1927, 1931). Seven of Lotze’s disciples from the University of Münster completed their dissertations between 1962 and 1966 in areas and topics related to the BCB (von Raumer 2008). Also, remarkable was Lotze’s seminal work on diapirism (Lotze 1934,

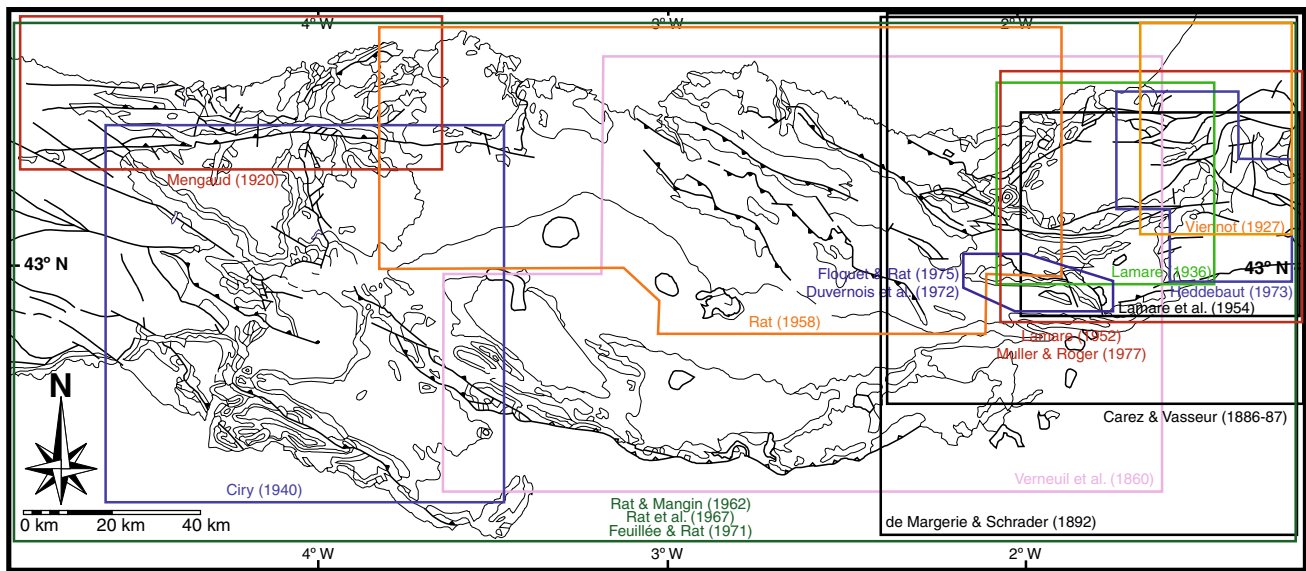
1936, 1938, 1953), which identified for the first time as diapirs some Triassic salt outcrops of the BCB. These were being interpreted as disturbed strata subconcordant under a younger sedimentary cover by contemporaneous authors (e.g.: Mendizábal and Cincúnegui 1932; de Jorge 1933; de la Peña 1935). Lotze’s work opened in the upcoming decades further investigations of Spanish (Ríos 1948a, 1952) and German geologists on diapirs. The latter were launched by Brinkmann, a Stille’s collaborator in Göttingen, and by his disciples from the University of Bonn (Brinkmann and Lötgers 1968, and references therein). After 1957, the German universities involved in the study of the BCB were principally those of Bonn, Clausthal, Heidelberg and Münster (before the early 1980s) and later Berlin, Freiburg and Tübingen (see Appendix 6).

Contributions of non-Spanish universities different from those cited above are unusual. Appendix 7 lists only four dissertations, completed between 1975 and 1999.

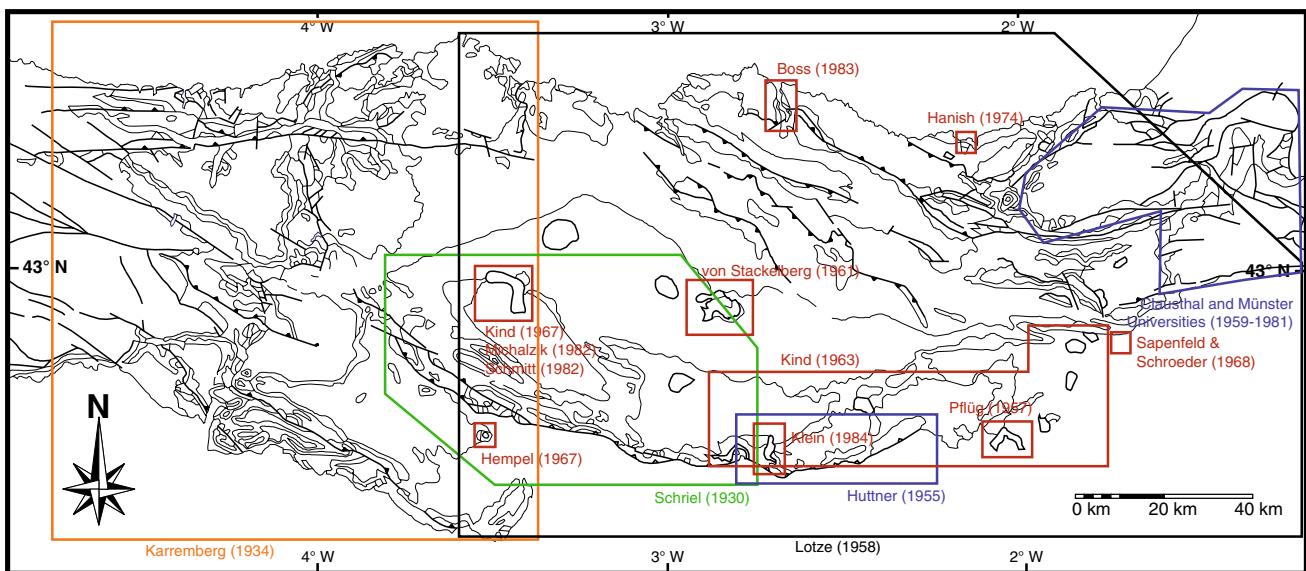
Spanish academic institutions are responsible for one hundred contributions. From them, 28 correspond to “Tesis Doctorales” and “Tesis de Licenciatura” issued between 1934 and 2014 (though most often after 1985), notably in the Universities of (in decreasing frequency) Zaragoza, Barcelona and Oviedo (Appendix 8). The remaining seventy-two contributions raised from the University of Bilbao, founded in 1968 and renowned as “Universidad del País Vasco/Euskal Herriko Unibertsitatea” (acronym UPV/EHU) in 1980. They were devoted to almost any subfield of the geological sciences relevant for the BCB after 1975 (Appendix 9). Notwithstanding, the most significant are those dealing with its Cretaceous and Palaeogene stratigraphy, remarkably influenced by the seminal works of the school of Dijon. Figure 9 presents the mapping areas covered before 1980 by the pioneers (Campos 1976; Pujalte 1977; García-Mondéjar 1979).

*Maps related to research progress or special events* A first group of maps is related to pioneering work related to the contributions reported above, done before the mid-twentieth century. They can be readily identified in the bibliographic compilations that accompany dissertation volumes and map descriptive reports. As regards the geological terrains comprised by the BCB, these early works can be ascribed to three nearly independent sections: (1) investigations related to the Asturian Massif, (2) investigations related to the Palaeozoic Basque massifs and (3) research contributions devoted to the BCB Meso-Cenozoic rocks.

The Asturian Massif has never been regarded as a constituent part of the BCB. In spite of the fact that it conforms the outcropping basement of the BCB, its geology has been related mostly to the pre-Mesozoic Iberian Massif and its Hercynian tectono-sedimentary evolution. Truyols and Marcos (1978) recorded the history of the rich geological



**Fig. 7** Sketch map of the BCB with superimposed polygons showing the areas mapped by French geologists before 1977 (see text for further details)

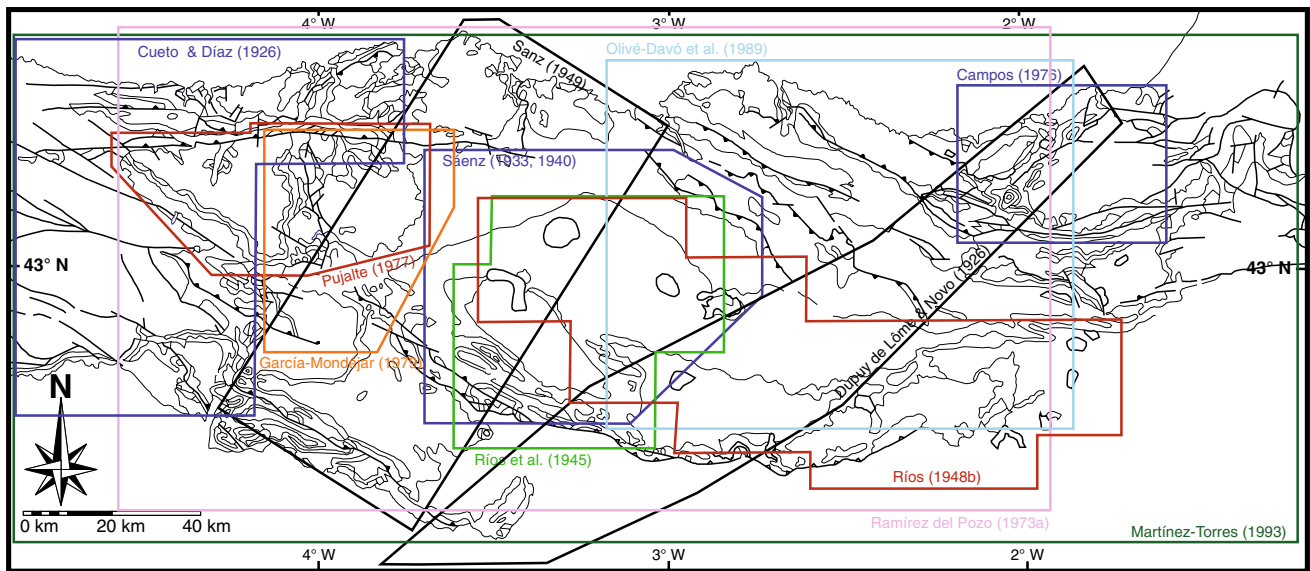


**Fig. 8** Sketch map of the BCB with superimposed polygons showing the areas mapped by German geologists before the early 1980s (see text for further details)

record of this realm, which is related to the external zone of the Variscan orogeny and its superb thin-skinned tectonics. Among the scarce early geological works that consider the relationships between Palaeozoic (basement) and Mesozoic (cover) rocks units, those of Termier (1905), Bertrand and Mengaud (1912a, b, c) and Mengaud (1912, 1920, 1932) concerning the possible existence of thrust nappes in Asturias and Cantabria are remarkable. Kegel (1927), after attending the field trip in Asturias of the XIV International

Geological Congress (Cueto et al. 1926), and latter Hernández-Sampelayo (1949), noticed the defaults of the nappe hypothesis, which had been already discarded. Cueto and Díaz (1926) published a geological map of the Cantabro-Asturian region west of Santander and Reinosa that established the general distribution of Triassic, Jurassic and Cretaceous rocks around the Asturian Massif (Fig. 9).

Contrary to the Asturian massif, pre-Mesozoic rocks of the western Pyrenees have often been included in



**Fig. 9** Sketch map of the BCB with superimposed polygons showing the areas mapped by Spanish geologists before 1980 (see text for further details)

geological descriptions and mapping projects of the BCB. Dubar (1925) recorded most of the early geological works done in the Basque Pyrenees by French geologists, including Stuart-Menteth (1881, 1891), Bertrand (1902, 1911, 1919), Fournier (1908, 1911, 1913), Termier and Bertrand (1911) and Lamare (1921). The Spanish contributions were rare at that time. Hernandez-Pacheco (1947), Busca-Isusi (1953), Heddebaut (1973), Martínez-Torres (1989), Barnolas et al. (1996), Santanach (2008) and Baceta et al. (2012) gathered thorough bibliographic compilations. Detailed geological maps of the Basque Massifs as a geological entity are uncommon in the bibliography. Exceptions are the syntheses presented by Lamare (1952) and Muller and Roger (1977). These contributions (Fig. 7) contain geographical references to the most frequent massif labelling, which distinguishes three major massifs: Cinco Villas to the W, Aldudes-Quinto Real to the SE and Labourd to the NE (see Muller and Roger 1977, for further insight on massif subdivision and alternative massif names).

As regards the mapping projects of parts of the BCB Meso-Cenozoic fill, it should be noticed that the early (pre-mid-twentieth century) French and German contributions were independent, as also were the Spanish with respect to them, in spite of the fact that interactions did exist between the personnel involved. The Spanish contribution includes the mapping projects issued before the flourishing of the MAGNA 1/50.000 maps (Cueto and Díaz 1926; Dupuy de Lôme and Novo 1926; Sáenz 1933, 1940; Ríos et al. 1945; Ríos 1948b; Sanz 1949; Ramírez del Pozo 1973a, b; Campos 1976; Pujalte 1977; García-Mondéjar 1979) and the subsequent syntheses (Olivé-Davó et al. 1989;

Martínez-Torres 1993a). The purpose underlying these projects (Fig. 9) was varied, including notably the construction of infrastructures and hydrocarbon exploration.

## The 1/200.000 geological map of the BCB

### General remarks

The new map presented here shows the onshore bedrock distribution of the BCB between the Asturian and the Basque pre-Mesozoic Massifs (supplementary file 1). This implies, on the one hand, that the geology of the area submerged has not been represented (by contrast with Martínez-Torres 1993a) in spite of the fact that interesting new data are being published (e.g. after Galparsoro et al. 2010). On the other hand, the superficial Quaternary deposits that exist along several rivers, estuaries and slopes have been overlooked, too, in order to highlight the bedrock geological relationships. The hydrographic network has been withdrawn so as not to embarrass the crowded representation of stratigraphic and tectonic contacts, as well of geologic symbols and geographical references. Almost the same can be said as regards the extension of several major towns (in some cases above tens of km<sup>2</sup>), which has been shrunk to a small square near their geometric centre. The exception to screening of anthropogenic features is the representation of principal water reservoirs from dammed rivers. In approximation, the map covers an area of ca. 30.000 km<sup>2</sup> between meridians 1°13' and 4°49'W, and between parallels 42°25' and 43°30'N. This rectangle

contains the BCB as defined by the geological constraints described in Sect. 2.1.

The map was prepared using Adobe Illustrator CS3 version 13.0.1 (2007). The base map used for the cartographic synthesis corresponds in most of its areal extension to 64 MAGNA 1/50.000 sheets (Appendix 1) published by the Instituto Geológico y Minero de España. They were issued between 1974 and 1997, and, in several cases, inconsistencies can be found in the distribution of the units mapped between adjacent sheets. Notably, this is the case for the older ones, covering the western Basque Arc (Fig. 4). As an alternative, in this area 27 1/25.000 maps were used, published by the Ente Vasco de la Energía between 1986 and 1994 (Appendix 4; Fig. 6). As regards the French portion of the BCB, five 1/50.000 sheets were used, published between 1963 and 1978 by the Bureau de Recherches Géologiques et Minières (Appendix 3; Fig. 5). All these digital documents were downloaded directly from the official websites of the cited organizations, which in some cases provided instructions and coordinates for multiple map assemblage. Locally, more recent maps of some small areas published as graphic parts of journal articles were used. These provide significant advances in geological interpretation of some key areas and include the maps already mentioned in Ábalos et al. (2008) together with the published by Hempel (1967), Badillo (1982), García-Mondéjar and García-Pascual (1982), Aranguren et al. (1990), López-Horgue et al. (1990, 1997, simplified version), Cuevas et al. (1999), Cuevas and Tubía (1999) and Carola et al. (2015). In a few cases, some contacts were redrawn using as a base the digital terrain model (DTM) of specific areas (with a grid resolution of 5 m), downloaded from the official site ([www2.ign.es/iberpixmap/visoriberpixmap/visorign.html](http://www2.ign.es/iberpixmap/visoriberpixmap/visorign.html)) of the Spanish “Instituto Geográfico Nacional”.

The base map so composed contains well above 300 different lithostratigraphic s.l. units, which have been merged into less than twenty in the new map. This involved several correlation decisions, as well as reinterpretation of the extension of some units and their contacts. This remains an open question in several cases, and, likely, future research will permit to modify prevalent schemes, as demonstrated by Bodego et al. (2015) for the case of the Early Cretaceous around the Cinco Villas Massif area.

I have chosen to represent in the BCB map chronostratigraphic, lithostratigraphic and unconformity-bounded units (as defined by Salvador 1994), each of which may be particularly useful for certain purposes. Chronostratigraphic units are based on the time of formation of rock bodies. They facilitate large-scale correlations and easy comprehension of their position in the stratigraphic column. Lithostratigraphic units are distinguished by specific lithologic properties and may consist of sedimentary, igneous or metamorphic rocks, or of an association of them. These are

easier to map, though they are areally restricted by the limited extent of the features that define them. Leaving apart the abnormal tectonic contacts, these two (formal) types of stratigraphic units can be bounded above and below by discontinuities in the succession, by their correlative continuities, or simply by concordant contacts. The units represented may correspond to formations or units of higher rank: groups and complexes (in the case of lithological mixtures with complicated horizontal and vertical stratigraphical relationships that difficult their individual mapping). The unconformity-bounded units so distinguished can coincide in some instances with those cited above and have the advantage that they are related to sedimentary cycles usually constrained by tectonism. Sometimes these units correspond to “sequences” (Mitchum et al. 1977, p. 53).

The stratigraphic organization and nicknaming of the units considered are based upon previously published stratigraphic charts of the BCB (Aurell et al. 2002; Martín Chivelet et al. 2002; Barnolas and Pujalte 2004; Robles 2014), and a simplified version accompanies the new map as a part of its legend. The colour palette employed for their graphical representation fits the latest proposal available of the International Chronostratigraphic Chart (version 2014/02; cf. Cohen et al. 2013, updated; <http://www.stratigraphy.org/ICSchart/ChronostratChart2014-02.pdf>). Sporadic departure of this procedure is related to representation of some special lithostratigraphic units: slightly in the case of sedimentary rocks (in which case colours of the same family as that of the hosting chronostratigraphic unit were employed) and markedly in the case of magmatic rocks. This differs from the criterion used in previous maps of the BCB or of its constituent quadrangles.

The election of geographical references and the toponymy has been guided by a personal viewpoint. Since only a selection of localities can be represented in the map, I have chosen to include sites of special geological interest, sites close to the type localities of special units, sites labelling outstanding geological structures, etc. The BCB extends across an area where four languages are used: Basque, Gascon, French and Spanish. In the areas of exclusive Spanish and French linguistic influence, toponyms are spelled in those languages, respectively. There are several localities, however, that can be named in various idioms even outside their area of direct influence (e.g.: Donosti—Saint-Sébastien—San Sebastian, or Iruñea—Pampelune—Pamplona). In fact, any of them has a more or less complete repertoire to label places outside its territory of influence (e.g. Baiona and Bayona for Bayonne). In this case, the principle followed was the adoption of names that appear in the titles of classic bibliographic references, in the base maps used, or that are more or less traditional. In some cases, these names may differ strongly of the current official toponyms

(notably in the Basque Country). Notwithstanding, they are very easy to track after the geographical references included.

### Legend of the BCB map

This section explains succinctly the geological units presented in the BCB map and, when necessary, the reasons for their election. The first appointment is of tectonic nature, since from this point of view a basement, a sedimentary cover and an intervening detachment layer can be distinguished. The basement is composed of Palaeozoic to Lower Triassic rocks that crop out principally in the Asturian and the Basque Hercynian massifs, and in their aureoles. The structural cover comprises essentially sedimentary rocks of Middle Triassic and younger ages. The detachment is associated with Middle–Late Triassic evaporites.

#### *Palaeozoic rocks*

The Palaeozoic sedimentary and metamorphic rocks that conform the exposed basements of the BCB have been gathered within a single unit. This ensemble comprises rocks of Cambrian to Permian age related to the Hercynian orogen of SW Europe. Out of the Asturian and the Basque Massifs' areas, Palaeozoic rock outcrops are restricted to small exposures around Puenteviesgo, to the SW of Garalda, to the SE of Azpeitia and Irún, and along the Leiza Fault between Elizondo and Areso. Rocks older than the Middle Carboniferous were affected by Hercynian deformations, whereas Late Carboniferous rocks conform syn- to post-tectonic units, and the Permian is post-tectonic. The most widely outcropping rocks are of Carboniferous age, and, subsequently, the colour selected for their representation was that used for the Carboniferous in the International Chronostratigraphic Chart. The description of these rocks in further detail is out of the scope of this paper (see, for further details, Muller and Roger 1977; Barnolas et al. 1996; Gibbons and Moreno 2002; Vera 2004).

The outcrop area of relevant stocks of intrusive granitoid rocks is depicted by a standard “cross” pattern. These include the Permian Aya granite from the Cinco Villas Basque Massif (Denèle et al. 2012) and the Peña Prieta, Cueto Iján, Pico Jano and Herrera de Pisuerga stocks of the Asturian Massif, which can sustain peaks with altitudes above 2,000 m above the sea level.

#### *Triassic rocks*

The Triassic is represented in the BCB by germanotype facies rocks, common in western Europe (Robles and Pujalte 2004). These include the siliciclastic, usually reddish Lower Triassic “Buntsandstein”, the calcareous

Middle Triassic “Muschelkalk” and the Upper Triassic evaporitic “Keuper”, which are relatively easy to identify. In the BCB map, three perceptible variations of pink colour have been assigned to the Lower, Middle and Upper Triassic by the International Chronostratigraphic Chart.

Mechanically, the Lower Triassic behaved as a constituent of the BCB basement. Usually it is bounded at its base by an angular unconformity and conforms a thinning upwards siliciclastic sequence whose uppermost terms resemble (and behave mechanically as) the evaporites of the Keuper. This unit is related to the initiation of an aborted Triassic rifting stage (Robles and Pujalte 2004; Robles 2014). Its lower limit is diachronous, and in several places it likely includes rocks of late Permian age. This is the reason why this unit is sometimes referred to as the “Permo-Trias”. On its hand, the Upper Triassic acted as detachment level when involved in tangential tectonism or as the gravitationally unstable trigger of salt structures in diapiric areas (Serrano et al. 1989; Serrano and Martínez del Olmo 1990, 2004). The Middle Triassic occupies its autochthonous chronostratigraphic position in few areas. Commonly it was removed from its position and tectonically reworked together with the Keuper evaporites, resulting in contorted outcrop patterns.

The well-known late Triassic to early Jurassic dolerites (“ophites” in the regional bibliography) are usually associated with the Keuper rocks. A particular deep blue colour was assigned to them, which permits to identify them readily at first sight in the BCB map. In several previous maps, they were collectively represented with the evaporites under a single pattern, which resulted in the false perception of the Keuper evaporites forming thick accumulations adjacent to several tectonic contacts. Representation of these rocks with contrasting colours permits to realize that at some places the ophites conform areally broad stocks or laccoliths (such as Maya del Baztán and Saint-Jean Pied-de-Port), whereas at other places, notably along some faults, detachments or thrust-type tectonic contacts, they represent the main constituent as compared to volumetrically restricted Keuper evaporites. This suggests that the contacts mentioned correspond to salt welds (e.g. as those highlighted by Tavani et al. 2013, in the Reinosa area).

#### *Jurassic*

The Jurassic is represented by two sedimentary assemblages. The lower one usually corresponds to carbonate rocks of marine platform facies, whereas the upper one is essentially terrigenous (see Aurell et al. 2002; Robles et al. 2004, for further details). The base of the lower association is of earliest Jurassic age. It evolved in facies continuity after the late Triassic succession. Usually it is dominated by carbonate rocks containing black shale episodes. The more

extensive outcrops in the BCB (in its western and eastern domains) usually include the Early and Middle Jurassic, though the later's completeness varies areally.

A regional discontinuity (ranging from a disconformity to an angular unconformity) separates the Jurassic of marine facies from upper Jurassic rocks of the lagoonal and lacustrine Purbeck facies. This lithostratigraphic unit is thicker and better exposed in the western BCB area (Aurell et al. 2002; Pujalte et al. 2004) and is much thinner or absent elsewhere. Its age spans across the Jurassic–Cretaceous boundary. It was related to the initiation of a Cretaceous rifting stage that led to strong facies and thickness changes across syn-sedimentary normal faults reactivated in compression and/or wrench regimes during the Alpine orogeny (e.g. Pujalte 1977; Tavani et al. 2013).

### *Cretaceous*

The most significant portion of the outcrop area and sedimentary fill of the BCB is composed of Cretaceous rocks (Martín-Chivelet et al. 2002; Barnolas and Pujalte 2004). In the BCB map presented herein, Cretaceous rocks have been subdivided into four major stratigraphic units, as explained below.

*The Weald Complex* It is composed of paralic, continental and freshwater sedimentary rocks Valanginian to late Barremian age (Pujalte et al. 2004). Many of its characteristics are closely related to those reported for the late Jurassic Purbeck assemblage (Pujalte 1977, 1981), from which it is separated by a stratigraphic discontinuity in the best exposed areas (western BCB). In the central and eastern BCB, the Weald is usually accepted to include at its bottom late Jurassic rocks of Purbeck facies that are not mapped in separate. Subsequently, the label Purbeck–Weald Complex is usually used to refer to these rocks in those areas (Ramírez del Pozo 1969; Martín-Chivelet et al. 2002).

*The Urganian Complex* It is conformed by Aptian to Early Albian successions of marine facies in most parts of the BCB, including as a distinctive element limestones of urgonian facies (Rat 1957, 1959, 1983). The exceptions are the SE and S outcrops, which present siliciclastic successions of continental to transitional environments, ascribed to the “Escucha Formation”. This unit was related to a generalized marine transgression and a less active tectonism than in previous stages (Martín-Chivelet et al. 2002; García-Mondéjar et al. 2004). Vertical and lateral facies and lithological changes, as well as considerable thickness variation across the BCB, are the rule in this unit, which is likely the most extensively and profoundly studied of the BCB after García-Mondéjar (1979; see Appendix 9). In the BCB map presented here, two types of rocks have been distinguished,

following Rat's (1959) original idea of representing with different colours the urgonian limestones and the hosting rocks. Here the “hosting” rocks are shown with the colour pattern allotted by the International Stratigraphic Chart to the Aptian stage, and a different (slightly contrasting but not vivid, as in Rat's 1959 map) green tint to the limestones. Actually, the internal complexity of the Urganian Complex is so considerable (as put forward by the maps that accompany the several PhD theses and scientific articles devoted to it) that its representation would require the use of a wider colour and pattern palette. However, it is out of the scope of this contribution.

*The Supra-Urganian Complex* This stratigraphic unit (of late Albian to early Cenomanian age; cf. López-Horgue et al. 2014) also exhibits a considerable internal complexity and remarkable geographical variation. In part, it is associated with instauration of a palaeogeographical organization of the sedimentary basin that perdured up to the Palaeogene (Martín-Chivelet et al. 2002; García-Mondéjar et al. 2004; Floquet 2004). In the BCB map, the colour assigned to the Albian by the International Stratigraphic Chart was used to represent this unit. However, it comprises various well-known formations not only in the BCB but also in the Pyrenees and the Iberian Chains. These are (e.g.: Pérez-García et al. 1993) the “Black Flysch/Flysch Noir/Flysch Negro” in the Basque Arc area (and outside the BCB along the North Pyrenean Zone), the “Valmaseda Formation” in the central BCB, and the “Utrillas Formation” in the southern BCB (also characteristic of the Iberian Chains). In the BCB map legend, two additional lithostratigraphic units are represented in separate, using colours contrasting with that assigned to the Albian. These are limestone packs of urgonian facies (though definitely younger than those of the Aptian Urganian Complex s.str.) and magmatic rocks that actually belong to a suite best developed and preserved in the Upper Cretaceous ensemble.

*The Upper Cretaceous* This unit comprises principally sedimentary rocks deposited between the Cenomanian and the latest Maastrichtian (up to the Cretaceous-Tertiary, or K-T boundary, which is exposed at various places within the BCB basin; cf. Baceta et al. 2005, 2012). This unit also exhibits considerable internal complexity and maintains the palaeogeographical organization of the sedimentary basin previously instaured (Floquet 1991, 2004; Martín-Chivelet et al. 2002). It is thus possible to distinguish a northern talus and deep basin (flysch) domain, a central-southern marine platform, and marginal areas transitional to continental environments during specific periods. This organization was not constant during the whole Upper Cretaceous, did not begin synchronously across the BCB and gave rise

to a varied lithostratigraphic organization in the vertical basin fill.

In the BCB map, the colour affixed to this unit was that assigned by the International Stratigraphic Chart to the Upper Cretaceous. However, three additional units (distinguished with contrasting colours) and an intra-late Cretaceous stratigraphic contact have been added. The first of the three units mentioned is the Turonian (usually represented by characteristic limestone lithologies across the BCB, among which the “Gárate Limestone” has regional interest). The stratigraphic position of this unit also tracks closely one of the best preserved and widely distributed Cretaceous oceanic anoxic events (the OAE2, which occurred at the Cenomanian/Turonian boundary, around 83 Ma ago). This was an episode of earth’s history marked by anoxic conditions in the oceans (Schlanger and Jenkins 1976) and was accompanied locally by deposition of organic carbon-rich sediments. The second unit corresponds to the “Subijana Limestone” Formation of the central BCB, which conforms the largest aquifer of the BCB. Additionally, its upper and lower contacts portray a set of long-wavelength folds that have been targets of hydrocarbon exploration and repeatedly drilled. The third unit corresponds to the essentially alkaline magmatic rocks that conform a complex of magmatic and subvolcanic rocks in the Biscay Synclinorium (e.g.: Castañares and Robles 2004; see Fig. 2). Finally, the basal contact of the Maastrichtian was added as a thin solid black line. This contact usually occurs in the BCB map close to the limit between the “green” Cretaceous and the “orange” Tertiary sequences. The presence of this contact permits the observer to assess the completeness of the outcropping Upper Cretaceous and highlight the geometrical characteristics of the Cretaceous–Tertiary contact, where it was not removed by erosion related to the Alpine orogeny in the area.

### *Tertiary*

The Tertiary is represented in the BCB map by two sedimentary assemblages. The lower one still preserves the palaeogeographical organization of the Cretaceous, with deep marine, talus, platform and transitional facies units being recognizable barely from N to S and E to W in the onshore BCB. The upper assemblage was deposited during and after Alpine deformations in the area and relates to a completely different palaeogeographical organization.

The base of the lower (pre-tectonic) Tertiary shows facies continuity with latest Cretaceous rocks, notably in the deep marine domains (Baceta et al. 2004). The vertical facies distribution contains evidence of various marine transgressive–regressive cycles reaching locally the mid-Eocene (mid- to late Lutetian). The widest outcrops of this sequence occur principally in the core of two synformal

structures: the Biscay Synclinorium to the N and the Villarcayo-Miranda de Ebro-Urbaña Syncline to the S, with extends further to the E into the South Pyrenean Pamplona-Jaca Palaeogene Basin (Fig. 2). Other relevant outcrops occur along the coast of Guipúzcoa (Baceta et al. 2012) and in two synclines near the Cantabrian coast near Santander and San Vicente de la Barquera. In the BCB map, the outcrops of this sequence are decorated with several thin lines that correspond to major internal lithostratigraphic contacts. They permit to disclose the presence of some major structures (Alpine folds) and occasionally the structural relationships resulting from syn-sedimentary emplacement of salt diapirs.

A regional discontinuity (ranging from a disconformity to an angular unconformity) separates the lower and upper Tertiary assemblages. The associated hiatus spans at least the mid- to late Lutetian to the early Oligocene. The sedimentary fill of this syn-tectonic to post-tectonic sequence can be thicker than 5 km, is essentially of continental facies (lacustrine, alluvial fan, braided river and palustrine facies, among others) and locally reaches the late Miocene and even the earliest Pliocene. The principal outcrops occur in the Villarcayo and Miranda de Ebro continental basins (that constitute models of syn-tectonic sedimentation after the classic paper of Riba 1976) and in the autochthonous southern foreland of the BCB (Ebro and Duero Basins, and the corridor that connects them between Burgos and Logroño; Riba 1955). In the BCB map, the outcrops of this sequence are decorated as well with several thin lines that correspond to major internal lithostratigraphic contacts and facies changes, in order to disclose the occurrence of internal deformations related to major structures such as Alpine thrusts, folds and diapirs.

### **Geologic contacts, structures and symbols**

In addition to the outcrop distributions of the stratigraphic units described above, the BCB map represents the nature of various types of stratigraphic/tectonic contacts and structures. In the case of stratigraphic contacts, conventional geological symbols are used to depict continuity relationships (thin solid black lines bounding areas with different colour tints) or unconformable relationships (depicted by dashed lines). Thin solid lines similar to those used for stratigraphical continuity relationships mark the intrusive contacts of plutonic (granitoids) and subvolcanic rocks (dolerites) with their country rocks. These are easily recognizable taking into account the vivid colours and patterns used to represent the igneous units.

Tectonic contacts are presented with solid lines thicker than those mentioned above. Faults (either of normal and transcurrent regime) and diapiric contacts of Keuper evaporites with their country rocks are represented with similarly



thick lines. Thrust contacts are depicted with still thicker lines decorated with solid triangles, as usual. Actually, these symbols depict the occurrence of both low- and high-angle inverse faults that can be distinguished taking into account their more or less contorted or straight map patterns, respectively. In the Tertiary outcrop area around the “Burgalesa Platform” (see Fig. 2), discontinuous thrust-type contacts are used in order to highlight the presence of remarkable buried structures, sometimes lacking a surface expression. These are currently buried structures recognized in seismic reflection profiles (e.g.: Serrano and Martínez del Olmo 2004; Carola et al. 2015) whose orientation and distribution are closely related to that of Alpine thrusts outcropping in neighbour areas.

Synclines and anticlines are represented with the conventional geological symbols. In this case, specific symbols were not used for differentiation of inclined and recumbent folds. The vergence and asymmetry of these folds can be inferred reasonably through consideration of the attitude of nearby thrust structures.

A special characteristic of the BCB geological map, never accomplished in previous versions, relates to the distinction of Hercynian and Alpine structures using symbols of different colour, since it has long been argued that thickness and facies distributions of the Mesozoic successions have been constrained by the reactivation of basement faults. Pre-Mesozoic rocks, as already mentioned, record a late Palaeozoic tectonic activity related to the Hercynian orogeny and were later subjected to rifting, wrenching and contractional deformation episodes during the Alpine tectono-sedimentary cycle. The Mesozoic and younger rocks, on their hand, only recorded the second tectonic evolution.

Faults and thrusts related to the Alpine orogeny, or reactivated then, are presented in black. As regards the Alpine folds, these are presented with brown symbols. The basement faults of the Asturian and Basque pre-Mesozoic Massifs that were related to the Hercynian orogeny, together with the associated folds, are represented using green structural symbols.

The structural vergence (or the thrust emplacement direction) of Alpine structures can be either towards the N (e.g. in the Basque Arc area) or the S (e.g. along the southern BCB boundary). The time relationships between Alpine N and S vergences, first noticed by Lotze (1931a), were described and discussed in further detail by Martínez-Torres (1989) and Martínez-Torres and Eguíluz (2014, and references therein). Martínez-Torres et al. (1994) related this structural vergence organization to Pyrenean Orogeny and to tectonic inversion and indentation of the Basque-Cantabrian whole crust. In addition to N- or S-vergent Alpine folds, Martínez-Torres et al. (1988) disclosed the presence of various N- to S-trending upright folds related to pre-Albian transcurrent deformations. Some of these

folds have been represented in the BCB map with dark red fold symbols. Inside the Asturian and Basque pre-Mesozoic Massifs, various structures overprint unconformable Mesozoic rocks (for example the “Buntsandstein” or younger formations). Under these circumstances, as they are obvious reactivated structures, they are traced in black, as the other Alpine structures.

In the case of the Asturian Massif, it is evident that the thin-skinned thrust piling of the Picos de Europa and Pisuega-Carrión domains of the Cantabrian Zone (Pérez-Estaún et al. 1988; Ábalos et al. 2002, and references therein) generated a compartmented and anisotropic BCB basement easy to reactivate under properly oriented stress regimes. The Pimiango, Alevia or Puenteviego-Puentenansa reverse E–W faults of western Cantabria are fine examples of Hercynian steepened thrusts reactivated as high-angle normal faults in the early Triassic and as Alpine high-angle reverse faults in the Alpine orogeny. The structural relationships shown by some of these reactivated faults relate to the previously mentioned early twentieth century “nappist” interpretations of the Cantabrian Mountains (e.g. Bertrand and Mengaud 1912a).

The internal Hercynian organization of the Basque Massifs exhibits N- to S-trending, steeply dipping thrusts and foliations (Muller and Roger 1977) cut across by transversal E–W faults that associate small displacements. In this case, as the Hercynian thrusts bear orientations that impede their reactivation under N–S extension or contraction, there are the transversal faults those prone to reactivation. Lower Triassic outcrops inside the Aldudes-Quinto Real and Cinco Villas Massifs are often constrained and overprinted by sets of faults of the orientation reported, thus demonstrating basement reactivation. Likely, other faults of the same orientation have been reactivated during the Alpine orogeny, but the lack of appropriate stratigraphic markers precludes currently a fair demonstration of such an interpretation.

Since the BCB has long been a target of hydrocarbon exploration (Dupuy de Lôme 1933, 1937; de Alvarado and Cantos 1941; Hernández-Sampelayo 1946; Ríos 1949b, Sanz 1949), map symbols marking the position of the wells drilled so far have been added to the BCB map. Additional information on them is recorded in a specific report by the Instituto Tecnológico GeoMinero de España (1990). Actualized data can be gathered from the Hydrocarbon and Subsurface Geological Databases at its websites (<http://info.igme.es/geologiasubsuelo/portada/default.aspx>; <http://info.igme.es/infogeof/>). In the BCB map, 160 drilling sites are identified, leaving apart the 53 hydrocarbon wells from the Ayoluengo field (denoted with a unique well symbol) and including several of the 16 wells drilled between 1900 and 1927 (reported by de Alvarado and Cantos 1941). They permit to realize readily that the sites explored are usually

related to Alpine structures such as anticlines and salt diapirs (both exposed and buried).

### Other map insets

The BCB map contains three insets (approximately of the area between 1°12' and 4°15' longitude W and 42°30' and 43°30' latitude N) in order to provide complementary geographical and geomorphological reference frameworks. Every inset contains its own explanation and full credits. The insets correspond to (1) a general physical and political map showing the principal physical features, political boundaries and communications, (2) a digital terrain model (DTM) depicting the terrain's topography and texture with a grid resolution of 5 m and (3) a SPOT 5 satellite multi-spectral image showing essentially the vegetation cover. In the third inset, grid boundaries and rectangle labels were added for precise identification of the 1/50.000 (solid lines) and 1/25.000 (dashed lines) base maps used for drawing the BCB map.

Finally, the map contains three text appends. The first, under the compass rose, describes the geographical framework (regarding the topographic base and heights). The second, at the lower left, corresponds to commemoration of the bicentenary of the publication in 1815 of the geological map of William Smith. Finally, at the lower right corner, a statement credited to the great American geologist John Rodgers (Rodgers 2001) is included.

### A new structural interpretation of the Basque Arc

The most intensely deformed portion of the BCB coincides with the so-called Basque Arc (Feuillée and Rat 1971). It is characterized by the arched shape of the regional structures and is composed by a number of N-vergent thrust sheets, strike-slip subvertical faults and major folds. The later include (from N to S) the Guipúzcoa Monocline, the North-Biscay Anticlinorium, the Biscay Synclinorium and the Bilbao Anticlinorium (Fig. 2). Usually these are the major structures represented in geological sketches of the BCB and the Basque Arc, without any major fault bounding them alongstrike. The principal fault portrayed is usually the Leiza Fault (e.g.: Mendia and Gil Ibarguchi 1991; Martínez-Torres 1993a; Mathey et al. 1999), regarded as the continuation of the North Pyrenean Fault (Choukroune 1992).

During completion of the BCB map, previous cartographic data were reinterpreted with the aim of expanding and connecting the subdivisión into onshore thrust slices proposed by Cuevas et al. (1998, 1999) for the internal domain (inner arc or intrados) of the Basque Arc, and by Ábalos et al. (2008) for its external domain (outer arc or

extrados). The outcrop areas of those tectonic slices have been extended in some cases to the W and E. The new tectonic interpretation of the Basque Arc thus developed is presented at the 1/400.000 scale map (supplementary file 2) using transparent colour overlays superimposed on a simpler version of the BCB 1/200.000 map. The criterion followed for tectonic slice definition consisted in prolonging their bounding structures without the constraint of terminating or fading them out in the Upper Triassic basal detachment, or wrapping them around the Basque Massifs boundaries. As a result, various thrust-bounded slices can be differentiated, which exhibit outcrops of the cover succession (in their western parts), locally of the cover basal detachment, and of the basement (in their western parts). The Basque Arc curvature described by the trace of slice-bounding thrusts is smaller than that perceived from the outcrop pattern of mapped tectono-sedimentary units. A detailed geometrical description of the structural features and boundaries of the units distinguished would require launching further tectonic investigations. Currently it is out of the scope of this contribution. The same can be said on the discussion of the tectonic implications. In the following, only the general traits will be summarized.

### The Aya Slice

The innermost thrust slice of the Basque Arc (structurally at the lowermost position) is the Aya Slice. In the North Iberian margin, this slice exhibits a gently dipping blind structure as basal thrust, floored by Triassic evaporites. It is assumed to be internally compartmented by some second-order thrusts. The Upper Cretaceous of this slice connects eastwards the Basque-Cantabrian outcrops of Guipúzcoa with those of the Mauléon sedimentary basin in SW France. The latter was tectonically emplaced onto the Arzacq Basin (Daignières et al. 1994; Jammes et al. 2009; Tugend et al. 2014) and is usually considered as an integral part of the North Pyrenean Zone (Choukroune 1992). The Aya Slice is here considered to comprise cover and basement outcrops. The later are represented by the Massifs of Aya-Rhune (also known as Larrune) and Ursuya (or Labourd; see also Muller and Roger 1977, for Basque massif labelling), in line with the ideas advocated by Jammes et al. (2009).

### The Pagoeta Slice

The Pagoeta Slice overlays the Aya slice and is floored by a gently dipping thrust in its western outcrop area. It is suggested here that this N-vergent fault might be prolonged through the Ereñozu NE-verging inverse fault and the so-called Arichulegui fault or shear zone (separating the Aya-Rhune and Cinco Villas massifs) to Vera de Bidasoa and Zugarramurdi, and further E to the tectonic boundary

between the Ursuya and Iparla-Baigoura basement massifs. The latter would correspond to a mid-Mesozoic lower crustal detachment (Jammes et al. 2009) reactivated as a N-vergent thrust during the Alpine orogeny. If correct, this would depict a complex structure with minor footwall and hangingwall ramifications always vergent towards the North. Westwards of its central segment, it involves the basement which overthrusts the Upper Cretaceous in the Ereñozu sector and other Palaeozoic units along the Arichulegui section. It appears that further East, between Zugarramurdi and Urdax, this N-verging structure fades out and transfers the associated tectonic displacement to the S-vergent structure associated with the Hasparren-Arberoue “croissant”. This slice is also interpreted to comprise cover, basement and intervening detachment outcrops. The basement is compartmented by NE–SW-striking steep faults (resembling inverted normal faults) that control the outcrop distribution of the Lower Triassic. Cuevas et al. (1998, 1999) described recumbent folds in the cover rocks of this slice, with associated tectonic foliations in their inverse limbs.

### The Azpeitia Slice

The Azpeitia Slice was emplaced onto the Pagoeta Slice along a basal thrust with a moderate dip towards the SSW (western segment) or the S (central segment). It exposes Mesozoic rocks ranging in age essentially between the Late Triassic and the Middle Cretaceous, with the exception of a small Palaeozoic outcrop near Azpeitia. Outcrops of Triassic evaporites played the role of basal detachments in the central segment, whereas in the western area they conform small diapiric structures such as those near Guernica and Baquio. Towards the E the basal tectonic contact of this unit becomes steeper and then inverted (becoming a N-dipping inverse fault), permitting the basement rocks of the Cinco Villas Massif to thrust onto the Mesozoic rocks of the so-called Depresión Intermedia (see Mathey et al. 1999, and Bodego et al. 2015, for further details on the latter). Cuevas et al. (1998, 1999) described a generalized foliation development within this unit, pointing to a higher internal ductile deformation of this unit as compared to the structurally underlying one. These authors also interpreted that such deformation was induced by a backstop effect induced by inversion of syn-sedimentary normal faults bounding this unit.

### The Biscay Sinclinorium-“Nappe des Marbres” Slice

The tectonic unit emplaced onto the Azpeitia Slice is bounded at its base by a steeply dipping or subvertical inverse fault (actually an inverted normal fault; e.g.: Rodríguez et al. 2008). Different segments of this structure have received several names in the literature. The

hangingwall block includes in its western extension the Biscay Sinclinorium and towards the eastern one the so-called Nappe des Marbres (Lamare 1936; Martínez-Torres 1989). Along the northern boundary of the latter, the structure is known as “Leiza Fault” and trends E–W. From Legorreta to Azcoitia, it has been labelled “Azcoitia Fault” (a retro-vergent backthrust; cf. Cuevas et al. 1999) and presents a WNW-ESE strike and a subvertical dip that can be prolonged to Elgóibar (“Elgóibar Fault”; cf. Agirrezabala and García-Mondéjar 2001) and to Aulestia, where it branches into a complex thrust and shear zone ensemble. This is often accompanied by tectonic foliations (Ábalos 1989) and exposures of marble rocks (Martínez-Torres, personal communication 2015), reaching the coast in the entangled Barrica-Sopelana structural zone (Cuevas et al. 1982; Rodríguez et al. 2008). Internal folding and dissection of this unit is notable. A progressive variation can be observed in the age of the outcropping units from W (upper Cretaceous and Tertiary) to E (Lower Cretaceous, Jurassic and Triassic). Concomitantly, an increase in metamorphic grade (Martínez-Torres 1989; Cuevas and Tubía 1999) and deformation ductility (Meschede 1987) can be appreciated. These transitions might represent a progressive deepening in the structural level exposed. Actually, its easternmost segment is proposed here to include as outcropping basement a portion of the Aldudes-Quinto Real Massif. The eastern closure of this slice, both in the basement and in the Mesozoic cover N of Lanz, is difficult to establish due to the lack or failure to recognize the precise boundary structures. The overall N-vergence of internal structures and slice-bounding faults is also transfigured in this SE domain, as exemplified by the southern, S-verging thrust boundary of the “Nappe des Marbres” that emplaces it onto a southern para-autochthon.

### The Ulzama-Valcarlos Slice

The Ulzama-Valcarlos unit is a tectonic slice defined here for the first time. It includes a sedimentary cover consisting of middle and late Cretaceous siliciclastics, and a basement (the southern half of the Aldudes-Quinto Real Massif). Its western (cover) segment forms the para-autochthon of the “Nappe des Marbres” (to the N) and the Aralar Slice (to the W). Its NE and E limits correspond to steeply dipping thrusts with alternating vergences. For example, along its NE limit this unit is emplaced onto a para-autochthonous block made of a basement (known in the literature as the Baigoura Massif) and its Mesozoic sedimentary cover (of the Mauléon north Pyrenean basin). On its hand, the southern limit corresponds to a S-vergent thrust. This is best exposed along the eastern segment, where Palaeozoic rocks of the Aldudes-Quinto Real Massif thrust onto the Tertiary deposits of the Jaca-Pamplona Basin along the

Roncesvalles thrust. To the W, this thrust splits into a number of also S-vergent thrusts with associated folds. These extend W of the diapir alignment known as the “Pamplona Fault”. In spite of the continuity of sedimentary formations across this limit, an evident change in structural style coincides with it (Larrasoaña et al. 2003).

### The Bilbao Anticlinorium thrust system

The tectonic units described so far are the para-autochthon of the four tectonic slices that conform the Bilbao Anticlinorium (Aralar, Durango, Mondragón and Gorbea Slices), the boundaries of which were described in further detail by Ábalos et al. (2008). The foundations of that proposal will be maintained here. The maximum shortening accommodated by the Bilbao Anticlinorium thrust system is of ca. 20 km. The Bilbao thrust fault constitutes both the north-eastern boundary and the sole thrust from which irradiate the other thrust branches of the N-verging Bilbao system. It dips steeply to the SSW and extends along more than 120 km from the Cantabrian coast to the SE of Irurzun. Along its strike, it is usually accompanied by development of tectonic foliations (Álvaro 1976; García Mondéjar and García Pascual 1982). Its dip-slip structural throw varies along strike from 5 to 10 km in the W to zero displacement at its eastern termination.

The Aralar Slice is bounded by the Bilbao and Cegama thrusts, the latter branching from the former near Zumárraga. Its internal organization presents a relatively complex anticlinal culmination above a hangingwall ramp. The maximum dip-slip throw of this unit’s bounding thrusts is of the order of 5–6 km and decreases towards their SE terminations near Irurzun (basal thrust) and Alsasua (Cegama thrust).

The Durango Slice is bounded at its sole by the Cegama and a segment of the Bilbao thrusts, and at its top by the Aitzgorri thrust. These boundary faults run subparallel and converge towards the WNW with an average angle of 10°. The internal structure of the slice includes NE-verging domal structures developed over hangingwall and footwall thrust ramps, hm-scale folds with axial-planar foliations, reverse faults, and minor folds with “en-échelon” axis arrangement oblique to the trace of the sole thrust.

The Mondragón Slice is bounded by the Aitzgorri and the Villaro thrusts. The Aitzgorri sole thrust extends along ca. 100 km. Its maximum dip-slip throw is of the order of 10 km and decreases to the SE until it disappears NE of Salvatierra. The sole and top bounding thrusts form an angle of ca. 10° in map view. This slice it is the most complexly deformed one of the Bilbao Anticlinorium, as it is internally compartmented by several oblique faults with vertical and tangential displacements, by sets of frontal duplex structures, and by various domal structures. This

likely points to forward progressive propagation of the thrust association.

The Gorbea Slice (a term first coined here) is bounded at its base by the Villaro thrust. The latter extends for more than 70 km until it dies out to the NE of Vitoria, with a maximum throw of ca. 8 km at its central segment. The Gorbea Slice forms an integral part of the relatively undeformed, southern coherent portion of the Basque-Cantabrian domain. Its internal organization is characterized by a large hangingwall anticline (likely an inverted Early Cretaceous depocenter) and by the formation of duplexes in the vicinity of the sole thrust. The trace of the N-verging basal thrust can be followed towards the WNW up to the Cantabrian coast. It is suggested here that the extension of the Gorbea Slice, considered as a unit tectonically displaced towards the NE, might be expanded towards the W up to the Laredo-Ramales de la Victoria N-S composite structure, and towards the S up to the Villasana de Mena-Murguía diapiric alignment, since the latter diapir has been interpreted after Ramírez del Pozo (1973b) as a salt structure deformed and displaced to the N during the Alpine orogeny.

### Discussion and conclusions

The geological map of the BCB presented here is aimed to contribute to future geologic developments in the central segment of the Pyrenean–Cantabrian, or North Iberian, Alpine orogenic system. Central to this objective, from my viewpoint, is the consideration of the usually overlooked scientific background, which is also presented. This contribution includes a thorough examination of the geological maps that served as a background to “state-of-the-art” geologic interpretation of the BCB presented. It is as well a course through the several academic memories from which the maps derived sometimes, or the converse. These usually resulted in scientific articles published in national or international journals, which surprisingly can be tracked for longer periods than their gradually fading sources. In separate appendixes, above 350 bibliographic citations of maps and academic reports are presented, as they are pivotal to this contribution. These have been usually overlooked or ignored. Also as separate digital documents, two large format maps of the BCB and the Basque Arc are included. Documents of this type do not use to accompany scientific articles, neither, usually for practical printing and cost reasons.

Tectonic analysis of the BCB map allows to present a new structural interpretation of the Basque Arc, after previously published partial reconstructions. The general features of a number of thrust slices are defined and described. By contrast with previous interpretations, in some cases

they are suggested to be composed of rocks from the basement (Palaeozoic to Lower Triassic), from the cover (uppermost Triassic to Tertiary), and from the intervening detachment (Upper Triassic evaporites and associated rocks).

The tectonic organization described permits to acquaint the magnitude of tectonic shortening accommodated at the scale of the BCB on large thrusts, which in most cases are inverted normal faults. Previously, the major folds already known did not suffice to accommodate the tectonic shortening inferred from independent studies (palaeogeographical, geophysical, etc.). In the central and western Pyrenees, shortening has been constrained by combination of surface geological and deep seismic geophysical studies. In the central Pyrenees, Vergés et al. (1995) reported a minimum shortening of 125 km after restoration of ECORS-Pyrenees deep reflection profiles (Choukroune and ECORS Team 1989; Roure et al. 1989). Teixell (1996, 1998) consigned a shortening decrease to 80 km near the Arzacq-West Pyrenees ECORS seismic profile (Daignières et al. 1994; Masini et al. 2015). Further W, shortening appears to be further reduced along the MARCONI Deep Seismic Reflection Survey, too (Fernández-Viejo et al. 2011; Roca et al. 2011).

Onshore observations highlight that there are both N- and S-verging structures accommodating orogenic contractions in the BCB. A minimum shortening of 25 km associated with N-verging structures (notably major folds and a few thrusts) was proposed by Gómez et al. (2002). With the considerations reported in the precedent section of this study, it can be doubled to ca. 50 km. The shortening accommodated by the frontal, S-verging thrust structures (essentially those associated with the southern thrust of the BCB, emplacing it on the Ebro-Duero basins) was smaller (15–20 km; Martínez-Torres 1993b; Ábalos and Llanos 1994; Serrano and Martínez del Olmo 2004). This results in a combined Tertiary shortening of ca. 60–70 km in the central BCB after inversion of Mesozoic palaeomargins that had been extended (or hyper-extended) nearly in a similar magnitude (Tugend et al. 2014).

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