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Geological and isotopic constraints on the structure of the Bilbao anticlinorium (Basque–Cantabrian basin, North Spain)

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ABSTRACT

The structure of the Bilbao anticlinorium is re-evaluated based upon new geological and isotopic data on Mesozoic evaporites and related groundwaters. A detailed geological survey to guide and monitor the construction of a 3.3 km tunnel provided new data on Early Cretaceous rocks with evaporite intercalations. S and O isotopes from evaporite minerals and from sulfate dissolved in groundwaters permitted us to ascribe the sampled subsurface rocks to the Early Cretaceous, rather than to the Triassic, and trace their distribution. We present a new structural map of the anticlinorium compartmented by four major branching thrusts. New and reinterpreted cross sections resolve its deep structure. Cover rocks extend to depths below 6–8 km. Hangingwall anticlines occur above hangingwall and footwall thrust ramps and the ensemble of slices forms an antiformal stack directly above a south dipping basement ramp. Shortening of ca. 15–20 km was accompanied by alongstrike sinistral displacements. Currently, the Bilbao anticlinorium relates to major geophysical anomalies and is regarded as the surface expression of an indenting wedge of deep crustal rocks at mid-crustal depths.

1. Introduction

Subsurface geological interpretation from sparsely distributed and incomplete surface and depth data (boreholes, seismic surveys) is commonly required for basic research and economic-oriented exploration. This involves uncertainties of various sources, principally inherent to the data and to the human bias (prior knowledge, regional tradition; cf. Bond et al., 2007). Interpretation uncertainties are even greater when upper and lower crustal domains of interacting plates and variations of the subsequent orogenic architecture are considered. This is the case of the western Pyrenees–Cantabrian Mountains, a doubly vergent Alpine orogen with along-strike variations of sedimentary cover age/thickness, structural trends, vergence, tectonic shortening, basement/cover relationships and geophysical characteristics.

In this paper we re-evaluate the geological structure of the Bilbao anticlinorium, based upon new geological (detailed surface mapping and underground excavations) and isotopic data concerning Mesozoic evaporites and related groundwaters. The anticlinorium is one of the principal tectonic elements of the Basque–Cantabrian basin. It separates to the North the most intensely deformed portion of the Basque–Cantabrian basin (Barnolas and Pujalte, 2004) and is related to major geophysical anomalies and deep crustal features (Aller and Zeyen, 1996; Pedreira et al., 2007).

2. Geological setting

The Basque–Cantabrian basin (Fig. 1) is an inverted basin connecting the Pyrenees and the Cantabrian Mountains. It contains a mainly Cretaceous sedimentary fill and was inverted during the Paleogene (Cámara, 1997; Vergés and García Senz, 2001). The basin was the target of extensive hydrocarbon exploration from the twentieth century's late fifties through the seventies. Several seismic reflection campaigns and tens of wells up to 6 km deep were drilled, notably in its southern and western domains (IGME, 1990). Its deep structure has been recently studied with the help of various geophysical techniques (Pedreira et al., 2003, 2007, and references therein) that depict a complex relationship between lithospheric inherited structures and lower crustal indentation.

The tectono-sedimentary evolution included two rifting episodes during the Triassic and the Cretaceous. For the sake of simplicity, henceforth we shall consider as Cretaceous pre-rift both the Triassic (germanotype) and Jurassic (marine) deposits. The age of the rifting stage was Early Cretaceous, and the post-rift stage was Late Cretaceous. The Cretaceous rifting stage, that already began in Tithonian times (Martín Chivelet et al., 2002), led to strong facies and thickness changes across faults that were reactivated and inverted during the Tertiary (e.g. Cuevas et al., 1998, 1999; Gómez

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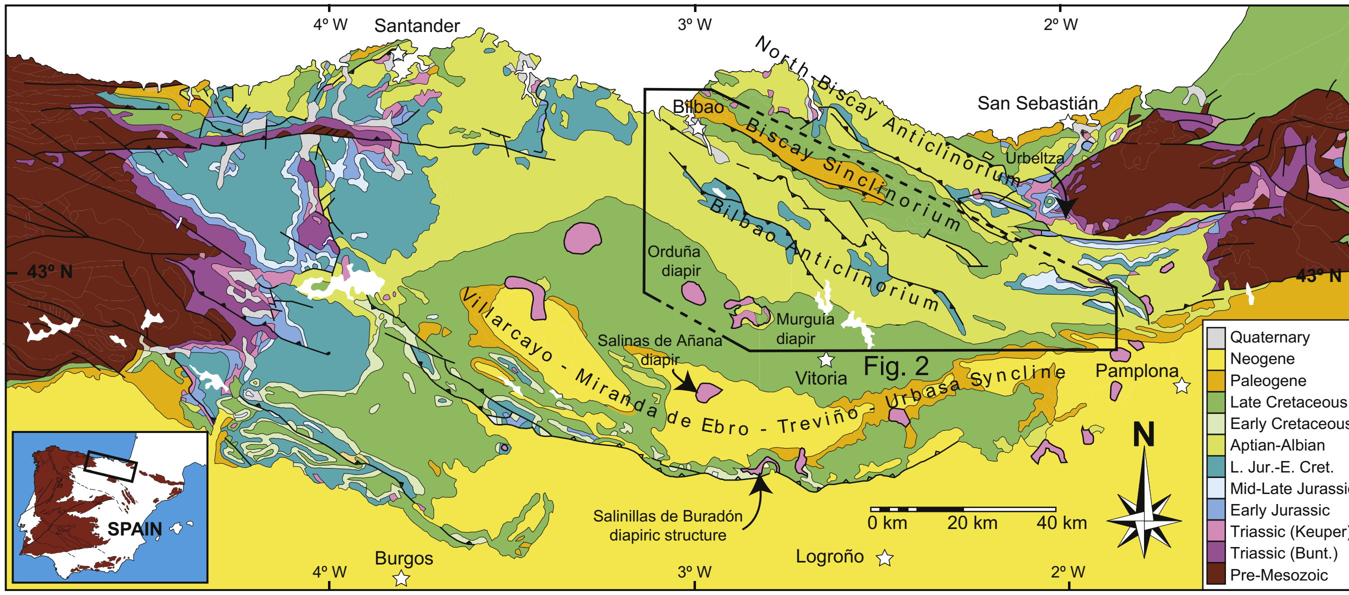

Fig. 1. Geological map of Basque–Cantabrian basin.

et al., 2002; Quintana et al., 2006). The Purbeck facies group (Late Tithonian to Early Valanginian) and the Weald facies group (Late Valanginian to Barremian; Pujalte, 1977, 1981) represent the earliest rifting phases, whereas the middle rifting is represented by Aptian to Early Albian successions (the Urgonian Complex; Rat, 1959) related to a generalized marine transgression and a less active tectonism.

The most intensely deformed portion of the Basque–Cantabrian basin 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 fold structures. The later include (from N to S) the North-Biscay anticlinorium, the Biscay synclinorium and the Bilbao anticlinorium (Fig. 1).

3. Stratigraphy and previous work

The Bilbao anticlinorium area (Fig. 2) constituted a depositional trough during the earliest rift stage, from the latest Jurassic to Valanginian times. It was filled with non-marine ("wealdian") sedimentary successions including black shales, fine-grained sandstones, limestones and dolostones interpreted as brackish deposits. Here, the Villaro Formation was defined by Pujalte (1982), studied in detail by García Garmilla, 1987, and correlated with the Vega de Pas and Bárcena Mayor Formations of the Cantabrian graben type-area (Pujalte, 1977, 1981; Pujalte et al., 2004). The thickness and lithology of the Villaro Formation vary both areally and vertically (García Mondéjar and García Pascual, 1982). Its sedimentary environment was fluviodeltaic and lacustrine, with sporadic marine influences. In the central part of the Bilbao anticlinorium it attains at least 2000 m in thickness, since the bottom does not crop out. Toward the east and south the thicknesses diminish to less than 100 m. Dolomitic limestones, dolostones and evaporitic relic textures ("chicken wire", algal laminae) occur towards the base of the "wealdian", pointing to evaporitic affinities of the sedimentary realms (Badillo, 1982; García Garmilla, 1990, 1992) and endorheic basins.

The occurrence of "wealdian" gypsum was cited first by Rat (1959). It was described as fibrous gypsum relics interbedded with glauconia-bearing black argillites and was found in the underground excavation of a tunnel connecting the Villarreal de Álava and Undurraga water reservoirs (Fig. 2). Gypsum, anhydrite and halite sedimentary intercalations were also registered by the exploration wells Ubidea-1 (drilled in 1964, 1812 m long), Aitzgorri-1 (1965, ca. 5000 m long) and Cegama-1 (1968, 4500 m long). In them, longitudinal tracts 400 to ca. 3000 m long were tested and logged as "wealdian" successions containing evaporite intercalations associated with silt, mudstone, sandstone and limestone. The Ubidea-1 and Aitzgorri-1 wells did not reach the base of the "wealdian", whilst the Cegama-1 showed that this unit rests on sandstones, limestones and shales (the basal 442 m of the well log; cf. IGME, 1990) interpreted as the stratigraphically younger Urgonian Complex. So far, these discoveries have contrasted with the almost total lack of evidence on the existence of "wealdian" evaporite outcrops.

Evaporite outcrops of Triassic rocks are not uncommon in the Basque–Cantabrian Pyrenees. They occur outside the Bilbao anticlinorium and correspond to the germanotype Keuper facies. They form diapiric structures, crop out at the base of thrust slices, in anticline cores, or as a variably transposed successions sandwiched between the base of the Mesozoic cover and the pre-Meosozoic basement (Fig. 1). The close association of Triassic evaporites with thrust structures and the realization that they conform a regional detachment has biased the structural interpretations during the last four decades. In fact, most geological syntheses of the area systematically interpreted subsurface evaporites as belonging to the Triassic Keuper.

Subsurface structure interpretations of the Bilbao anticlinorium often include cross-sections with lateral extrapolations of the well data cited above. Ramírez del Pozo (1973) presented a geological cross section in which the Triassic Keuper was situated directly under the Urgonian Complex, instead of the 600 m long "wealdian" original log tract of the Aitzgorri-1 well. Olivé-Davó et al. (1989) followed this idea, giving a thickness of several hundreds of meters to a Keuper evaporite layer overlying an antiformal stack of pre-Mesozoic basement slices. Garrote et al. (1995) presented cross sections with less than 1000 m thick "wealdian" rocks below the Urgonian (Fig. 3). The "wealdian" was supposed to rest directly on kilometers-thick Keuper masses coring the principal anticlinal structures. Here again, the basal evaporite and salt tracts of the Aitzgorri-1 and Cegama-1 wells were interpreted in disagreement with the original log reports.

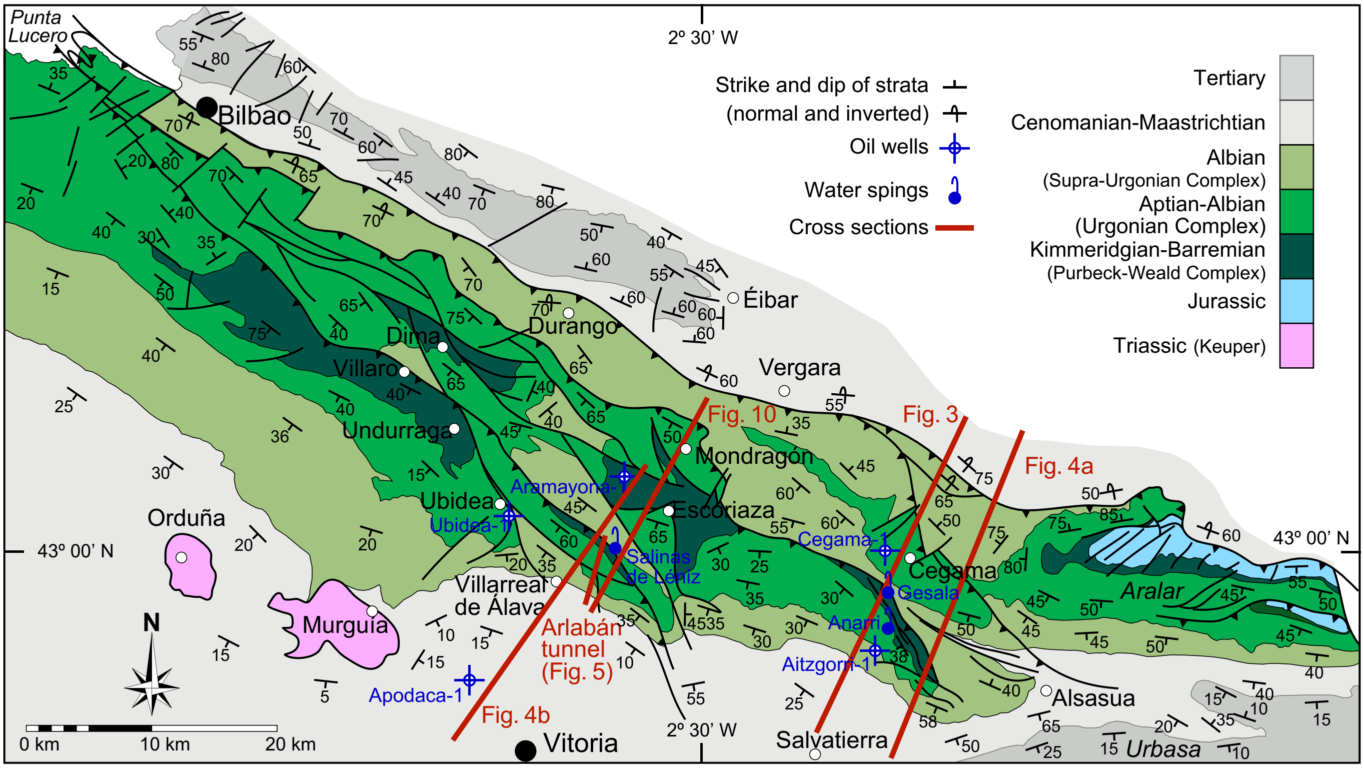

Fig. 2. Geological map of the Bilbao anticlinorium.

The idea that great volumes of Keuper evaporites occupy the core of major geological structures in the Basque–Cantabrian basin has prevailed during the last four decades. Diapirs occur principally to the south of the Bilbao anticlinorium (Brinkmann and Lötgers, 1967). Serrano et al. (1989) drew isopach maps of the Triassic evaporites with hundreds of square kilometers of the southern Basque–Cantabrian basin underlain by more than 2000 m thick evaporite layers. This was the case, too, for the southeastern part of the Bilbao anticlinorium. Serrano and Martínez del Olmo (2004) reinterpreted reflection seismic profiles across the Bilbao Anticlinorium and Cegama-Aitzgorri areas (Fig. 4a and b) following these ideas. Sedimentological and hydrogeological arguments (Antigüedad et al., 1985) have also been used as indirect evidences suggesting that the southeastern Bilbao anticlinorium is cored by Triassic evaporites.

Geological maps and syntheses of the Bilbao anticlinorium segment situated to the NNE of Vitoria (Fig. 2) are not conclusive even on the adscription of the outcropping units. The area between Villarreal de Álava, Salinas de Léniz and Escoriaza was mapped as Aptian-Albian (supra-Urgonian) by Rat (1959), Ramírez del Pozo (1973), Ramírez del Pozo et al. (1978) and Olivé-Davó et al. (1989), and as Aptian (Urgonian) and Albian (supra-Urgonian) by Garrote et al. (1995). Outcrops of Urgonian-facies limestones a few kilometers long and 100–200 m thick were recognized and mapped in different stratigraphic positions by these authors. Ramírez del Pozo et al. (1978) dated micropaleontologically as Albian the uppermost part of the succession well above the limestone layers. These were not included in the Urgonian Complex on the basis of regional correlations that assumed intervening cartographic unconformities related to the reliefs of the basin floor. Previously, Lotze (1958)

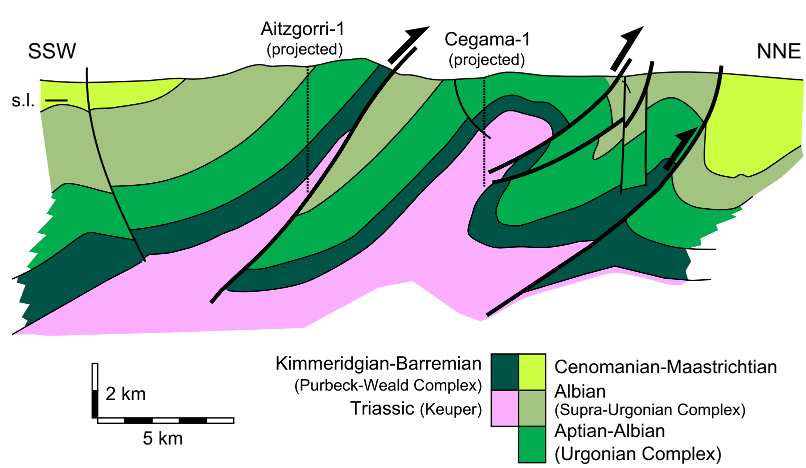

Fig. 3. Cross section of the Bilbao anticlinorium with the structural interpretation simplified after Garrote et al. (1995). s.l.: sea level. See Fig. 2 for location.

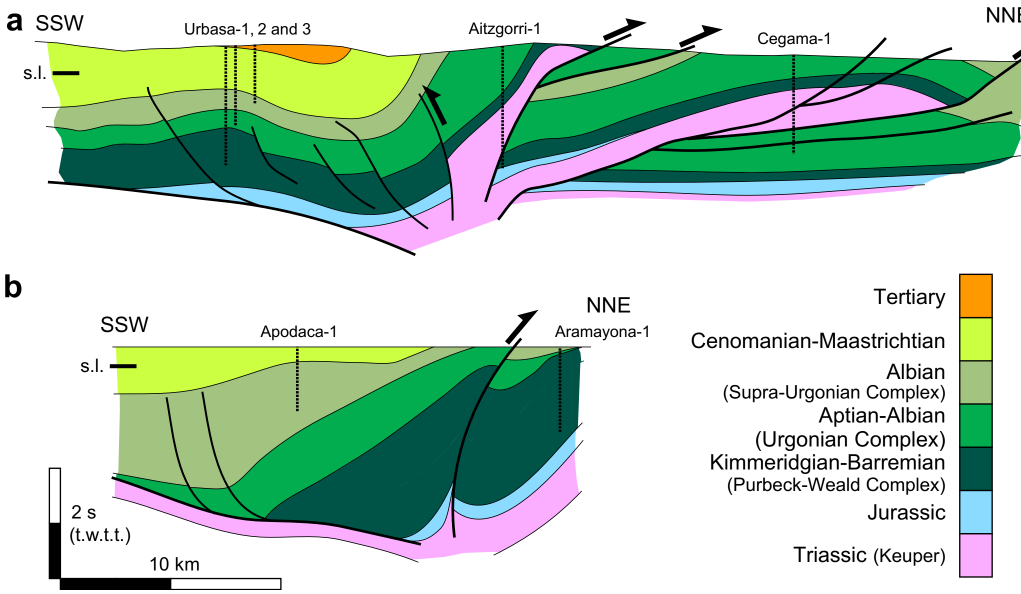

Fig. 4. Cross sections of the Bilbao anticlinorium from seismic reflection profiles with the structural interpretation simplified after Serrano and Martínez del Olmo (2004). t.w.t.t.: two-way travel times (seconds). s.l.: sea level. See Fig. 2 for location.

mapped as "wealdian" (his "Neokomien") the sediments situated stratigraphically under the lowermost urgonian-type limestone (his "Untere Kalke"), as supra-Urgonian the series situated above the uppermost limestone layer ("Ubere Kalke"), and as Urgonian the succession containing them.

4. New geological data

A detailed geological survey of the area between Villarreal de Álava and Escoriaza has been carried out by Euroestudios (2003) to guide and monitor the construction of the 3.3 km long Arlabán double tunnel (Fig. 2) of the Vitoria-Éibar highway. Surface geology at the 1:5000 and 1:1000 scales and several boreholes up to a few hundreds of meters deep provided new data on the nature and depth distribution of the Early Cretaceous rocks. A sketched cross section of the tunnel tract and a simplified lithostratigraphic column of the materials traversed are presented in Fig. 5.

The stratigraphically older materials are shales and sandstones with limestone and evaporite intercalations (gypsum and anhydrite) that can be lithologically correlated with the earliest "wealdian" sediments of the Villaro Formation (Ibarreche Member; cf. García Garmilla and Carracedo Sánchez, 1989) and, possibly, with the deepest portions of the Ubidea-1, Aitzgorri-1 and Cegama-1 wells (Fig. 2). These materials, for which the informal "Bolivar Formation" label will be used henceforth, are separated by moderately dipping thrust contacts from the underlying and overlying successions. Their basal contact does not crop out and their thickness exceeds several hundreds of meters.

The northernmost thrust of the tunnel section (Fig. 5) is subparallel to the internal dip and azimuth of the "Bolívar Fm.". This fault associates a hangwingwall flat and cuts obliquely the strata of the footwall unit. These geometrical relationships occur also in the southernmost thrust contact traversed by the tunnel. Other minor thrusts subparallel to the strata repeat internally the formation, conforming footwall and hangingwall flats. In addition, in the central part of the tunnel a steep, reverse fault and a moderately dipping thrust occur. The latter is oblique to the strata of the footwall (a footwall ramp). The former is oblique to the strata of both the hangingwall and the footwall blocks (likely an out-of-sequence backthrust).

The "Bolivar Fm." occupies most of the head area of the upper Deva River. Its clayey nature and the climatic/botanic characteristics of the area have facilitated the development of up to 15 m thick soils that hide fresh rock outcrops. In the neighborhood of the Arlabán tunnel, parts of the "Bolívar Fm." are repeated by thrusts or refolded and compartmented by subvertical faults. A number of lithological/geomechanical subunits can be differentiated in this formation. These are, from the base to the top, the following (Fig. 5).

(1) Black, carbonaceous shales. They are less than 100 m thick and contain fossils (bivalves and glauconiae), veins of gypsum, pyrite nodules, sandstone and limestone intercalations (ca. 30% and 5% of the section, respectively) and rare, meters-thick secondary gypsum beds and millimeter-thick native sulfur veins.
(2) Sandstones with intercalations of shales and limestones. This is a ca. 120 m thick unit made of fine- to medium-grained sandstone beds with millimeter-thick carbonaceous shale intercalations (that can reach a proportion of 40%). Less common are dark, recrystallized limestone layers up to 1 m thick.
(3) Black shale and anhydrite/gypsum alternations (the later in decimeter- to meter-thick beds) with minor intercalations of fine-grained sandstones. The original sedimentary organization of this unit has been largely obscured by diagenetic processes and by the volume reduction and deformations associated to the transformation of gypsum to anhydrite during burial, and the converse during uplift and meteorization. The microstructure of the gypsum layers is always secondary (microcrystalline and massive). They often exhibit a brecciated structure with angular fragments of shale and sandstone. Relic structures of precursor anhydrite are present as enterolitic folds, nodules and "chicken wire" growths. Secondary gypsum recrystallizations are the rule as massive or fibrous layers and as vein fills. X-ray diffraction tests indicate anhydrite proportions below 2% in the samples collected from the surface. Samples from drilling explorations and the tunnel excavations (situated 250–300 m under the current surface) contain larger anhydrite proportions. Apart from the potential incidence of the evaporite hydration/dehydration in anthropogenic constructions, the related volume changes can explain also

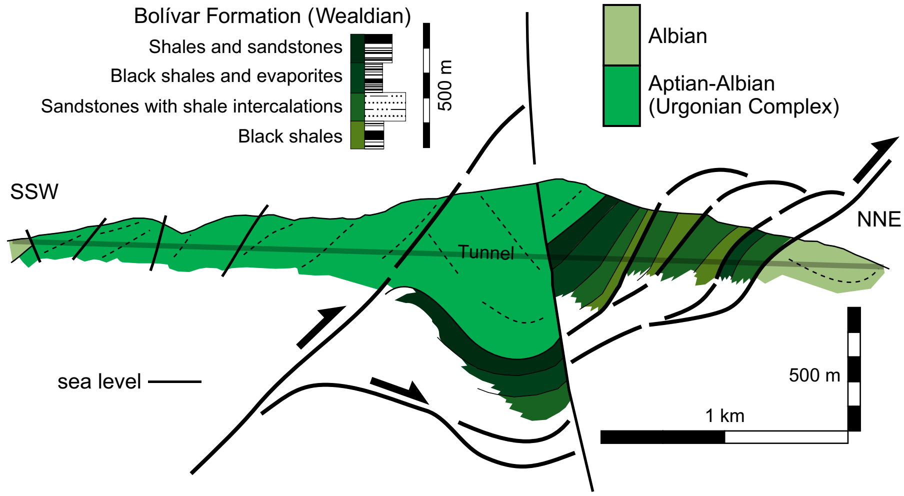

Fig. 5. Structural interpretation and cross section of the Arlabán tunnel, including stratigraphical details of the Early Cretaceous rocks of the Bolívar Formation. See Fig. 2 for location.

complex fault deformation patterns at the map scale (De Paola et al., 2007).

(4) Shales with sandstone intercalations. These are grayish to black, carbonaceous, laminated shales interbedded with scarce (less than 10%), decimeter-thick sandstone beds.

These subunits occur in four thrust slices in the Arlabán tunnel due to additive fault repetition. The mechanical stratigraphy of the slices is composed of either the subunits (1)–(2), (2)–(3) or (1)–(2)–(3)–(4). The subunits (1) and (3) are always in the hangingwall of the thrusts, in direct contact with fault rocks or with other footwall units. Also, their strata are subparallel to the thrust contacts. This suggests that they acted as detachment horizons and that, given the regional entity of the thrusts, they might constitute a décollement in the Bilbao anticlinorium area. The basal shales (subunit 1) are the most conspicuous detachment. The thrust fault with the maximum stratigraphic overlap (northernmost thrust of Fig. 5) presents the evaporite-rich subunit (3) as hangingwall detachment. The contact of the "Bolivar Fm." with the younger rocks of the Urgonian Complex (here informally labeled "Arlabán Fm.") is marked by the first occurrences of reef patchy limestones with marine sedimentary influence, following the original criteria of Lotze (1958).

5. Isotopic characteristics

In this work the isotopic signatures of S and O in gypsum SO_4 from outcropping and well-logged evaporite formations, and in SO_4 anions of groundwater springs are studied with the aim to relate them to their likely sources and origins (e.g.: Seal et al., 1999; Clark and Fritz, 1997). Both in minerals and waters, the application of the isotopic techniques can be divided into two categories: as tracers and as records of the geochemical processes that modify the original isotope composition (sulfide oxidation, sulfate reduction, dissolution and precipitation, metamorphism, etc.).

When isotope study is applied to evaporites, the aim is usually to unravel their marine or continental origin. If evaporite origin is marine, the S and O isotopic composition is very close to that of coeval marine waters (Claypool et al., 1980; Botrell and Newton, 2006). If the origin is continental, the source of sulfates can be related to recycling of older evaporites or to the oxidation of sulfides of various potential origins. In evaporites whose stratigraphic relationships are lost (e.g. in drill cuttings or veins), the isotopic composition can be used as a tracer to relate them to other well-known or outcropping evaporitic formations. When applied to surface and groundwater, the origin of sulfates can be related additionally to atmospheric deposition, anthropogenic contamination and soil sulfate washing. Saline groundwater usually relates to evaporite dissolution. Therefore, SO_4 isotope studies of saline water springs can be used to trace the source of the solutes, particularly where evaporitic formations with different isotopic signatures are present. To obtain information on the underground distribution of the evaporitic rocks, it is necessary to unravel the groundwater circulation pathways. In absence of piezometers or observation wells, the groundwater circulation depth and the topographic height of recharge area can be inferred through the complementary study of water temperature and $^{18}O/^{16}O$ and $^{2}H/^{1}H$ relationships.

5.1. Sample description and preparation

The rock samples studied are of various sources (Figs. 1 and 2, Table 1). They include gypsum from "wealdian" evaporites drilled in exploration wells and the Arlabán tunnel, bedded Triassic evaporites and recrystallized gypsum veins from the Salinillas de Buradón diapir, from an abandoned gypsum mine slope near the Aitzgorri thrust southwest of Cegama and rocksalt from the Aitzgorri-1 exploration well, drilled in 1965. The later samples were originally collected at depths between 2920 and 4200 m. These were provided by the Spanish Geological Survey and selected from its lithotheque (Table 2). The samples of the Aitzgorri-1 exploration well are composed of halite as the dominant mineral phase, with secondary quantities of calcite, pyrite, muscovite, quartz and anhydrite, as determined with X-ray diffraction techniques.

Table 1
Sulfur and oxygen isotopic compositions of gypsum

Location	Sample	$\delta^{34}S$	$\delta^{18}O$
Salinillas de Buradón diapir	SB-1	14.70	12.39
Salinillas de Buradón diapir	SB-2	13.80	14.13
Salinillas de Buradón diapir	SB-3	14.30	13.36
Salinillas de Buradón diapir	SB-4	14.20	14.70
Salinillas de Buradón diapir	SB-5	13.90	15.18
Salinillas de Buradón diapir	SB-6	13.60	13.29
Arlabán tunnel	AR-1	20.00	19.10
Arlabán tunnel	AR-2	21.20	19.57
Aitzgorri thrust	AT	19.70	18.26

Water samples were taken from five saline springs. Three of them were close to outcrops of Triassic evaporites (Urbeltza and the diapirs of Salinas de Añana and Orduña; Fig. 1) and two were close to the Arlabán tunnel and the surrounding exploration wells (Gesala and Salinas de Léniz; Fig. 2). Samples from the Gesala and Salinas de Léniz springs were taken at two different times. An additional non-saline spring was sampled (Anarri); it is situated in the Arlabán tunnel area though at a higher altitude than the saline springs (Fig. 2). Flow and temperature of water in the springs were recorded during sampling, and the dissolved contents of SO_4 and Cl were analyzed at the Universidad del País Vasco (Table 3).

Gypsum samples were dissolved in distilled water. These dissolutions and spring waters were acidified to pH < 2, and then $BaCl_2 \cdot 2H_2O$ was added. The resulting $BaSO_4$ precipitate was filtered and sent to the laboratory for isotopic analysis of S and O. As regards the drill cuttings, the lithotheque of the Spanish Geological Survey only provided limited amounts of samples from the Aitzgorri-1 well (Table 2). A fraction of the drill cuttings was dissolved, and the SO_4 content of the dissolution was analyzed to estimate the SO_4 content of the whole sample. Since the isotope laboratory requirement is 30 mg of SO_4, only the drill cutting samples with higher SO_4 content were used for isotopic analysis. $BaSO_4$ was precipitated following the same procedure as for the gypsum and spring samples. ^{34}S and ^{18}O isotope contents from SO_4 were analyzed at the Universidad de Salamanca with a VG-Isotech SIRA-II mass spectrometer. ^{2}H and ^{18}O isotope contents from H_2O were determined at the Universidad Autónoma de Madrid with a VG-PRISM Series II mass spectrometer. The results of $\delta^{34}S$ are given in terms of (‰) relative to VCDT (Vienna Cañón Diablo Troilite; Ault and Jensen, 1963); and the results of $\delta^{18}O$ and $\delta^{2}H$ are given in terms of (‰) relative to VSMOW (Vienna Standard Mean Ocean Water; Baertschi, 1976).

5.2. Rock samples

Sulfur and oxygen isotopic composition of gypsum and drill-cutting samples are presented in Tables 1 and 2, and in Fig. 6. It is compared with the isotopic signature of evaporites from the Basque–Cantabrian and the nearby Cameros basin published so far (Utrilla et al., 1992; Alonso-Azcárate et al., 2006) and with the isotopic composition of coeval marine sulfate (Triassic to Cretaceous; Claypool et al., 1980). The Cameros basin contains Berriasian evaporites deposited in a continental setting and is located 120 km south the Aitzgorri area.

The rock samples analyzed can be divided into two groups. The first includes the six samples from Salinillas de Buradón diapir (SB-1 to SB-6 in Table 1) and the deepest sample from the Aitzgorri-1 well (taken at a depth of 4200 m, close to a lithological contact with underlying evaporites richer in sandstone and shale layers). They have a composition comparable to that of Triassic evaporites and to that of Triassic marine water. Rock samples of the second group (from the Arlabán tunnel, AR-1 and AR-2 in Table 1, the Aitzgorri thrust, AT, and the two shallower samples from the Aitzgorri-1 well: from depths of 2920 and 3640 m, A-2920 and A-3640 in Table 2) have compositions ranging between $\delta^{34}S = 17.7$ to 21.2‰ (mean = 19.6‰) and $\delta^{18}O = 14.8$ to 19.6‰ (mean = 17.3‰). These compositions are different from that of Triassic evaporites. If compared with the Berriasian evaporites of the Cameros basin, they have a similar composition in $\delta^{34}S$, but at variance in $\delta^{18}O$. The isotopic composition this second group can be compared with that of Cretaceous marine water records. In the Early Cretaceous, a rapid decrease in $\delta^{34}S$ mean values from 17‰ to 14‰, was recorded by Claypool et al. (1980) and confirmed by a more detailed register by Paytan et al. (2004). Samples of the second group exhibit a $\delta^{34}S$ composition similar to that marine water between 130 and 125 Ma (when mean $\delta^{34}S$ values decreased from 20‰ to 15.5‰). The comparison of $\delta^{18}O_{SO4}$ content of rock samples with the Early Cretaceous marine water is less conclusive, since the $\delta^{18}O_{SO4}$ marine record is currently less precise than the $\delta^{34}S$ record. Claypool et al. (1980) reported interpolated values of $\delta^{18}O$ for the Early Cretaceous ranging between 12‰ and 16‰.

As regards the Aitzgorri-1 samples (Table 2), the isotopic signature of the uppermost part of the well (at depths of 2920 and 3640 m) is similar to the likely Cretaceous evaporites, whereas the lowermost part (4200 m) has $\delta^{34}S$ and $\delta^{18}O$ values similar to those of Triassic evaporites. Ortí et al. (1996) reported, too, Br compositions at variance with Triassic evaporites in the uppermost part of Aitzgorri-1. Br content of samples taken at depths of 2425 and 3886 m was below 13 ppm, whereas the mean Br content of Triassic evaporites sampled in other oil exploration wells was 150 ppm. The different isotopic composition between the upper and the lowermost part of Aitzgorri-1well can be related to three causes: (1) a primary stratigraphy in which the Triassic directly occurs under Cretaceous evaporites, (2) the early Cretaceous recycling and redeposition of Triassic evaporites, or (3) thermochemical sulfate reduction processes.

The possibility that the original isotopic signature of "wealdian" rocks had been modified after deposition by thermochemical sulfate reduction processes (TSR) or by circulation of hydrothermal brines cannot be ruled out. The TSR process depends on ambient temperatures above 140 °C and on the existence of organic matter in the sediment. Wealdian rocks contain abundant organic matter and likely attained temperatures of 200 °C during burial (Arostegui et al., 1991). TSR processes would generate a large amount of native Sulfur deposits and a significant secondary porosity. However, very small native sulfur deposits have been found in these sediments, which hydrogeologically have remained essentially impermeable. Therefore, though TSR certainly took place in these sediments, it was volumetrically very limited, highly localized and would have not produced significant modifications of the $\delta^{34}S$ composition of original sulfates. As regards the hydrothermal circulation, Zn–Pb and Fe sulfides as well as barite ore deposits are common in the Bilbao anticlinorium area. They are hosted in Urgonian carbonate rocks of Lower Aptian and Lower Albian age and were studied by

Table 2
SO_4 content, isotopic composition and mineralogy of Aitzgorri-1 drill cuttings

Sample depth (m)	Sample weight (g)	SO_4 content[a] (mg)	Dissolved sample (g)	SO_4 precipitated (mg)	$\delta^{34}S$ SO_4	$\delta^{18}O$ SO_4	XRD mineralogy
A-2920	13.46	30.9	11.106	91.2	17.70	14.98	
A-3640	14.86	56.9	6.792	15.0	19.30	14.83	
A-3720	8.72	[b]					Halite (calcite, pyrite, muscovite, quartz, anhydrite?)
A-4100	5.51	19.3					
A-4135	6.77	13.1					
A-4170	10.71	193.6					
A-4200	12.88	203.4	5.010	144.0	14.20	13.15	Halite (gypsum?)

XRD, X-ray diffraction.
[a] Initial estimation.
[b] Below detection limit.

Table 3
Isotopic and chemical composition of springs

Sample	Spring	Flow (l/s)	Height (masl)	Temp. (°C)	Cl (mg/l)	SO_4 (mg/l)	$\delta^{34}S$ SO_4	$\delta^{18}O$ SO_4	$\delta^{18}O$ H_2O	$\delta^{2}H$ H_2O
SL-1	Salinas de Léniz	0.2	430	13.5–14.1	104000–85504	3000–1185	15.10	13.96		
SL-2	Salinas de Léniz	<0.1	430	10.5–13.2	156000–96900	6000–2300	19.80	14.70	−7.2	−48
GE-1	Gesala	<0.5	650	10.3–11.0	57163–27200	5036–1379	19.00	17.46		
GE-2	Gesala						17.90	16.28	−7.39	−48.7
SA	Salinas de Añana	1–10	605	17.0	153158	5017	11.09	12.40		
OR	Orduña	<1	270	13.0	6775	1967	13.08	15.20		
UR	Urbeltza	330	263	11.0	4–9	640–360	13.38	15.70		
AN-1	Anarri	50	905	7.0–10.0	6.5	8.5			−7.85	−49.4
AN-2	Anarri								−8.35	−49.5

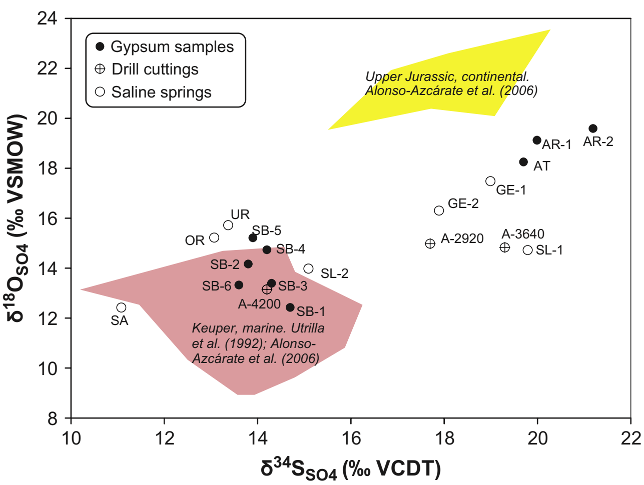

Fig. 6. $\delta^{34}S$, $\delta^{18}O$ composition of SO_4 from gypsum, drill cuttings and saline springs. See Tables 1–3 for sample label description.

Velasco et al. (1994). These authors conclude that the mineralizing brines had a temperature ranging between 120 and 230 °C, circulated at depths up to 4000 m, leached Paleozoic basement materials and ascended through fractures during Late Aptian to Early Albian times. The $\delta^{34}S$ isotopic compositions reported for sulfide ores and barite range between 0‰ and 7‰ and 25‰ and 30‰, respectively. The carbonate wall rocks next to ore bodies exhibit very limited signs of alteration due to the action of hydrothermal fluids. These evidences support the idea that hydrothermal fluids would have not been capable of changing the Sulfur isotopic composition of large masses of Triassic gypsum or "wealdian" evaporites, that would have remained close to that of the marine record.

5.3. Groundwater

Sulfur and oxygen isotopic compositions of water-dissolved sulfate from saline springs are presented in the Table 3 and Fig. 7. The saline springs spatially related to Triassic evaporite diapirs (samples SA, OR, UR) have a similar isotopic composition, whereas the Gesala spring (samples GE-1, GE-2) presents a composition close to that of Early Cretaceous evaporites.

Salinas de Léniz is composed by a group of smaller, convergent springs. Sample SL-1 was taken from the collective water spring, whereas the sample SL-2 was taken from the most saline spring. While SL-2 sample has an isotopic composition that compares to Triassic evaporites, the collective sample (SL-1) has the composition of Cretaceous evaporites.

The $\delta^{18}O_{H2O}$ and $\delta^{2}H_{H2O}$ composition is used to obtain information about the origin and the topographic height of the springs recharge area (Fig. 7). The Salinas de Léniz and Gesala springs' $\delta^{18}O$-$\delta^{2}H$ composition shows that they have meteoric origin. These springs are located at heights of 430 and 650 m, respectively, and their composition is similar to the Anarri spring (AN-1 and 2 in the Table 3), located at 905 m. Using the local topographic elevation-isotopic relationship (about −0.2‰ $\delta^{18}O$/100 m; cf. Iribar and Antigüedad, 1996, Iribar et al., 2003), it can be inferred that the recharge area of these springs is located at 800 (Salinas de Léniz) and 1000 m (Gesala). Complementary to this, water temperatures of the Salinas de Léniz and Gesala springs are ca. 6 °C and 3 °C higher than the temperature of the Anarri spring (Table 3). Taking into account the regional geothermic gradient (2.5 °C/100 m; cf. Garrote et al., 1995), the groundwater circulation through evaporites must have attained subsurface depths of 240 and 120 m, respectively, below the spring elevation. These depths are minimum values, as the water may cool during ascent and the cooling effect may be important in modest flow springs. Q5

6. Discussion

The geological and isotopic evidence given above suggests that volumetrically significant units of the subsurface in the Bilbao anticlinorium, traditionally regarded as Triassic evaporites, can be in fact Cretaceous evaporite successions. This demands a revision of the structure of the anticlinorium, which is discussed below.

6.1. Structural implications

No Triassic (Keuper) or Jurassic outcrops exist in the Bilbao anticlinorium area. To the South, the nearest Keuper outcrops occur

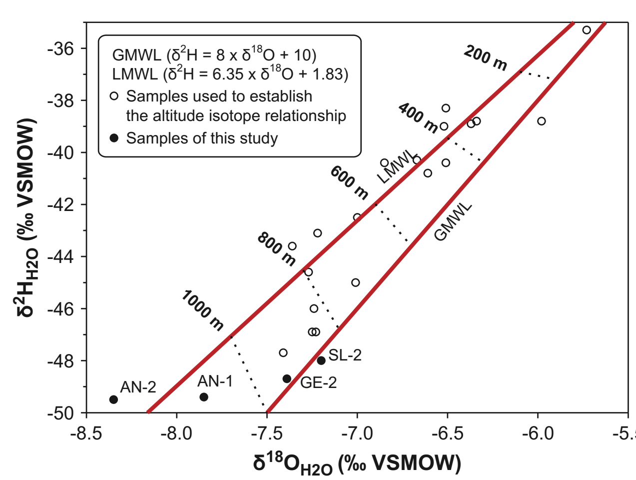

Fig. 7. $\delta^{18}O_{H2O}$, $\delta^{2}H_{H2O}$ diagram of the spring samples. GMWL: Global Meteoric Water Line; LMWL: Local Meteoric Water Line. Dashed lines show the height of the recharge area of the springs. See Table 3 for sample label description.

at ca. 20 km of the anticlinorium axis and form diapirs aligned subparallel to it. Much smaller diapirs and saline structures occur to the North, at a similar distance (Fig. 1). Alongstrike, non-diapiric Triassic evaporite outcrops occur at the anticlinorium ends (west of Bilbao, Fig. 1, and in the Aralar area, Fig. 2), below Mesozoic successions including middle Jurassic rocks deposited in marine environments. Their structural position can be related either to normal (NW anticlinorium closure) or reverse faults (SE termination). This regional organization and the nature and completeness of the Jurassic successions (Robles et al., 2004) suggests that (1) the Triassic evaporites and Jurassic rocks were not deposited in the Bilbao anticlinorium area, (2) these rocks were removed by Late Jurassic erosion and halokinetic/tectonic processes, or (3) that pre-Cretaceous rocks occupy structural positions below a lower Cretaceous evaporite detachment.

The Triassic Keuper sedimentation was expansive and covered the Basque–Cantabrian basin (Serrano et al., 1989; Ortí et al., 1996). As regards marine Jurassic sedimentation in the Bilbao anticlinorium area, Aurell et al. (2002) documented subaerial exposure and widespread erosion of Jurassic marine rocks prior to the latest Jurassic and Robles et al. (2004) published isopach maps supporting its absence or scarcity. Serrano and Martínez del Olmo (2004) support the occurrence of Jurassic rocks in the subsurface of the Bilbao anticlinorium based upon the interpretation of reflection seismic profiles in which Jurassic formations are drawn below outcropping Early Cretaceous successions and above not exposed formations interpreted as Triassic evaporites. This follows the assumption, after Ramírez del Pozo (1973), that the Aitzgorri-1 well drilled Triassic instead of Cretaceous evaporites. In conclusion, in the Bilbao anticlinorium Triassic evaporites might have been partly removed, together with the marine Jurassic, by erosion before the latest Jurassic.

The geometrical organization of Early Cretaceous rocks shown in Fig. 4a and b constitutes a clear demonstration of structural inversion after syn-halokinetic sedimentation and salt withdrawal (Warren, 2006). This is the case of the downlap geometry of Early Cretaceous lithostratigraphic contacts. Their structural discordance against the basal detachment, currently a primary weld of the "overburden touchdown" type (Jackson and Cramez, 1989) is also remarkable, as well as the induced thickness variations in the southern sectors of the cross sections (expulsion rollovers). Inversion is reflected, too, in the thickness variations and contact organization of coeval formations across secondary welds, currently steep reverse faults (Fig. 4b). These exhibit "normal" hangingwall and footwall contact drags in the deepest fault segments and "reverse" drags in the hangingwall of the shallower fault sectors. As can be inferred from the cross sections, the syn-kinematic sedimentation occurred during Early Cretaceous times, along a period encompassing the deposition of the Purbeck–Weald and the Urgonian complexes. These geometries have implications in the formation of Early Cretaceous minibasins and in the structural role of primary and secondary salt welds.

Thick earliest Cretaceous sedimentation on top of an incompetent Triassic salt and clay layer would favor differential loading and the formation of minibasins. As the minibasin floor subsides and pushes the underlying salt aside, the accumulated sediments form migrating depocenters and wedge-shaped lithosomes with contacts displaying rollover geometries. The process continues until the minibasin floor touches down, which transforms it into a primary weld and initiates minibasin inversion as a mock turtle structure (Warren, 2006). The occurrence of an earliest Cretaceous elongated depocenter in the Bilbao anticlinorium is demonstrated by the up to 2000 m thick sediments coring it and by the much thinner formations of the same age outcropping in the surroundings or detected in the subsurface (e.g. Fig. 4b). The elongation of the depocenter in a NNW–SSE direction would have been influenced by basement faults of such orientation. The initial sedimentary fill of the Early Cretaceous minibasin was evaporitic and, taking into account the palaeogeography suggested here, would have easily incorporated recycled (Triassic) evaporites of the substrate.

Primary salt welds (Jackson and Cramez, 1989) form after autochthon evaporite thinning and salt withdrawal to a point where the original layer is no longer resolvable on seismic profiles. The welds can retain some evaporites, unable to be removed, that can play a fundamental role as cover detachments during post-sedimentary tectonic inversion. In sedimentary basins these welds can be inverted, resulting in a thin-skinned structural style. These structures can be recognized in Fig. 2 as regional thrusts carrying a few-kilometer-thick sedimentary allochthon. In map view they are subparallel to the lithostratigraphic contacts and the internal strata of the allochthons. The two southwestern thrusts shown in Fig. 2 exhibit characteristics that enable us to ascribe parts of them to this category of tectonic contacts.

Another important structural element of this syn-sedimentary evolution corresponds to cover structures associated to reactivated basement faults or induced by their activity. When basement faults propagate across the sedimentary cover they can create further syn-sedimentary structural complexity, enabling Keuper salt halokinesis, making easier salt evacuation and leading to the formation of secondary salt welds such as that imaged in Fig. 4b. The latter structures can retain salt. They usually cut through the stratigraphic contacts in cross section and map views. Also, they are connected to autochthonous salt layers and primary welds in cross sections. When these structures are inverted under compression, they can be reactivated as reverse faults. Involvement of large tangential displacements can convert them in thrust ramps connected to flats (inverted primary welds).

6.2. *Reinterpretation of cross sections*

The development of antiformal structures in terrains with a thin-skinned structural style can be conditioned by various factors. Fault bend antiforms can develop above footwall thrust ramps. Accommodation folds form when hangingwall ramps accommodate on footwall flats. Antiformal culminations form due to duplex or thrust slice stacking (e.g.: Woodward et al., 1989). Fig. 2 shows that the Bilbao anticlinorium is a complex structure. It is more than 100 km long and displays a broad antiformal organization with a half-wavelength of ca. 20 km. It is compartmented by four major thrusts that converge towards the NW and by a larger number of longitudinal and oblique faults. The latter exhibit both dip-slip and strike-slip tectonic displacements and are collectively arranged as a map-scale, brittle, sinistral shear zone. These structures had a Cretaceous syn-sedimentary history and were reactivated during the Tertiary, as they deform Eocene marine strata.

Figs. 8 and 9 present a structural reinterpretation of the cross sections shown in Figs. 3 and 4a, respectively. They assume that subsurface evaporites of the Bilbao anticlinorium are Early Cretaceous instead of Triassic. In Fig. 8 it is obvious the development of hangingwall anticlines above hangingwall and footwall ramps, as well as the collective organization of the thrust slices as an antiformal stack. Likely, the slices were stacked above a basement ramp drawn in the section for geometrical consistence. In our opinion, the large volume of Triassic salt necessary to fill the core of the antiform (as drawn in Fig. 3) would have been mechanically unstable and buoyant over short geological time scales. Had it really existed, it would have flown spontaneously through a diapiric structure towards the surface. The postulated subsurface organization is resolved here (Fig. 8) with the stacking of Early Cretaceous thrusts slices. The basement would be located at depths of ca. 6–10 km under the anticlinorium axis, with

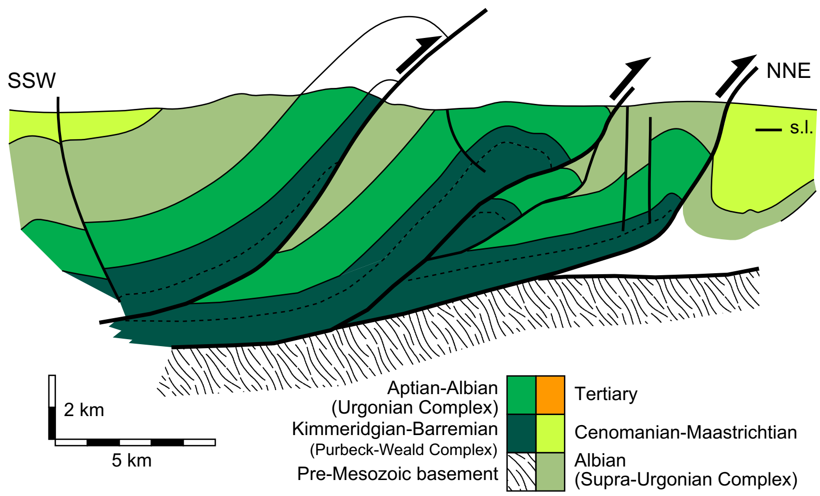

Fig. 8. Structural reinterpretation of the cross section of Fig. 3. s.l.: sea level. See Fig. 2 for location and the text for further details.

a local, gentle dip of 15° toward the South. The anticlinorium core would be filled with a stack of Early Cretaceous "wealdian" rocks. These are partly of evaporitic affinity (the basal section portions) and, locally, can attain a thickness of a few hundreds of meters. This is demonstrated by the Aitzgorri-1 well in the Cegama–Ubidea area (Fig. 2). A comparable structural organization is presented in Fig. 9. Geometrical differences with Fig. 8 are due in part to the fact that Fig. 9 corresponds to the reinterpretation of a reflection seismic profile (after Serrano and Martínez del Olmo, 2004) whose vertical scale actually corresponds to two-way travel times. The reinterpretation resolves the inconsistency of presenting the smallest "wealdian" thicknesses under the antiform axis (Fig. 4a), whilst field mapping demonstrates that several hundreds of meters thick successions occur there.

Fig. 10a is a cross section constructed after the Garrote et al. (1995) map. It traverses the central part of the Bilbao anticlinorium (Fig. 2) along the Arlabán tunnel section and its NE prolongation towards Vergara. The southernmost thrust slice places Aptian–Albian rocks with a hangingwall flat disposition onto a footwall ramp cutting across Early Cretaceous to Albian formations. The structure of the anticlinorium core is essentially unresolved at relatively shallow depths below 2 km. In Fig. 10b the new structural interpretation is shown. This cross section includes "wealdian" rocks at the sole of the southernmost thrust slice, whose detailed near-surface structure was presented in Fig. 5. The "wealdian" core of the anticlinorium is presented as an uplifted block (pop-up) between two steeply dipping faults with normal and reverse-slip components. This structure is superimposed on a thrust slice stack that results from the prolongation towards the WNW of the slices recognized in the cross sections of Figs. 8 and 9. Hangingwall antiforms develop above footwall ramps and internal duplexes and thrust branches bifurcate from the major thrusts. The reinterpreted cross section resolves the deep structure of the Bilbao anticlinorium with cover rocks extending to depths below 6–8 km. An antiformal thrust stack developed directly on a basement ramp gently dipping towards the south.

6.3. *Revised structure of the Bilbao anticlinorium*

The revision of published geological maps of the Bilbao anticlinorium area (Olivé-Davó et al., 1989; Garrote et al., 1995) and correlation of the thrust slices recognized in the cross sections drawn along its strike enable us to present in Fig. 11 a new structural map of the anticlinorium. We regard this major structure as the southern boundary of the most intensely deformed Basque Arc (Feuillée and Rat, 1971). Cuevas et al. (1998) considered the Basque Arc formed by three major, north vergent thrust sheets. These are, from the lowermost (located to the NNE) to the uppermost one (located at the SSW), the Aya, Pagoeta and Azpeitia slices. They are floored by Triassic evaporites. The Aya basal thrust is a gently dipping blind structure. The Pagoeta and Azpeitia thrusts crop out and bear gentle and moderate dips, respectively, towards the SSW. Forward propagation of these structures accommodated minimum

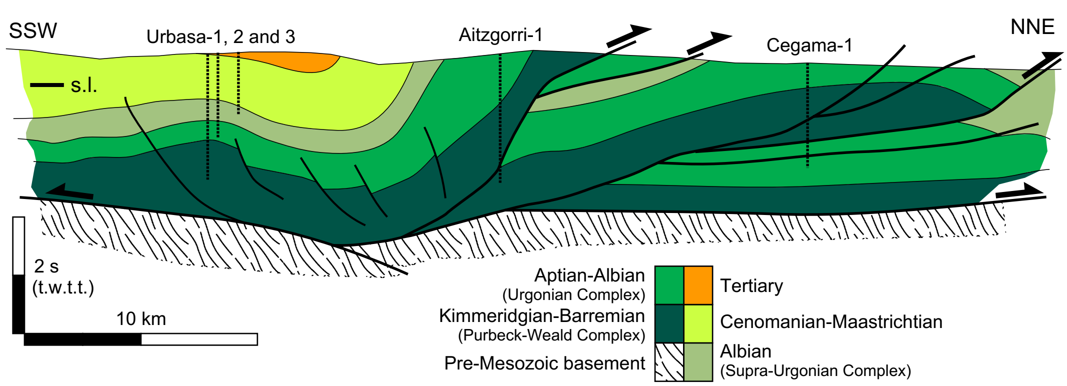

Fig. 9. Structural reinterpretation of the cross section of Fig. 4a (drawn after Serrano and Martínez del Olmo, 2004). t.w.t.t.: two-way travel times (seconds). s.l.: sea level. Discontinuous vertical segments with labels on top are projected oil wells. See Fig. 2 for location and the text for further details.

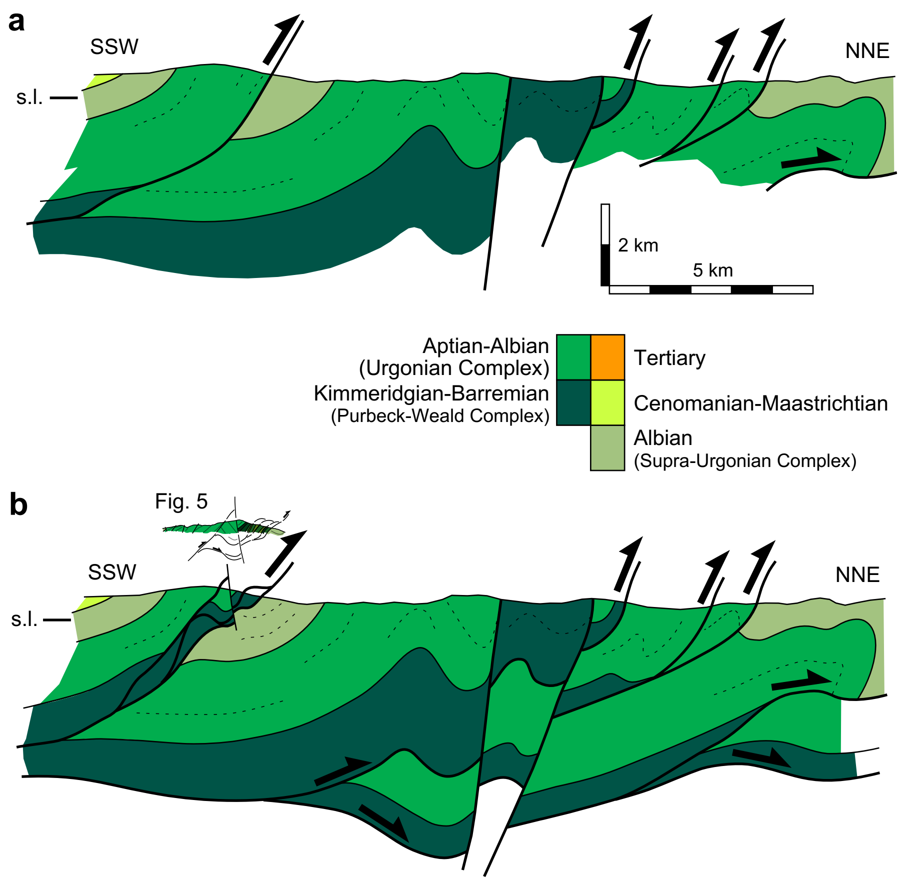

Fig. 10. (a) Geological cross section of the Bilbao anticlinorium drawn after the Garrote et al. (1995) 1:100,000 scale map. (b) Structural reinterpretation of the cross section (a) including the information provided by the Arlabán tunnel (shown in Fig. 5). s.l.: sea level. See Fig. 2 for location and the text for further details.

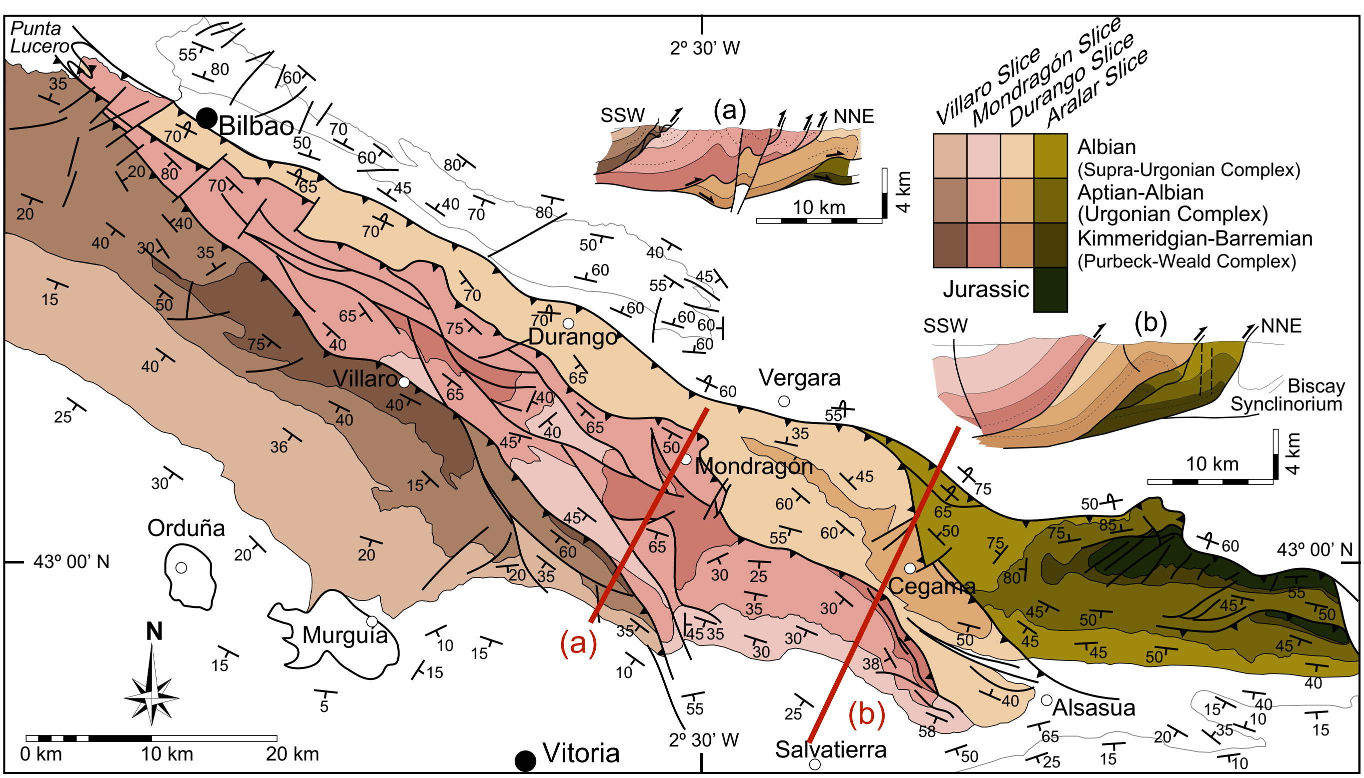

Fig. 11. Structural organization and nomenclature of the thrust slices that constitute the Bilbao anticlinorium. See text for further details.

shortening components above 20 km (Cuevas et al., 1998). The Azpeitia slice is bounded to the south by a subvertical, retro-vergent backthrust (the Azcoitia fault) that separates the aforementioned slice from the Biscay synclinorium. This is also a NE-facing allochthonous structure carrying mid-Eocene foliated and metamorphosed rocks (Cuevas and Tubía, 1999) and refolding pre-existing folds and thrusts.

The Bilbao thrust fault (Fig. 11) is the southwestern limit of the Biscay synclinorium and the northeastern boundary of the Bilbao anticlinorium. This thrust dips steeply to the SSW and extends along more than 120 km from the Cantabrian coast to the NW of Pamplona (Fig. 1). East of Vergara (Fig. 11) it is known in the regional literature as the Aralar thrust (Martínez Torres, 1989). The dip-slip structural throw of the Bilbao thrusts varies along strike, as it dies out at its eastern termination. In the cross sections presented in this study it is of the order of 5–10 km.

East of Vergara, the Cegama thrust branches from the Bilbao thrust and permits the individualization of the Aralar slice (Fig. 11). Its internal organization presents a relatively complex anticlinal culmination above a hangingwall ramp. The maximum dip-slip throw of the Cegama thrust is also of ca. 5–6 km (Fig. 11, cross section b). In map view it forms an angle of ca. 40° with the mean trend of the Bilbao thrust and extends along 25 km to the SE until it terminates near Alsasua.

The Bilbao, Cegama and Aitzgorri thrusts bound the Durango slice. The latter thrust runs subparallel to the former, but both converge towards the WNW forming an average angle of 10°. The internal structure of the Durango slice is relatively simple. Stratigraphic contacts dip moderately in its southeastern sector, where a domal structure developed over hangingwall and footwall thrust ramps (Fig. 11, cross section b). García Mondéjar and García Pascual (1982) described a widespread, subvertical or steeply dipping, NE verging foliation affecting a considerable proportion of the material of this slice in the area located to the SW of Bilbao. This penetrative structure is associated to dam/hm-scale folds and reverse faults, also verging toward the NE. Associated minor fold axes are slightly oblique to the trace of the Bilbao thrust. They plunge toward the ESE and their periclinal closures display "en-échelon" arrangements. The Aitzgorri thrust extends along ca. 100 km and dies out NE of Salvatierra. Its maximum dip-slip throw is of the order of 10 km (Fig. 11, cross sections a and b).

The Mondragón slice is bounded by the Aitzgorri and the Villaro thrusts. They form an angle of ca. 10° in map view. The slice conforms the outcropping core of the Bilbao anticlinorium. Its stratigraphic thickness can attain 8 km and it is the most complexly deformed of the slices studied. It is internally compartmented by several oblique faults with vertical and tangential displacements, by sets of frontal duplex structures (Fig. 10) and various domal structures develop alongstrike. According to our geometrical reconstruction, its basal thrust is refolded by accommodation to flat-ramp structures developed in the footwall (Fig. 11, cross section a). This suggests a forward propagation of the thrust association. At the WNW, in the Punta Lucero area, Aranguren et al. (1990) described a folded and faulted, north verging thrust with associated fault bend folds that can be correlated with the structures and materials of the Mondragón slice and its para-autochthon (Durango slice). In their tectonic reconstruction, the prolongation of the Aitzgorri thrust was folded and then fractured in the fold's reverse limb to actually form a younger reverse fault (the Bilbao thrust reported here). The coalescence of both structures can be observed to the west of Bilbao in Fig. 11.

The Villaro thrust forms the northern tectonic limit of the relatively undeformed, southern coherent portion of the Basque–Cantabrian domain (Barnolas and Pujalte, 2004), emplaced onto the Ebro–Duero tertiary basins (Fig. 1). Its internal organization is characterized by a large hangingwall anticline developed above a footwall thrust ramp and by the formation of duplexes in the vicinity of the sole thrust. The hangingwall anticline likely represents an inverted Early Cretaceous depocenter. In this study we have extended the thrust trace toward the WNW, up to the Cantabrian coast. It coalesces there with the underlying Aitzgorri thrust, whereas to the ESE it is connected with the complex thrust association recognized in the Arlabán tunnel area (Figs. 5 and 10). The resultant structure extends for more than 70 km until it dies out to the NE of Vitoria (Fig. 11). Its dip-slip throw varies from zero at its termination to ca. 8 km at its central segment (Fig. 11, cross section a).

6.4. Tectonic model

Tectonic shortening accommodated by the Bilbao anticlinorium thrust system is of ca. 15–20 km. Individual thrusts can associate maximum dip-slip throws of up to 10 km. Their organization as a branching/"en echelon" structural ensemble and their footwall propagation mode enabled the progressive spatial and temporal transfer of tectonic shortening from east to west and from south to north. The components of transversal shortening were likely accompanied by alongstrike sinistral displacements in some of the major faults. At the scale of the Basque–Cantabrian basin, the magnitude of tectonic shortening accommodated by N-verging structures can thus be estimated in 40–50 km (a minimum of 25 km was established by Gómez et al., 2002). The shortening accommodated by the frontal, S-verging thrust structures was smaller (15–20 km; Serrano and Martínez del Olmo, 2004). This resulted in a Tertiary transversal shortening of ca. 60–70 km for the Basque–Cantabrian basin. Shortening resulted from the inversion of a Mesozoic crustal extension of the same magnitude (Vergés and García Senz, 2001). Vergés et al. (1995) reported a minimum shortening of 125 km for the central Pyrenees from the ECORS-Pyrenees deep reflection profiles (Choukroune and ECORS Team, 1989; Roure et al., 1989). Teixell (1996, 1998) disclosed a shortening decrease to 80 km near the ECORS West Pyrenees seismic profile (Daignières et al., 1994). This variation denotes a reduction in thrust displacement towards the west that has also been constrained with the ESCI-N2 and ESCI-N4 seismic profiles (Álvarez-Marrón et al., 1997; Pulgar et al., 1997).

As regards the current mid- and deep- crustal organization of the Basque–Cantabrian basin, it is widely accepted that the Iberian lithosphere was subducted northward under the European plate both in the Pyrenees (Choukroune and ECORS Team, 1989; Roure et al., 1989; Daignières et al., 1994; Teixell, 1998), in the Basque–Cantabrian basin (Cuevas et al., 1999) and under the Cantabrian Mountains (Gallart et al., 1995; Pulgar et al., 1996). In the latter realm subduction of the Bay of Biscay under the Cantabrian Mountains had been assumed previously (Álvarez-Marrón et al., 1995). Recent papers have revealed a complex deep crustal structure of the Pyrenean–Cantabrian orogen with a thinner plate (Europe) indenting into a thicker one (Iberia) and forcing the N-directed subduction of the latter (Pedreira et al., 2003, 2007). Central to this organization is the existence of an indenting wedge of deep crustal rocks at mid-crustal depths under the Basque–Cantabrian basin. Pedreira et al. (2007) studied the geometry of this wedge and argued that its top occurs at depths of 5 to 15 km. The wedge dips to the SSW between 15° (at the western part) and 25° (to the east) and is thrusted by a mid-crustal allochthon whose top defines the antiformal culmination geometry. From a geological perspective, this wedge occurs directly under the Bilbao anticlinorium. Cuevas et al. (1999) postulated a remarkably comparable organization of the cover-basement relationships in the area. This enabled these authors to trace the western prolongation of the North-Pyrenean fault to the south of the Biscay synclinorium and fit

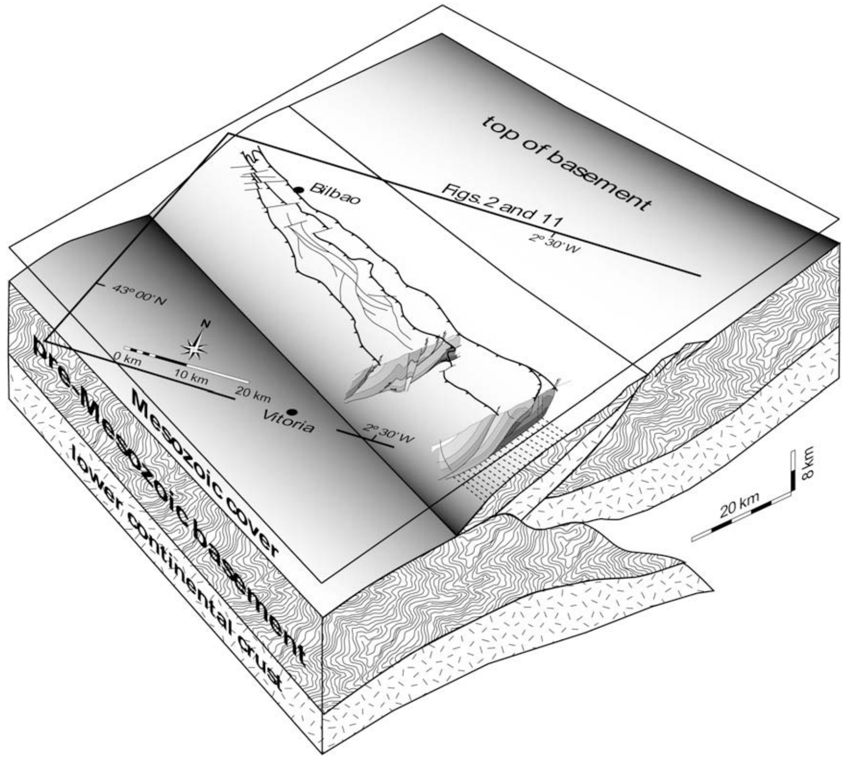

Fig. 12. Block diagram showing the likely structure of the continental crust in the Basque–Cantabrian basin. The Mesozoic cover is shown as a transparent layer for convenience. The surface trace of thrusts and the cover cross sections were drawn after Figs. 8, 10b and 11. Schematic crustal-scale cross section after Pedreira et al. (2007). See text for further details.

it with gravimetric (Casas et al., 1997) and aeromagnetic (Aller and Zeyen, 1996) positive anomalies. The reconstructed position and dip of the base of the thrust slices are in good agreement with the geophysical interpretations. The Bilbao anticlinorium slices form a culmination resting directly above a S-dipping surface that coincides with the top of the pre-Meosozoic basement (Fig. 12). Taking into account the geophysical information, the latter would be a mid-crustal slice thrusted to the north, with a thickness of 2–5 km, similar to that of the succession preserved in Palaeozoic massifs of the western Pyrenees.

7. Conclusions

Reinterpretation of the geological structure of the Bilbao anticlinorium permits us to postulate that volumetrically significant units of the subsurface, traditionally regarded as Triassic evaporites, can be in fact Cretaceous evaporite successions. A new structural map of the anticlinorium shows that it is compartimented by four major branching thrusts that separate four allochthonous slices. The new and reinterpreted cross sections presented resolve the deep structure of the Bilbao anticlinorium with Mesozoic cover rocks extending to depths below 6–8 km. Hangingwall anticlines developed above both hangingwall and footwall thrust ramps and the slices are collectively organized as an antiformal stack. Footwall thrust propagation enabled the progressive spatial and temporal transfer of tectonic shortening from east to west and from south to north.

The Bilbao anticlinorium can be regarded as the surface expression of an indenting wedge of deep crustal rocks situated at mid-crustal depths under the Basque–Cantabrian basin. The anticlinorium developed directly on a basement ramp gently dipping towards the south. Tectonic shortening accommodated by the thrust system was of ca. 15–20 km and was likely accompanied by alongstrike sinistral displacements.

Acknowledgments

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