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Key Points:

- The independent plate kinematics of the Landes High played an important role during the formation of the Bay of Biscay
- Results of deformable plate models suggest the Ebro Block had minimal impact on the deformation experienced within the Bay of Biscay
- Major lithospheric boundaries played a significant role in shaping the present-day crustal structure of the Bay of Biscay

Supporting Information:

Supporting Information may be found in the online version of this article.

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Investigating the Plate Kinematics of the Bay of Biscay Using Deformable Plate Tectonic Models

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Abstract The plate kinematics of the Iberian plate and their implications on the plate tectonic evolution of the Bay of Biscay during rifting and subsequent opening of the southern North Atlantic continue to be topics of scientific discussion and debate. Constrained by previous plate reconstruction, geophysical, and geological studies, deformable plate tectonic reconstructions of the Bay of Biscay-Parentis rift system are created in this study using the GPlates software. These deformable plate models are used to investigate the kinematics of the Landes High, Le Danois High, and Ebro Block previously recognized as independent continental blocks within deformable regions. A comparison between results calculated via deformable plate models with previously published and newly presented gravity inversion crustal thickness estimates provided a good metric for delineating the most probable plate kinematic scenario for the Bay of Biscay-Parentis system and investigating the effect of the plate kinematic scenarios on the present-day structure. The preferred plate kinematic model implies a transtensional Bay of Biscay-Parentis rift system from the Jurassic to Early Cretaceous, with the onset of significant crustal thinning initiating during the Late Jurassic (~150 Ma) induced by the motion of the Landes High and its interplay with the Ebro Block. Aside from demonstrating the role of the Landes High and its suggested interplay with structural inheritance on the deformation experienced within the Bay of Biscay, the timing and orientation of regional stress directions, and the velocities induced by the preferred deformable model provide good comparisons with previously calculated subsidence rates.

1. Introduction

The plate kinematic evolution of the Bay of Biscay during rifting and subsequent opening of the southern North Atlantic (Figure 1a) has been a subject of debate for several decades (Barnett-Moore et al., 2016; Cadenas et al., 2018; García-Mondéjar, 1996; Gong et al., 2008; Jammes et al., 2010c; Nirrengarten et al., 2018; Sibuet et al., 2004; Srivastava et al., 1990; Tugend et al., 2014, 2015a). Bounded by several margins that host numerous sedimentary basins (Figure 1b), the Bay of Biscay has drawn significant interest for independent geological and geophysical studies that provide valuable insight into its regional plate kinematic evolution and natural resource potential (Boillot et al., 1979; Bois et al., 1997; Brunet, 1984; Cadenas & Fernández-Viejo, 2017; Jammes et al., 2009, 2010c; Thinon et al., 2002, 2003; Tugend et al., 2015b).

Subject to western European tectonic events dating back to the Paleozoic, the present-day crustal structure of the Bay of Biscay is the product of poly-phase and multistage rifting that initiated within a complex pre-rift template encompassing inherited Variscan to Late Carboniferous-Early Permian structures and crustal heterogeneities (Burg et al., 1994; Cadenas et al., 2020; Jabaloy et al., 2002; Matte, 1991, 2001; Schiffer et al., 2019; Tavani et al., 2018). From the Triassic to Early Cretaceous, the Bay of Biscay experienced transtensional and extensional rifting episodes that caused significant crustal thinning prior to the onset of compressional deformation during the Alpine Orogeny (Cadenas et al., 2018; Nirrengarten et al., 2018; Olivet, 1996; Roca et al., 2011; Sibuet et al., 2004; Tugend et al., 2015a). As a result of its complex evolution, interpretations derived from regional seismic, potential field, and well data within the Bay of Biscay will often accompany uncertainties regarding temporal variations in plate kinematics and stress orientations.

The ability to study regional plate kinematic evolution using plate tectonic reconstructions has evolved significantly since the introduction of plate tectonic theory (Barnett-Moore et al., 2018; Bullard et al., 1965; Gurnis et al., 2018; Matthews et al., 2016; Müller et al., 2018; Nirrengarten et al., 2018; Seton et al., 2012;

Figure 1. Maps of the southern North Atlantic and the specific study area (outlined in dashed yellow box in a). Crustal sutures, fracture zones, and chron 34 (C34) magnetic anomaly locations extracted from Welford et al. (2012), and sedimentary basin outlines extracted from Nirrengarten et al. (2018). (a) Southern North Atlantic with sedimentary basins along the Newfoundland margin, Irish margin, Bay of Biscay, West Iberian margin, and Iberian Interior, highlighted in green. Fracture zones and crustal sutures shown in white and black solid lines, respectively. (b) Map of the Bay of Biscay with outlines of sedimentary basins, geological features and boundaries, and location of wells from the Ocean Drilling Program (ODP) and Deep Sea Drilling Project (DSDP), and Parentis exploration wells extracted from Tugend et al. (2014). AB = Asturian Basin, AMB = Arzacq-Mauleon Basin, ASZ = Armorican Shear Zone, BCB = Basque-Cantabrian Basin, CB = Cameros Basin, DH = Le Danois High, EB = Ebro Block, EUR = Europe, FC = Flemish Cap, GB = Galicia Bank, GIB = Galicia Interior Basin, GS = Goban Spur, IB = Iberia, IR = Ireland, LH = Landes High, NL = Newfoundland and Labrador, NPF = Northern Pyrenean Fault, OK = Orphan Knoll, OB = Orphan Basin, PaB = Parentis Basin, PB = Porcupine Bank, PBs = Porcupine Basin, PoB = Porto Basin, RB = Rockall Bank, RT = Rockall Trough, SPF = Southern Pyrenean Front, STZ = Santander Transfer Zone, UK = United Kingdom, VF = Ventaniella Fault, WAB = Western Approaches Basins, WAM = Western Approaches Margin.

Sibuet et al., 2004; Srivastava et al., 2000; Williams et al., 2012). In light of recent improvements made to plate tectonic modeling software, deformable plate tectonic reconstructions allow one to investigate temporal variations in strain rate, crustal thickness, and stretching (beta) factors within deformable regions (Gurnis et al., 2018). Thus, they provide an excellent tool for addressing complex plate kinematic problems and uncertainties inherent to less informative rigid plate reconstructions (Ady & Whittaker, 2018; King

et al., 2020; Müller et al., 2019; Peace et al., 2019b; Welford et al., 2018). Considering previous applications, this approach has proven to be advantageous for studying the complex plate kinematic evolution of the southern North Atlantic (Peace et al., 2019b). In particular, recent deformable plate reconstructions of the southern North Atlantic have demonstrated the significance of continental blocks, their independent kinematics, and interplay with inherited structures in order to produce present-day crustal thickness results more akin to present-day observations within deformable regions (King et al., 2020; Peace et al., 2019b; Welford et al., 2018).

In this study, following a similar methodology presented in previous deformable plate modeling studies (King et al., 2020; Peace et al., 2019b), deformable plate tectonic models of the Bay of Biscay are built using the GPlates software (Müller et al., 2018; Williams et al., 2012), version 2.2, and recently published constraints along the North Iberian, Armorican, and Western Approaches margins (Angrand et al., 2020; Cadenas et al., 2018; Nirrengarten et al., 2018; Peace et al., 2019b; Tugend et al., 2014, 2015b). The deformable plate models presented will be used to analyze temporal variations in deformation within the Bay of Biscay and assess the kinematic role of continental blocks and their impact on its present-day crustal structure. To validate the kinematic evolution and resultant crustal thicknesses calculated by deformable plate models, each model is analyzed in comparison with previously published and newly presented gravity inversion crustal thickness estimates, and interpretations made from previously published seismic and well data. The objective of this approach is to investigate the plate kinematics of the Landes High, Le Danois High, and Ebro Block, and the timing, style, and extent of deformation experienced within the Bay of Biscay.

2. Geological Background

The Bay of Biscay is a V-shaped oceanic basin situated between France and Spain along the eastern side of the southern North Atlantic. The present-day crustal architecture of the Bay of Biscay is a result of southern North Atlantic and Western Tethys related deformation dating back to the Permian (Angrand et al., 2020; Leleu et al., 2016; Williams, 1975). Following Late Permian-Early Triassic rifting and the subsequent breakup of Pangaea initiating ~200 Ma, the future Bay of Biscay was subjected to two of the three main rift phases acknowledged within the southern North Atlantic: (1) Late Triassic to Early Jurassic and (2) Late Jurassic to Early Cretaceous (Barnett-Moore et al., 2018; Boillot et al., 1979; Cadenas et al., 2018; Lundin, 2002; Peace et al., 2019a; Tugend et al., 2015a; Ziegler, 1988). These two main phases of rifting between Iberia and Europe led to significant crustal thinning along its offshore regions during the Early Cretaceous prior to a short lived period of sea-floor spreading initiating during Aptian-Albian time (Montadert et al., 1979; Nirrengarten et al., 2018; Sibuet et al., 2004; Thinon et al., 2003; Tugend et al., 2015a; Vissers & Meijer, 2012). Extensional deformation migrated into the Pyrenean realm during the Early to Mid Cretaceous (Jammes et al., 2009; Tavani et al., 2018; Tugend et al., 2015a). The southern Bay of Biscay experienced reactivation from the Late Cretaceous to Cenozoic caused by compressional deformation induced from the Alpine Orogeny (Alvarez-Marrón et al., 1996, 1997; Boillot et al., 1979; Cadenas & Fernández-Viejo, 2017; Cadenas et al., 2018; Derégnaucourt & Boillot, 1982; Fernández-Viejo et al., 2011; Gallastegui et al., 2002; Roca et al., 2011; Tugend et al., 2014).

2.1. The Bay of Biscay-Parentis Rift System

The offshore regions encompassing the Bay of Biscay-Parentis rift system are the primary areas of interest for this work. The Bay of Biscay-Parentis rift system is interpreted to encompass the North Iberian, Armorican, and Western Approaches margins, and the Parentis Basin. The crustal structure of the Bay of Biscay-Parentis system based on previous rift domain mapping is interpreted to be highly segmented showing significant along strike crustal variabilities (Cadenas et al., 2018; Thinon et al., 2003; Tugend et al., 2014). Its diverse present-day structure is interpreted to be a result of spatial variations in the timing and orientation of principle stresses during rifting, occurrence of inherited structures and prerift salt, and each region's exposure to compressional deformation during the Pyrenean Orogeny (Cadenas et al., 2018, 2020; Ferrer et al., 2008; Jammes et al., 2009, 2010b, 2010c; Lagabriele et al., 2020; Roca et al., 2011; Thinon et al., 2003; Tugend et al., 2014).

2.1.1. The North Iberian Margin

The North Iberian margin consists of the region between northwest Galicia and west of France. This margin plays host to sedimentary basins such as the Asturian Basin (Cadenas & Fernández-Viejo, 2017), major lithospheric structures such as the Ventaniella Fault (Cadenas et al., 2018; Fernandez-Viejo et al., 2014) and interpreted transfer zones such as the Santander Transfer Zone (Roca et al., 2011), and continental blocks such as the Landes High and Le Danois High (Cadenas et al., 2018; Ferrer et al., 2008; Tugend et al., 2014). In this study, continental blocks, such as the Landes High, Le Danois High, and Ebro Block, are relatively undeformed units of continental crust (≥ 20 -km thick) that are separated from interior continental domains by sedimentary basins having undergone various amounts of crustal thinning without evolving to oceanic seafloor spreading. The crustal architecture along the North Iberian margin based on previous rift domain mapping significantly varies from west to east (Cadenas et al., 2018; Tugend et al., 2014). Along the western North Iberian margin, a narrow necking region, bounded to the east by the Ventaniella Fault, is interpreted. At the central part of the North Iberian margin, a region of hyperthinned crust is interpreted to be underlying the Asturian Basin and Santander Transfer Zone. The Le Danois crustal block (~ 20 -km thick) separates the hyperthinned Asturian Basin from the underthrust hyperextended domains to the north (Cadenas et al., 2018). Ocean-ward of the Le Danois High, uncertainties still remain regarding the nature and structure of this under thrust domain to the undisputed regions of oceanic crust further west (Cadenas et al., 2018; Sibuet et al., 2004; Tugend et al., 2014). These uncertainties are primarily associated with crustal thickening of a former distal margin during the Pyrenean Orogeny and the present day distinction between hyperthinned continental crust, exhumed mantle, and oceanic crust within this region interpreted as a fossil accretionary wedge (Alvarez-Marrón et al., 1997; Cadenas et al., 2018; Fernández-Viejo et al., 2012; Gallastegui et al., 2002). However, seismic refraction results obtained along the North Iberian margin (Ruiz et al., 2017) suggest an area of exhumed mantle with minor magmatic additions ocean-ward of the Le Danois High. The easternmost region of the North Iberian margin consists of the Landes High and surrounding areas of slightly thinned crust (necking region) in its vicinity. The crustal thickness of the Landes High varies from ~ 20 to 35 km as deduced from gravity inversion results (Tugend et al., 2014).

2.1.1.1. The Parentis Basin

The offshore Parentis Basin is characterized as a smooth-slope sedimentary basin located between the Landes High and the southern edge of the Armorican margin (Bois et al., 1997; Brunet, 1984; Ferrer et al., 2008, 2012; Jammes et al., 2009; Lagabrielle et al., 2020; Tugend et al., 2014, 2015b). Analogous to the definition of a smooth-slope sedimentary basin, the Parentis Basin exhibits gradually dipping smooth slopes toward the center of the basin, a smooth basement top, a lack of seismically imaged normal faulting, and a region of significantly thinned crust (< 10 km) within the center of the basin (Jammes et al., 2010a; Lagabrielle et al., 2020; Pinet et al., 1987; Tugend et al., 2015b). Hyperextension is interpreted to have occurred from Valanginian/Barremian—Late Aptian time within the Parentis Basin based on age correlations calibrated from wells interpreted on seismic sections (Ferrer et al., 2008; Jammes et al., 2010a; Tugend et al., 2015b). However, a Late Jurassic increase in subsidence calculated from exploration well data and a thickening of Late Jurassic sedimentary sequences interpreted from seismic reflection profiles could suggest a Late Jurassic initiation of significant crustal thinning within the Parentis Basin (Bois et al., 1997; Brunet, 1984). The mode of crustal thinning within the Parentis Basin has been a subject of debate in the literature (Bois et al., 1997; Ferrer et al., 2008; Jammes et al., 2010a; Lagabrielle et al., 2020). This is primarily due to a lack of significant normal faulting interpreted on seismic sections within the center of the basin (Lagabrielle et al., 2020). One explanation for these phenomena suggests an asymmetrical mode of opening within the southern Parentis Basin, whose structure is depicted as a lower plate sag basin with crustal thinning controlled by a top-basement detachment system (Jammes et al., 2010a). In addition, Jammes et al. (2010b) highlight the presence of a thick prerift salt decollement promoting extreme crustal thinning within a ductile regime, causing layers below and above the prerift salt layer to deform differently. Following the end of extension during the Mid Cretaceous, the Parentis Basin was partially reactivated during the Late Cretaceous and Cenozoic as a result of compressional deformation caused by the Alpine Orogeny (Ferrer et al., 2008; Tavani et al., 2018; Tugend et al., 2014). This compressional deformation within the Parentis Basin was partially buffered by the presence of the Landes High along its southern border (Ferrer et al., 2008).

2.1.2. The Armorican and Western Approaches Margins

The Armorican and Western Approaches margins correspond to segments of the northern Bay of Biscay margins (Figure 1b). The Armorican margin, immediately north of the Parentis Basin, is interpreted to have a general continent to ocean-ward variation in crustal architecture. From continent to ocean-ward, a narrow necking zone is interpreted inboard of a zone of hyperthinned crust whose structure is characterized by large scale detachment faulting and extensional allochthons (Thinon et al., 2002, 2003; Tugend et al., 2014, 2015b). In addition, the Armorican margin hosts a wide deep basin (Armorican Basin) whose basement shows atypical velocity structure interpreted as exhumed mantle (Thinon et al., 2003; Tugend et al., 2014) and localized volcanic edifices (Thinon et al., 2003). The exterior boundary of this exhumed mantle domain approximately corresponds to the landward limit of oceanic crust (LaLOC) (Nirrengarten et al., 2018; Tugend et al., 2014). The Western Approaches margin is characterized by a wider necking domain in comparison to the Armorican margin (Thinon et al., 2003; Tugend et al., 2014). In addition, S-reflections, ocean-ward faults and “classical” tilted fault blocks are all commonly described throughout the Western Approaches margin (Barbier et al., 1986; De Charpal et al., 1978; Le Pichon & Barbier, 1987).

The Armorican Shear Zone, a set of onshore inherited Variscan structures that extend into offshore north-east-southwest trending transfer zones, is interpreted as the boundary separating the Armorican and Western Approaches margins (Tugend et al., 2014). Along the Western Approaches and Armorican margins, a number of transfer zones delimit different margin segments which are characterized by architectural variations (Thinon et al., 2003; Tugend et al., 2014).

2.2. Previous Plate Reconstructions of the Bay of Biscay

The prolonged debate concerning Iberian plate kinematics has caused many uncertainties and discrepancies to arise when studying the Bay of Biscay plate kinematics (Angrand et al., 2020; Barnett-Moore et al., 2016; Causer et al., 2019; Gong et al., 2008; Jammes et al., 2009; Nirrengarten et al., 2018; Sibuet et al., 2004; Srivastava et al., 2000; Vissers & Meijer, 2012). Although the majority of previously published plate reconstructions demonstrate some form of transtensional motion within the Bay of Biscay until the Late Jurassic, the Early-Mid Cretaceous Iberian plate kinematics have been extensively disputed (Barnett-Moore et al., 2016). The three main plate kinematic scenarios proposed for Iberia during the Early-Mid Cretaceous consist of a strike-slip and rift-perpendicular scenario along the Iberia-Eurasia plate boundary (Jammes et al., 2009), a strike-slip scenario (Olivet, 1996; Stampfli & Borel, 2002), and a scissor scenario implying subduction within the Pyrenean realm (Sibuet et al., 2004; Vissers & Meijer, 2012). The origins of these three contrasting plate kinematic scenarios arise from geological observations in the Pyrenees, the integration of the southern North Atlantic and Alpine-Tethys plate kinematics, discrepancies with paleomagnetic data, and the uncertain nature of offshore M-series magnetic anomalies and their inappropriate use as plate kinematic indicators prior to M0 (Angrand et al., 2020; Barnett-Moore et al., 2016; Causer et al., 2019; Nirrengarten et al., 2017, 2018; Szameitat et al., 2020; van Hinsbergen et al., 2020).

The majority of previous plate reconstructions of Iberia only consider the motion of rigid tectonic plates (Angrand et al., 2020; Barnett-Moore et al., 2018; García-Mondéjar, 1996; Jammes et al., 2009; Nirrengarten et al., 2018; Sibuet et al., 2004; Vissers & Meijer, 2012). Recent deformable plate reconstruction studies focused within the southern North Atlantic have proven to be advantageous for studying complex plate kinematic problems (King et al., 2020; Peace et al., 2019b). In particular, the ability to account for temporal variations in strain rate, crustal thickness, and beta factors within deformable regions provides a more informative approach when addressing discrepancies inherent to previous rigid plate reconstructions. Naturally, deformable plate models must be consistent with global plate models derived from reliable plate kinematic constraints such as oceanic magnetic anomalies (Müller et al., 2019). With respect to uncertainties such as those associated with the Bay of Biscay plate kinematics, results calculated via deformable plate models often provide a better method of comparison with independent observations such as gravity inversion crustal thickness and the timing and styles of deformation derived from interpretations made from seismic and well data. Thus, previous studies focused on investigating the present-day structure within the Bay of Biscay through analysis of seismic, potential field, and well data (e.g., Bois et al., 1997; Jammes et al., 2010c; Thinon et al., 2003; Tugend et al., 2014, 2015a, 2015b) provide an excellent source of compar-

Figure 2. General GPLates deformable plate modeling workflow originally from Peace et al. (2019b) and modified after King et al. (2020).

ison for assessing the validity of results produced by deformable plate models as demonstrated elsewhere (King et al., 2020; Peace et al., 2019b; Welford et al., 2018).

3. Methodology

To study the plate kinematic evolution of the Bay of Biscay, the deformable plate tectonic modeling methodology introduced by Gurnis et al. (2018), and applied in other studies (Flament et al., 2014; Gurnis et al., 2018; King et al., 2020; Müller et al., 2019; Peace et al., 2019b; Welford et al., 2018), was implemented using the GPLates software, version 2.2 (Müller et al., 2019). Using this approach (Figure 2), deformable plate tectonic models were constructed to analyze the plate kinematics of continental blocks within the Bay of Biscay, and resultant present-day crustal thickness estimates within deformable regions. The primary objective of this work was to investigate the independent motion of previously recognized microblocks such as the Landes High, Le Danois High, and Ebro Block during rifting and opening of the Bay of Biscay using various continental block geometries and poles of rotation. Subsequently, a comparison between present-day crustal thickness estimates and observations from potential field, seismic studies, and well data

provided a good metric for deducing the most probable plate kinematic scenario and the timing and extent of deformation experienced within the Bay of Biscay.

3.1. General Model Setup

In this study, five deformable plate tectonic models of the Bay of Biscay were built using the GPlates software (Müller et al., 2018; Williams et al., 2012), version 2.2, similar to those presented in previous deformable modeling studies (Peace et al., 2019b; Welford et al., 2018). Identical to previous deformable plate model setups (King et al., 2020; Peace et al., 2019b), the time frame considered for four out of five deformable models (models 1 and 3–5) is from 200 Ma to present day (0 Ma) with a uniform 30 km crustal thickness estimate assumed at 200 Ma. One deformable plate model (model 2) based on the Late Permian to Mid Cretaceous rigid plate tectonic reconstruction of Iberia from Angrand et al. (2020), was designed using a time frame of 270 Ma to present day. A uniform 30 km crustal thickness estimate at 270 Ma was also chosen for this deformable plate model. An initial 30 km crustal thickness estimate was considered for all deformable models and was chosen to capture potential minor crustal thinning caused by Triassic rifting over the continental shelves adjacent to the Bay of Biscay (Cadenas et al., 2020; De Charpal et al., 1978; Montadert et al., 1979; Ruffell, 1995). Due to the longer runtime for model 2, it experienced more thinning than the other four models. A 0.15625° mesh point spacing (GPlates density level 8) with no random offset was used for all crustal thickness calculations. A mesh point spacing (distance between points used to calculate crustal thicknesses within topological networks) of 0.15625° was considered an appropriate value to obtain regional-scale crustal thickness trends within the Bay of Biscay and was a more computationally feasible value in contrast to smaller point spacing options when making calculations in GPlates. Estimates of crustal thickness obtained from alternative methods/techniques such as gravity inversion serve as the primary method of comparison for investigating the validity of deformable plate models, in conjunction with observations from seismic and well data.

3.2. Gravity Inversion: A Compilation of Different Approaches

Crustal thickness estimates calculated from gravity inversion provide valuable insight into the present-day crustal architecture of rifted margins (Gozzard et al., 2019; Kuszniir et al., 2020; Tugend et al., 2014; Welford et al., 2010, 2012) and offer a good method of comparison to assess the validity of crustal thicknesses calculated by deformable plate models (King et al., 2020; Peace et al., 2019b; Welford et al., 2018). In this study, three different gravity inversion crustal thickness calculations are considered to examine the present-day architecture of the Bay of Biscay and to compare with crustal thicknesses calculated in the Bay of Biscay by deformable plate models. One gravity inversion crustal thickness calculation obtained using the scheme of Welford et al. (2010, 2012) will be visualized throughout this study (Figure 3), while the other two gravity inversion calculations obtained using an alternative inversion scheme (Alvey et al., 2008; Chappell & Kuszniir, 2008; Cowie & Kuszniir, 2013; Greenhalgh & Kuszniir, 2007; Tugend et al., 2014) can be found in Supplementary Material.

Gravity inversion crustal thickness estimates (Figure 3) were produced using the same minimum-structure gravity inversion methodology applied in previous studies over areas such as the Irish margin (Welford et al., 2010), Newfoundland margin (Welford et al., 2012), and West Iberian margin (King et al., 2020). Using the GRAV3D inversion algorithm (Li & Oldenburg, 1996, 1998), a smoothed depth-weighted 3-D density anomaly model was obtained by inverting the DTU10GRA free-air gravity data set from the DTU National Space Institute (Anderson, 2010). To construct a reference density anomaly model (relative to 2,850 kg/m³) and account for appropriate density ranges (delimited by bounds) for the seawater, sediments, crust, and mantle, this inversion scheme used depth to basement and bathymetric constraints from the NOAA total sediment thickness of the world's oceans and marginal seas data (Divins, 2003) and the ETOPO1 1 arc-min global relief model, respectively. A more detailed explanation regarding the inversion scheme and parameters chosen can be found in Welford et al. (2012).

Figure 3. Comparison of Moho depths derived from gravity inversion (GI) and previously published seismic refraction velocity models. Profile locations are shown on the gravity inversion crustal thickness map calculated using the inversion scheme from Welford et al. (2010, 2012). (a) Moho depth comparisons along IAM-12 (line a-a' on crustal thickness map) (Fernández-Viejo et al., 1998). (b) Moho depth comparisons along Marconi 1 (Ruiz et al., 2017) (line b-b' on crustal thickness map). (c) Moho depth comparisons along Norgasis 14 (Thinon et al., 2003) (line c-c' on crustal thickness map).

3.3. Present-Day Crustal Structure: Insights From Gravity Inversion and Seismic Refraction

In this section, Moho depths derived from each gravity inversion method are compared with those derived from previously published seismic refraction lines throughout the Bay of Biscay (Figure 3) (Ayarza et al., 1998; Fernández-Viejo et al., 1998; Ruiz et al., 2017; Thinon et al., 2003), to investigate the present-day crustal structure of the Bay of Biscay and address discrepancies.

As demonstrated in Figure 3, all three gravity inversion results are in general agreement with Moho depths interpreted from various seismic refraction velocity models throughout the Bay of Biscay (Fernández-Viejo et al., 1998; Ruiz et al., 2017; Thinon et al., 2003). Considering lines IAM-12 and Marconi 1 along the North Iberian margin (Figures 3a and 3b), the calculated Moho depths from each gravity inversion demonstrate an

approximate ± 5 km discrepancy compared to Moho depths obtained from seismic refraction. The magnitude of these crustal thickness discrepancies is deemed appropriate given the depth resolution nonuniqueness challenges of gravity inversion. Examining the Norgasis 14 refraction line along the Armorican margin (Figure 3c) (Thinon et al., 2003), Moho depths calculated by gravity inversion also demonstrate an approximate ± 5 km discrepancy with the Moho horizon interpreted from the seismic refraction velocity model. With reference to the high velocity body interpreted inboard of the oceanic domain along Norgasis 14 by Thinon et al. (2003), interestingly, the Moho depth calculated using the scheme of Welford et al. (2010, 2012) is nearly identical to the horizon representing the top of the high velocity body. This observation is primarily a result of the assumption that the Moho can be characterized by a constant density isosurface. Here, that assumption results in anomalously high crustal densities corresponding to mantle.

3.4. Model Inputs: Deformable Boundaries and Continental Blocks

The timing and magnitude of deformation produced via deformable plate tectonic models are dependent on the timing and geometry of deformable model boundaries associated with the motion of larger tectonic plates and the independent motion of features within deformable regions such as continental blocks. Throughout the southern North Atlantic, the timing and extent of these phenomena have and continue to be a topic of scientific interest, and research (Neuharth et al., 2021; Nirrengarten et al., 2018; Peace et al., 2019b; Péron-Pinvidic & Manatschal, 2010; Tugend et al., 2014; Welford et al., 2010).

In this study, the exterior deformable boundary used for all models is the edge of the continental crust (ECC) used in previous studies (King et al., 2020; Nirrengarten et al., 2018; Peace et al., 2019b) (Figure 3), but slightly modified in the region west of the present-day Landes High to avoid overlap between the ECC and Landes High during the Mid-Late Cretaceous opening of the Bay of Biscay. The interior deformable boundary implemented in this work is a combination of two previously published geometries of the necking line, a rift domain boundary where onset of the main thinning of the continental crust and lithosphere is observed/interpreted (Nirrengarten et al., 2018; Tugend et al., 2014) (Figure 3). The necking line from Tugend et al. (2014) encompasses the Bay of Biscay, Pyrenees, and central regions of Iberia (Figure 1b) and was expanded by Nirrengarten et al. (2018) to encompass additional regions throughout the southern North Atlantic (Figure 1a).

The independent motion of relatively undeformed continental blocks and their significant role in shaping the present-day crustal architecture of rifted margins throughout the southern North Atlantic have been highlighted in previous deformable plate modeling studies (King et al., 2020; Peace et al., 2019). In the Bay of Biscay, the Landes High, Le Danois High, and Ebro Block are continental blocks of different sizes defined in previous potential field, rigid plate reconstruction, and seismic studies, and are considered to have played an important role in partitioning/distributing transtensional and extensional deformation during rifting and the short-lived opening of this region (Cadenas et al., 2018; Nirrengarten et al., 2018; Tugend et al., 2015a). To investigate the independent role of each of these continental blocks on the Bay of Biscay present-day crustal architecture, various geometries and poles of rotations for these continental blocks are tested in the deformable models presented herein.

To define polygons whose geometry is representative of these relatively undeformed continental blocks, a combination of previous and newly defined polygons is used within the interior of deformable plate models. All models that include the Ebro Block use the geometry defined in Tugend et al. (2014), except for one model which uses the geometry defined in Angrand et al. (2020). Considering the Le Danois High, the geometry defined in Cadenas et al. (2018) is used in all models that include the Le Danois High. For the Landes High, two different polygon geometries are tested. One Landes High geometry consists of that defined in Tugend et al. (2014). The other consists of a newly defined geometry based on gravity inversion crustal thickness (Supplementary Material). The motivation for this new Landes High geometry was primarily based on gravity inversion crustal thickness estimates provided in Tugend et al. (2014) (Supplementary Material), and the new geometry was designed to include the additional regions of relatively undeformed continental crust surrounding the Landes High geometry defined in Tugend et al. (2014).

Table 1
Poles of Rotation of the Landes High, Le Danois High, and Ebro Block Used in Model 4

Continental block	Poles of rotation	Age	Latitude	Longitude	Angle	Reference plate
Landes High	This study	200	46.1322	9.1813	−3.1577	Ebro Block
	Nirrengarten et al. (2018)	122	30.56	−1.68	−7.34	Ebro Block
	Nirrengarten et al. (2018)	122	44.29	−0.79	−23.27	Europe
	Nirrengarten et al. (2018)	100	43.99	−1.75	−6.53	Europe
	Nirrengarten et al. (2018)	86	0	0	0	Europe
	Nirrengarten et al. (2018)	0	0	0	0	Europe
Le Danois High	This study	200	42.8989	−6.5973	−24.59	Iberia
	This study	160	42.2887	−5.5266	−34.5511	Iberia
	This study	140	48.2862	−2.7192	5.2955	Iberia
	This study	125	40.1242	4.8354	−3.7703	Iberia
	This study	120	43.99	−1.75	−6.53	Iberia
	This study	115	44.546	−4.0572	−15.9683	Iberia
	This study	86	0	0	0	Iberia
	This study	0	0	0	0	Iberia
Ebro Block	Nirrengarten et al. (2018)					

3.5. Poles of Rotation

Poles of rotation defined within GPlates, or elsewhere, are used to govern the temporal kinematic variations of major tectonic plates, microplates, continental blocks, and individual points or lines (Müller et al., 2018; Williams et al., 2012). Consequently, the deformation experienced within topological networks designed in GPlates is governed by the poles of rotation associated with the boundaries to deformable regions and interior rigid features used to construct deformable plate models (Gurnis et al., 2018).

The poles of rotation and associated plate kinematics of Iberia have and continue to be a subject of scientific debate (Barnett-Moore et al., 2016; Causer et al., 2019; García-Mondéjar, 1996; Gong et al., 2008; Jammes et al., 2009; Nirrengarten et al., 2018; Olivet, 1996; Olivet et al., 1984; Sibuet et al., 2004; Srivastava et al., 2000; Vissers et al., 2016). Building upon the work of Peace et al. (2019b) and King et al. (2020), the Iberia poles of rotation used in this study are the poles defined in Nirrengarten et al. (2018), except for one model that uses the poles of rotation defined in Angrand et al. (2020). Additionally, the poles of rotation for all models that include the Ebro Block and select models that include the Landes High are from Nirrengarten et al. (2018) aside from the one model using poles of rotation from Angrand et al. (2020). For some models that include the Landes High, new poles of rotation were defined based on the motivation for each model (Table 1). The poles of rotation used for the Le Danois High were all newly defined in this study (Table 1). The Le Danois High poles were designed based on model motivation so as to avoid overlap with the Landes High and Ebro Block throughout the entirety of all models to avoid escaping mesh points within deformable plate models caused by overlapping continental blocks.

3.6. Model Specifics

Five deformable plate tectonic models of the Bay of Biscay (Figure 4) were constructed and evaluated in this study to investigate the Mesozoic plate kinematics of the Landes High, Le Danois High, and Ebro Block. An additional five models were also considered in this analysis and can be found in Supplementary Material. The additional models excluded from the main text were designed to test alternative plate kinematic scenarios for various continental blocks and deformable model boundaries. The primary differences between each model (Table 2) are the poles of rotation for Iberia, the time frame of interest, and the inclusion, geometries, and poles of rotation of various continental blocks.

Figure 4. Initial setup for deformable plate models of the Bay of Biscay. All models are reconstructed back to 200 Ma, except for model 2, which is reconstructed back to 270 Ma. The deformable domain for all models is shown in green, undeformable domains in gray, Ebro Block filled in red, Landes High filled in magenta, Le Danois High filled in black, and coastlines outlined in red. AF = Africa, EUR = Europe, IB = Iberia.

Model 1 is the simplest model as no continental blocks are included within the region of deformation. The motivation for this model was to investigate the impact of not having continental blocks included within deformable plate tectonic reconstructions along the Iberia-Eurasia plate boundary, similar to that proposed in previous rigid plate tectonic reconstruction studies (Sibuet et al., 2004; Vissers et al., 2016). Model 2, identical to the rigid plate reconstruction of Angrand et al. (2020), includes the Ebro Block and Landes High using the geometries and poles of rotation proposed by Angrand et al. (2020). This is the only model that uses a time frame of 270 Ma to present day (0 Ma) and is also the only model that does not use poles of rotation for Iberia defined in Nirrengarten et al. (2018). Model 3 includes the Landes High and Ebro Block using the poles of rotation defined in Nirrengarten et al. (2018). The geometries of the Ebro Block and Landes High are identical to those defined in Tugend et al. (2014). The reconstruction of the southern North Atlantic from Nirrengarten et al. (2018) was the first to provide independent poles of rotation for the Landes High and Ebro Block, and the motivation for model 3 was simply to investigate the kinematic role of these continental blocks using a deformable plate modeling approach. Model 4 is the first model where the Le Danois High, defined in Cadenas et al. (2018), is introduced. The motivation for including the Le

Table 2
Description of Boundary Conditions for All Deformable Plate Models Tested in This Study

Model #	Iberia poles of rotation	Model start time (Ma)	Le Danois High included	Landes High included	Landes High starting point	Landes High geometry	Ebro Block included	Ebro Block geometry
1	Nirrengarten et al. (2018)	200	No	No	NA	Tugend et al. (2014)	No	NA
2	Angrand et al. (2020)	270	No	Yes	Angrand et al. (2020)	Angrand et al. (2020)	Yes	Angrand et al. (2020)
3	Nirrengarten et al. (2018)	200	No	Yes	Nirrengarten et al. (2018)	Tugend et al. (2014)	Yes	Tugend et al. (2014)
4	Nirrengarten et al. (2018)	200	Yes	Yes	This study	This study	Yes	Tugend et al. (2014)
5	Nirrengarten et al. (2018)	200	No	Yes	This study	This study	Yes	Tugend et al. (2014)

Danois High is based upon recent seismic and potential field studies which interpret the Le Danois High as a rift-inherited basement block with a distinct evolution during extensional and compressional stages of deformation experienced along the North Iberian margin (Cadenas et al., 2018, 2020). The geometry of the Le Danois High is the same as that defined in Cadenas et al. (2018) and new poles of rotation for the Le Danois High are defined in this study. Model 4 also includes the Landes High and Ebro Block with a newly defined geometry and poles of rotation for the Landes High. This new geometry of the Landes High is designed based on gravity inversion crustal thickness estimates (Supplementary Material) and its new poles of rotation are designed to simulate the Landes High starting further west within the Bay of Biscay at 200 Ma, causing the Landes High to move more independently from the Jurassic to Mid Cretaceous as proposed in previous studies focusing on the Bay of Biscay plate kinematics (Tugend et al., 2014, 2015a). Model 5 is identical to model 4 but it does not include the Le Danois High. The motivation for this model was to investigate the effect of the Le Danois High on deformation.

4. Results

4.1. Kinematic Evolution and Resulting Crustal Thicknesses

Herein, the present-day crustal thickness results calculated by deformable plate models (Figure 5) described in the previous section are analyzed. For models 1–5, the inclusion of various continental blocks and their varying poles of rotation and geometries produced highly variable present-day crustal thickness results throughout the Bay of Biscay.

Model 1 is the only model that does not include any continental blocks within the interior deformable region. In model 1, crustal thicknesses along the North Iberian margin range from ~30 to 40 km. Within the Parentis Basin and along the Armorican margin, crustal thicknesses also vary from ~30 to 40 km. Moving northward toward the Western Approaches margin and Goban Spur, a gradual decrease in crustal thickness is observed with regions of thinner crust ranging from 15 to 20 km along the Western Approaches margin and regions of significantly thinned crust (~2–10 km) in the vicinity of the Goban Spur.

Model 2 is identical to the plate reconstruction of Iberia proposed by Angrand et al. (2020). Along the North Iberian margin within the vicinity of the Le Danois High, crustal thicknesses vary from ~40 km land-ward to ~25 km ocean-ward. An area of localized thinned crust ~10–15-km thick is observed within the so-called Santander Transfer Zone (Roca et al., 2011), west of the Landes High, as well as within another localized region of the Parentis Basin varying from ~15-km to 20-km thick. To the north of the Parentis Basin along the Armorican margin, crustal thicknesses vary from ~15 to 30 km, with a localized area of increased crustal thickness ~25–30-km thick within the central region of the Armorican margin. Moving further north, crustal thicknesses vary from ~10 to 15 km along the Western Approaches margin to areas of ~5–10-km thick along the Goban Spur margin.

In model 3, the independent kinematics of the Landes High resulted in regions of thinner crust within the northern Bay of Biscay and Parentis Basin in comparison to models 1 and 2. Along the Western Approaches and northern regions of the Armorican margin, crustal thicknesses generally range from 15 to 25 km with a localized area of thinned crust (~10 km) in the southern region of the Western Approaches margin. Within the Parentis Basin, crustal thicknesses range from ~5 to 10 km within the center of the basin and 10 to 15 km along the basin edges. Along the North Iberian margin, present-day crustal thicknesses are identical to those calculated in model 1, with the exception of the 30 km crustal thickness of the rigid Landes High.

Model 4 is the only model that includes the Le Danois High as a continental block, in addition to the Landes High and Ebro Block. In proximity to the Le Danois High, a localized crustal thinning is observed within the Asturian Basin (10–15 km). Regions of significantly thinned crust (10 km or less) are observed west and ocean-ward of the rigid Le Danois High. In model 4, a NW-SE oriented indented region of thinned crust (indicated by the black arrow in Figure 5) is observed west of the Landes High ranging from ~10 to 15 km until a localized area of thicker crust (~35–40 km) is observed east of the Le Danois High near the so-called Santander Transfer Zone. Within the Parentis Basin, symmetric crustal thinning is observed in the center of the basin (~5–10 km), and crustal thicknesses along its northern and southern borders increase to as high as 30 km. A region of significantly thinned crust (<5 km) occurs ocean-ward of the Parentis Basin. From the southern Armorican margin to the Goban Spur margin, crust thicknesses calculated by model 4

Figure 5. Present-day (0 Ma) crustal thickness results for deformable plate models 1–5 and gravity inversion crustal thickness estimates. The starting point for the northwest corner of the Landes High (magenta circle) and the Landes High motion path at 10 Ma increments (black circles) with respect to Iberia are shown for each model. Outline of the Western Approaches Basins (dashed black line) used to distinguish the boundary between the Armorican and Western Approaches margins. Interior (necking line, outlined in black) and exterior (ECC, outlined in red) deformable model boundaries and Le Danois High geometry (white polygon) displayed on the gravity inversion crustal thickness map. AM = Armorican margin, GS = Goban Spur, NIM = North Iberian margin, PB = Parentis Basin, WAB = Western Approaches Basins.

vary considerably. Across strike of the southern Armorican margin, there is a gradual northeast to southwest decrease in crustal thickness ranging from 40 km near the continent-ward edge to ~8–15 km near the ocean-ward edge. Across the north Armorican margin, a localized wide region of thinned crust (~5–10 km) is observed until a widely distributed increase in crustal thickness (~15–20 km) is observed along the Western Approaches margin. This broad region of thicker crust along the Western Approaches margin continues northwestward until significant crustal thinning occurs within the Goban Spur vicinity.

Aside from crustal thickness variations along the North Iberian margin and south of the Western Approaches Basins, model 5 produces near identical crustal thickness results to those calculated by model 4 along the Western Approaches and Armorican margins, and within the Parentis Basin. Along the North Iberian margin, however, there is a continuous decrease in crustal thickness varying from ~30 km near the coastline to ~5–15 km near the exterior deformable boundary. Immediately west of the Landes High, similar to model

4, an indented region of thinner crust ranging from 5 to 15 km is observed. In proximity to the Le Danois High, the observed crustal thickness ranges from 20 to 30 km.

5. Discussion

5.1. Comparison of Deformable Plate Modeling and Gravity Inversion

The main observations to investigate from comparing gravity inversion crustal thickness maps to deformable plate models include the symmetric crustal thinning within the Parentis Basin, localized crustal thinning within the Santander Transfer Zone and Asturian Basin, and approximate gradual continent to ocean-ward crustal thinning along the North Iberian margin, Armorican, and Western Approaches margins (Figure 5).

5.1.1. Comparison of Deformable Plate Modeling and Gravity Inversion: Models 1–3

Model 1 reveals significant present-day crustal thickness discrepancies in comparison to gravity inversion crustal thickness estimates. The most significant variations are the larger crustal thicknesses (~15–20-km thicker) calculated along the North Iberian margin, Parentis Basin, and Armorican margin.

Model 2 also demonstrates several discrepancies. Within the vicinity of the Asturian Basin and the Le Danois High, a gradual ocean-ward thinning is achieved, however, the magnitude of crustal thicknesses calculated by model 2 are ~10–15-km thicker compared to gravity inversion estimates. Crustal thicknesses calculated by model 2 within the so-called Santander Transfer Zone (Roca et al., 2011), west of the Landes High, show good correlations with those calculated by gravity inversion, however, crustal thicknesses within the Parentis Basin calculated by model 2 are ~10–15-km thicker. Along the Armorican margin, crustal thicknesses calculated by model 2 are generally larger than those calculated by gravity inversion by ~10–15 km. Transitioning northwards from the Armorican to the Western Approaches margin, model 2 demonstrates similar crustal thicknesses to those calculated by gravity inversion with slightly thicker areas of crust (by ~5 km) within ocean-ward areas of the Western Approaches Basins.

Model 3 produced similar unrealistic crustal thickness results along the North Iberian and Armorican margins, however, a notable difference is the region of localized crustal thinning (~5–10 km) within the Parentis Basin. This localized crustal thinning within the Parentis Basin, similar to that observed from gravity inversion, demonstrates the importance of the Landes High and its independent motion causing crustal thinning within this region. The removal of unrealistic significant crustal thickening within the Parentis Basin in models 2 and 3 also demonstrates the role of the Landes High as a regional buffer of compressional deformation during the Alpine Orogeny (Ferrer et al., 2008), preventing significant crustal thickening within the Parentis Basin during the Late Cretaceous and Cenozoic.

5.1.2. Comparison of Deformable Plate Modeling and Gravity Inversion: Models 4 and 5

Considering all models tested, crustal thicknesses calculated by models 4 (Figure 5) and 5 (Figure 6) provided the best crustal-scale match with gravity inversion crustal thickness estimates and these will be discussed in greater detail.

Model 4 introduces the Le Danois High, as well as a new geometry and poles of rotation for the Landes High. The kinematics of the Le Danois High in model 4 and their interplay with the Landes High correlate with localized crustal thinning within the Asturian Basin (~10–15 km), similar to present-day crustal thicknesses measured by Cadenas et al. (2018). West and north of the rigid Le Danois High in model 4, significantly thinned regions of crust (~5–10 km) are observed, demonstrating good correlations with gravity inversion estimates. Within the Santander Transfer Zone, an area of localized crustal thinning (~5–15 km) is observed, analogous to crustal thicknesses calculated by gravity inversion. The crustal thickness of the Le Danois High itself (30 km) generates the main discrepancy between crustal thickness calculations made in this region by gravity inversion. In addition, larger crustal thicknesses along the eastern edge of the Le Danois High (~35–40 km) are observed, in contrast to those calculated by gravity inversion. It is important to denote that the present-day crustal thickness of the Le Danois basement block results from Mesozoic crustal thinning and subsequent Alpine crustal thickening, which led to underthrusting of highly thinned crust underneath the Le Danois rift-inherited crustal block (Cadenas et al., 2020). Thus, these discrepancies with the results calculated by model 4 are interpreted to be a result of the assumption that all continental

Figure 6. Comparison of crustal thickness maps produced from deformable plate model 5 and gravity inversion estimates. Overlain on each crustal thickness map are the Bay of Biscay structures compiled by Tugend et al. (2014) and references therein and deformable model boundaries used to construct all deformable plate models (white). Variscan domain boundaries (orange) compiled from Farias et al. (1987) and Martinez-Catalan (2014). ASZ = Armoric Shear Zone, GTOMZ = Galicia-Tras Os Montes Zone, WAB = Western Approaches Basins.

blocks are rigid and unable to experience deformation within deformable models built in GPlates. Although the crustal geometry of the Le Danois High and crustal thinning within the Asturian Basin have been clearly identified in previous seismic studies (Cadenas et al., 2018), these features are not as clearly identified in the gravity inversion crustal thickness maps considered. Given that gravity inversion results are largely dependent on input sedimentary thicknesses, this phenomenon is likely a result of regional and local structural features such as the Asturian Basin not being included within the regional compilation of sedimentary thicknesses used in each gravity inversion calculation. Within the Parentis Basin, crustal thicknesses calculated by model 4 show good correlations with gravity inversion estimates, with crustal thicknesses ranging from 5 to 10 km within the basin center, and increasing to as high as 30 km along its northern and southern edges. Along the southern Armorican margin, crustal thickness values range from 30 to 40 km continent-ward to ~5 km ocean-ward, showing a good general correlation with gravity inversion results. The largest crustal thickness discrepancy between model 4 and gravity inversion estimates near the Parentis Basin is the region of significantly thinned crust (<5 km) calculated by model 4 near the southeast corner of the Bay of Biscay. Along the north Armorican margin, similar to the south, gravity inversion crustal thickness estimates generally suggest a gradual decrease in crustal thickness ocean-ward. Comparing this with crustal thicknesses calculated by model 4 in this region, a wide area of thinned crust (~5–10 km) is revealed as opposed to the smooth ocean-ward transition of decreasing crustal thickness suggested by gravity inversion estimates. Based on observations from previous seismic studies (Thinon et al., 2003), crustal thinning along the Armorican margin is restricted within a narrow domain, suggesting localized crustal stretching within this region. Considering the starting position of the Landes High in model 4, the Landes High at 200 Ma is situated within this region and in close proximity to the hard interior deformable boundary. Thus, the overestimation of crustal stretching and thinning calculated by model 4 in this region could be a result of the significant deformation accommodated by the motion of the Landes High away from its starting position. Further north along the Western Approaches margin, a wide area of larger crustal thicknesses (~15–20 km) is calculated by each deformable model in contrast to a wide necking region and ocean-ward crustal thinning (~5–15 km) suggested by gravity inversion estimates.

Model 5 is identical to model 4 aside from the exclusion of the Le Danois High in model 5. Considering all models, present-day crustal thickness estimates calculated by model 5 provide the best correlations with those calculated by gravity inversion estimates. Along the North Iberian margin, model 5 captures similar variations in crustal thickness to those observed in each gravity inversion crustal thickness map considered,

Figure 7. Crustal thickness profiles extracted from deformable plate model 5 and all three gravity inversion crustal thickness estimates considered. Profile a-a' (black dashed line), b-b' (solid black line), and c-c' (solid white line) locations and interior continental regions (solid gray) shown on crustal thickness map (top right panel).

as demonstrated by crustal thickness profiles (Figure 7). In particular, the localized crustal thinning observed within the Santander Transfer Zone and the gradual ocean-ward thinning of the crust in proximity of the Le Danois High. In contrast to model 4, crustal thickness variations within the vicinity of the Le Danois High suggested by previous seismic studies (Cadenas et al., 2018, 2020) are not captured in model 5 due to the omission of the Le Danois High. However, this is preferred as the inclusion of the Le Danois High in model 4 causes too much regional deformation relative to its small size as compared to other continental blocks considered. The large amounts of regional deformation caused by the Le Danois High in model 4 can also be associated with the difficulty of accounting for multistage and poly-phased deformation within deformable plate models built using GPlates, which are interpreted to have specifically affected the central North Iberian margin (Cadenas et al., 2020). Arguably, the largest discrepancy in crustal thicknesses calculated in all models along the North Iberian margin is the crustal thickness of the Landes High, which remains a constant value of 30 km for all models as rigid blocks are not permitted to deform in GPlates. Based on gravity inversion, crustal thicknesses for the relatively undeformed Landes High range from ~20 to 35 km.

5.2. Comparison of Deformable Plate Modeling With Regional Seismic and Well Data

In this section, the plate kinematic evolution of model 5 (Figures 8 and 9) is analyzed in comparison to interpretations made from previously published seismic and well data throughout the Bay of Biscay (Alvarez-Marrón et al., 1996; Avedik et al., 1982; Bois et al., 1997; Brunet, 1984; Cadenas & Fernández-Viejo, 2017; Cadenas et al., 2018, 2020; De Charpal et al., 1978; Fernández-Viejo et al., 2011; Ferrer et al., 2008; Gallastegui et al., 2002; Montadert et al., 1979; Pinet et al., 1987; Roca et al., 2011; Thinon et al., 2003; Tugend et al., 2014, 2015b). In model 5, the kinematics of the Landes High play a major role in the variations in Mesozoic deformation experienced within the Bay of Biscay. The Ebro Block, although included within the interior of deformable model 5, exerts minimal influence on the deformation experienced within the Bay of Biscay in contrast to its significant role during deformation within the Pyrenean realm (Angrand et al., 2020; Tugend et al., 2015a).

Figure 8. Temporal variations in strain rate within the interior of deformable plate model 5 and the kinematics of the Ebro Block (turquoise), Landes High (green), Galicia Bank from King et al. (2020) (magenta), deformable boundaries, and larger tectonic plates in model 5 relative to Europe.

5.2.1. Mesozoic Rift Evolution Within the Bay of Biscay

Model 5 tests a starting point for the Landes High near the Western Approaches Basin, with its long axis aligned approximately east-west at 200 Ma. From 200 to ~150 Ma, the slow eastward motion of the Landes

Figure 9. Model 5 crustal thickness evolution and the reconstructed orientations of present-day transfer zones from 200 to 100 Ma at 25 Ma increments. IB = Iberia, EUR = Europe, and AF = Africa.

Figure 10. Comparison of Landes High velocity magnitude (cm/year) versus time (Ma) in model 5 (bottom panel) and subsidence rate (m/Ma) versus time (Ma) from Bois et al. (1997) (top panel). Aside from model 2, Triassic subsidence velocities originally calculated by Brunet et al. (1984) are outside the time frame considered for deformable plate models (200 Ma to present day).

High in model 5 causes limited transtensional deformation to occur within the Bay of Biscay, and minimal crustal thinning. These results are generally consistent with little post-Triassic subsidence and crustal thinning inferred by Early-Mid Jurassic shallow marine lithologies dredged and penetrated by exploration and deep ocean drilling program wells and similar prerift units interpreted on seismic sections (Bois et al., 1997; Cadenas et al., 2018; Montadert et al., 1977, 1979; Pastouret & Auffret, 1976; Thinon et al., 2002, 2003; Tugend et al., 2014, 2015b). In the latest Jurassic (~150–145 Ma), the increasing velocity of the Landes High moving southeast corresponds to an increase in crustal thinning (~10–20 km) experienced along the Western Approaches, Armorican, and North Iberian margins in model 5. The increasing velocity of the Landes High relative to Iberia during this time and the initiation of significant crustal thinning within the Bay of Biscay suggested by model 5 correlate with increasing subsidence rates during this time documented by exploration well data within the Parentis Basin (Figure 10) (Bois et al., 1997; Brunet, 1984). During the Early Cretaceous (~145–100 Ma), the most significant rifting episode is experienced within the Bay of Biscay, consistent with subsidence curves derived from deep sea drilling program (DSDP) results (Montadert et al., 1977). Throughout the Early Cretaceous (~145–100 Ma), the Landes High continues to travel eastward with the progressive opening of the Bay of Biscay until it reaches its present-day position at ~100 Ma. This period of time also corresponds to the largest velocity pulse of the Landes High relative to Iberia, directly corresponding to the largest pulse in subsidence velocity recorded within the Parentis Basin (Figure 10) (Bois et al., 1997). Model 5 produces areas of hyperextended crust along the North Iberian, Armorican, and Western Approaches margins by 125 Ma, corresponding well to the onset (Berriasian-Barremian) and end (Aptian) of hyperextension documented from previous seismic, well data and subsidence analyses within the Northern Biscay margin (Montadert et al., 1977; Thinon et al., 2002, 2003; Tugend et al., 2014, 2015b). However, in the central North Iberian margin, borehole constrained seismic interpretations define a period of transtensional deformation accommodated by local crustal thinning within narrow and laterally confined basins, interpreted as pull-apart basins from the Upper Jurassic to Barremian (Cadenas et al., 2020). In contrast to that suggested by model 5, the onset of hyperextension leading to high degrees of crustal

thinning and mantle exhumation is interpreted to initiate during the Aptian due to the emplacement and activity of extensional detachment faults (Cadenas et al., 2020). Comparing the onset of hyperextension suggested by model 5 and borehole constrained seismic interpretations (Cadenas et al., 2020), model 5 predicts significant crustal thinning along the central North Iberian margin to have ceased during the early Aptian (~125 Ma). This discrepancy between model 5 and that suggested by borehole constrained seismic interpretations (Cadenas et al., 2020) is interpreted to be caused by the inability to model deformation caused by rheological and depth-dependent processes in deformable plate kinematic models. This results in a lack of significant crustal thinning calculated by model 5 along the central North Iberian margin during the Aptian-Albian.

By 100 Ma, significant crustal thinning is calculated by model 5 within the Parentis Basin. The present-day crustal architecture of the Parentis Basin has caused many to question and postulate explanations regarding the mode of deformation responsible for the significant crustal thinning observed within this region (Bois et al., 1997; Ferrer et al., 2008; Jammes et al., 2010a; Lagabrielle et al., 2020; Pinet et al., 1987). Some authors emphasize the presence of a thick prerift salt layer and a ductile mode of deformation (Lagabrielle et al., 2020), while others propose an asymmetric opening of a lower plate sag basin with crustal thinning induced by a top-basement detachment system (Jammes et al., 2010a). However, in all cases, a common consensus is reached that supports the observation of gently dipping smooth slopes along its basin edges, a lack of steeply dipping normal faults capable of explaining the crustal thinning documented toward the basin axis, and the presence of a thick prerift salt layer responsible for decollement of the prerift sedimentary cover along the sedimentary basement (Ferrer et al., 2012; Jammes et al., 2010a, 2010b; Lagabrielle et al., 2020). Aside from localized areas and rift systems (Cadenas et al., 2020; De Charpal et al., 1978; Ferrer et al., 2012; Montadert et al., 1979; Zamora et al., 2017), this prerift salt decollement layer is not as prevalent along the North Iberian, Armorican, and Western Approaches margins. The mode of deformation within these regions is interpreted to be similar to that interpreted along the Iberia-Newfoundland margins (Cadenas et al., 2018, 2020; Lagabrielle et al., 2020; Thinon et al., 2003; Tugend et al., 2014), and primarily consists of upper crustal thinning caused by brittle deformation, an abundance of normal faulting, and the occurrence of extensional allochthons (Lagabrielle et al., 2020; Peron-Pinvidic et al., 2013).

5.2.2. Compressional Reactivation Within the Bay of Biscay

Beginning in the Late Cretaceous, the orientation of stress fields along the Iberia-Eurasia plate boundary were significantly modified as a result of the collision between Iberia and Eurasia during the Alpine Orogeny. Considering the impact of compressional deformation within the northern Bay of Biscay, an area encompassing the Western Approaches and Armorican margins, these regions are interpreted to have experienced only minor reactivations in the Late Cretaceous and Eocene (Thinon et al., 2001). However, the preorogenic template of the southern Bay of Biscay is interpreted to have been significantly modified by compressional deformation during the Alpine Orogeny, resulting in variable amounts of tectonic inversion and crustal thickening along strike of the North Iberian margin (Alvarez-Marrón et al., 1997; Cadenas et al., 2018, 2020; Ferrer et al., 2008; Gallastegui et al., 2002). Analogous to previous plate kinematic studies (Roest & Srivastava, 1991; Rosenbaum et al., 2002), the crustal thickness evolution of model 5 (Figure 11) suggests that extension across the Iberia-Eurasia plate boundary ceased during the Campanian (~83 Ma). However, the onset of compressional deformation throughout the entire Pyrenean-Cantabrian Orogeny and particularly, the North Iberian margin, still remains a matter of debate. The onset of Alpine contraction within the Parentis Basin has been ascribed to the Late Cretaceous, with major deformation occurring from Eocene to Middle Miocene (e.g., Ferrer et al., 2008; Roca et al., 2011). Well calibrated seismic interpretations constrained ages of synorogenic sequences within the continental platform of the central and western North Iberian margin, ranging from Upper Eocene to Lower Miocene (e.g., Cadenas & Fernández-Viejo, 2017; Gallastegui et al., 2002). Within the abyssal plain in the western North Iberian margin, Álvarez-Marrón et al. (1997) dated synorogenic sequences within the accretionary wedge from Middle Eocene to Middle Miocene through projection and extrapolation of ODP-118 onto the IAM-12 profile, located at the western corner of the Bay of Biscay. However, the lack of timing constraints within the abyssal plain also contributes to uncertainties regarding the age of synorogenic sequences constraining the onset and end of contractional deformation. From the evolution of model 5 (Figure 11), minor crustal thickening is observed within the so-called Santander Transfer Zone during the Late Cretaceous. However, considering the hard exterior boundaries used to construct deformable plate models, the proximity of these hard boundaries to

Figure 11. Model 5 crustal thickness evolution from 100 Ma to present and the reconstructed orientations of present-day transfer zones and the English Channel from Tugend et al. (2014) and references therein. STZ = Santander Transfer Zone, VF = Ventaniella Fault, WAB = Western Approaches Basins.

other rigid features such as continental blocks can often produce edge effects, a phenomenon that could have an impact on the magnitude of this localized compressional deformation experienced in areas such as the Santander Transfer Zone during the Late Cretaceous. Although compressional reactivation may have initiated during the Late Cretaceous, major crustal thickening along the southern Bay of Biscay in model 5 does not occur until Eocene onwards, in agreement with time constraints deduced from synorogenic sequences within the continental platform in the North Iberian margin and with the major period of compression within the Parentis Basin. This would support and suggest that the onset of compressional deformation was unlikely to be synchronous along the Iberia-Eurasia plate boundary.

During the Alpine Orogeny, the majority of compressional deformation experienced along the North Iberian margin was focused within and outboard of the hyperthinned domain, resulting in the formation of an accretionary wedge at the toe of the continental slope (Alvarez-Marrón et al., 1997; Fernández-Viejo et al., 2012; Gallastegui et al., 2002), and under thrusting of highly thinned crust and exhumed mantle to the south underneath the continental platform (Cadenas et al., 2020; Fernández-Viejo et al., 2012; Roca et al., 2011). Considering recent studies that focus on the tectonic evolution of the southern Bay of Biscay (Cadenas et al., 2020), the Le Danois High is considered to be a rift-related crustal block with an independent evolution during the subsequent Alpine Orogeny. Within this region, compressional deformation is interpreted to be accommodated beneath the Le Danois crustal block caused by under thrusting of hyperthinned and exhumed domains, resulting in uplift and tilting of the block (Cadenas et al., 2020). Based on seismic interpretations within the Asturian Basin, minor reactivation of rift-related structures contrast with that experienced in areas outboard (Cadenas & Fernández-Viejo, 2017; Cadenas et al., 2018). Comparing these observations with the crustal thickness evolution of model 5 within the southern Bay of Biscay during the Alpine Orogeny (Figure 11), these changes in structure and rift-related crustal thickness are not observed. This is mainly due to the resolution of crustal thickness variations that can be calculated by

Figure 12. Reconstruction of model 5 at 200 Ma with crustal sutures (solid black lines) from Welford et al. (2012), reconstructed position of present-day transfer zones (dashed black lines) from Tugend et al. (2014), and an approximate boundary of regions within the Bay of Biscay (BoB) and beyond affected by prerift evaporites (magenta dashed line) modified after Lagabrielle et al. (2020). EB = Ebro Block, EUR = Europe, FC = Flemish Cap, GB = Galicia Bank, GTOMZ = Galicia-Tras Os Montes Zone, IB = Iberia, IRE = Ireland, LH = Landes High, PB = Porcupine Bank, UK = United Kingdom, VF = Ventaniella Fault, WAB = Western Approaches Basins, WALZ = West Asturian-Leonese Zone.

deformable plate models built in GPlates, and more importantly, the fact that localized deformation associated with the reactivation of basement morphologies within outer rift domains, as interpreted along the North Iberian margin, cannot be accounted for using GPlates.

5.3. Assessing Discrepancies Between Deformable Plate Models and Independent Observations

5.3.1. Analyzing the Interplay of Inheritance and Rifting Within the Bay of Biscay

In comparison to previously published geological and geophysical observations, deformable plate model 5 provides good crustal-scale correlations both in terms of present-day structure and temporal evolution of deformation. However, although regional-scale crustal thickness variations within the Bay of Biscay are captured, model 5 still demonstrates localized crustal thickness discrepancies within areas where major lithospheric boundaries and heterogeneities have been previously interpreted.

Considering crustal thicknesses calculated by model 5 within the Western Approaches margin and similar estimates calculated by gravity inversion, crustal thicknesses calculated by model 5 are ~5–10-km thicker. For the westernmost North Iberian margin, an area conjugate to the Western Approaches margin, crustal thicknesses calculated by model 5 within hyperthinned domains (Cadenas et al., 2018, 2020) are also ~5–10-km thicker compared to gravity inversion estimates. To explain these discrepancies, two different scenarios, or their combination, are proposed.

One scenario emphasizes the role of Variscan trends within these two regions during rifting within the Bay of Biscay. Along strike of the northern Bay of Biscay rifted margin, significant changes in crustal architecture have been documented to occur in the vicinity of the interpreted offshore prolongation of the Armorican Shear Zone (Thinon, 1999; Tugend et al., 2014). Within the western North Iberian margin, we suggest that the offshore prolongation of the onshore limit between the Galicia-Tras Os Montes Zone (GTOMZ) and the Western Asturian Leonese Zone (WALZ) (e.g., Farias et al., 1987; Martínez Catalán et al., 2014) occurs in the area showing anomalous thicker crust. Based on the reconstructed orientations of these offshore prolonged major lithospheric boundaries at 200 Ma (Figure 12), these two regions of thicker crust calculated by model 5 appear to be highly compartmentalized by these previously interpreted transfer zones, possibly following former Variscan domain boundaries (between GTOMZ and WALZ) or post-Variscan lithospheric structures (ASZ). Another interesting observation in proximity to the Western Approaches margin at 200 Ma is the presence and orientation of the Armorican Shear Zone and the offshore Ventaniella-Cantabrian Fault (Fernandez-Viejo et al., 2014). Based on previous interpretations made from seismic and potential field data

(Cadenas et al., 2018; Tugend et al., 2014), the Armorican Shear Zone and Ventaniella Fault along the Armorican and North Iberian margins, respectively, are interpreted to have played a significant role in shaping the crustal architecture of present-day necking domains. In particular, the Ventaniella Fault is interpreted to represent the boundary between the necking and proximal domains along the western North Iberian Margin (Cadenas et al., 2018). The transfer zone in the inferred prolongation of the Armorican Shear Zone was interpreted at the boundary between the wider necking zone along the Western Approaches margin in contrast to the narrow necking zone along the Armorican margin (Tugend et al., 2014). Considering these observations and crustal thicknesses calculated within these regions by model 5, we suggest that inherited structures played a key role in distributing deformation and the resultant crustal thinning within this region, a phenomenon that cannot currently be reproduced by deformable plate models built using GPlates.

In addition, another scenario not captured by model 5 is the potential role of Permian to Early Liassic rift basins within the English Channel that may have previously thinned the crust as a result of intracontinental rifting (Ruffell, 1995). Model 2 was the only deformable plate model that included Late Permian-Triassic related deformation. Comparing crustal thicknesses calculated by model 2 and gravity inversion within this region, a good crustal-scale correlation is observed despite slightly higher crustal thicknesses (~5 km) calculated by model 2 within ocean-ward regions of the Western Approaches margin. However, a uniform crustal thickness of 30 km during the Late Permian-Triassic considered in model 2 is deemed highly unlikely given the expectation of larger crustal thickness variations within this region as a result of compressional deformation experienced during the Variscan Orogeny (Matte, 2001). Although crustal thinning caused by orogenic collapse could potentially result in crustal thicknesses closer to the 30 km estimate prior to the Jurassic (Matte, 1991; Ziegler, 1988), crustal thicknesses within the Bay of Biscay are still considered to be highly variable prior to Late Triassic and Early Jurassic rifting, suggesting that localized strain partitioning and deformation were more likely to be influenced by inherited structures. In addition, significant widespread crustal thinning calculated by all deformable plate models along the Goban Spur margin (5 km or less) in contrast to estimates calculated by gravity inversion (10–20 km) also suggest that the orientation of major lithospheric boundaries and their interplay with regional stress directions played a key role in localizing deformation during Mesozoic rifting.

5.3.2. Investigating the Interplay of Continental Blocks and Transfer Zones

The position of the Landes High at 200 Ma tested in model 5 and its interplay with the reconstructed orientation of interpreted transfer zones (Figure 12) provide interesting observations along the Western Approaches margin. One observation is the intersection of the Landes High with an interpreted north-east-southwest trending offshore prolongation of one branch of the Armorican Shear Zone. Based on this relationship, it is postulated that the transfer zone at this location potentially localized deformation and delimited the Landes High throughout the Jurassic as a result of the crustal stretching induced from its interplay with this branch of the Armorican Shear Zone and progressive eastward motion. This could partially explain the relatively undeformed nature of the Landes High suggested by gravity inversion crustal thickness estimates. In addition, this observation can also provide clues about the origin of the Le Danois High. In particular, whether the Le Danois High has always been an independent continental block or whether it was originally connected to the Landes High and later detached as a result of deformation experienced within the Landes High. Considering the first scenario, having the Le Danois High act as an independent continental block as tested in model 4 seemed to cause too much regional deformation given its small size in comparison to other continental blocks. In contrast, considering previous paleo geographic maps of the Bay of Biscay (Tugend et al., 2015a), it can be postulated that the Landes High was once a larger continental block having undergone deformation during the Mid-Late Cretaceous. This scenario would also support recent seismic interpretation within the Bay of Biscay (Cadenas et al., 2020) suggesting that the Le Danois High corresponded to a rift-related continental block which developed particularly from the Aptian to Albian due to the emplacement of extensional detachment faults. However, future studies in this region are needed in order to address these theories regarding the deformation history and potential link between these two continental blocks.

5.4. Implications for Iberian Plate Kinematics

Considering traditional plate reconstruction studies of the Iberian plate that propose subduction in the Pyrenees (Vissers & Meijer, 2012), strike-slip motion along the Northern Pyrenean Fault (Olivet, 1996; Stampfli & Borel, 2002), or transtensional and rift-perpendicular motion along the Iberia-Eurasia plate boundary (Jammes et al., 2009), all of these reconstructions propose Iberia to act as single, rigid, tectonic plate. In light of more recent studies that consider the Iberian plate kinematics (Angrand et al., 2020; Nirrengarten et al., 2018), the partitioning of Iberia into continental blocks and microplates such as the Ebro Block and Landes High (introduced in Tugend et al. (2014, 2015a)) provides a more robust and dynamic approach to investigate temporal variations in strain partitioning along the Iberia-Eurasia plate boundary. Rigid plate tectonic reconstructions can often lead to inappropriate overlap of continental domains and a limited ability to make comparisons with results obtained from independent geological and geophysical observations. This study presents the first deformable plate tectonic reconstruction of the area allowing for the investigation of deformation experienced within continental domains based on previously published, and newly presented plate kinematic models. The preferred kinematic model suggests oblique rifting within the Bay of Biscay from the Jurassic to Early Aptian (~125 Ma) in agreement with previous reconstructions made by Nirrengarten et al. (2018). However, an independent assessment of the Landes High plate kinematics conducted herein, and its interplay with the Ebro Block provide an improved model of the Bay of Biscay plate kinematics based on regional-scale crustal thickness correlations with gravity inversion estimates and observations from seismic and well data. Considering the models tested herein, models that exclude the Landes High as an independent continental block often underestimate the amount of deformation experienced within the Bay of Biscay. This observation also suggests that kinematic models proposing subduction within the Pyrenean realm or pure strike-slip along the Northern Pyrenean Fault are highly unlikely due to their inability to account for the deformation experienced within the Bay of Biscay, in addition to their limited ability to reconcile geological and geophysical observations (Barnett-Moore et al., 2016; Tavani et al., 2018). Moreover, the results of this study suggest that continuing to modify the poles of rotation for Iberia using updated oceanic magnetic anomaly and paleomagnetic constraints is not the only approach when continuing to address problems related to the Mesozoic plate kinematics of Iberia. In contrast, giving more detailed consideration to the kinematics of continental blocks and their interplay with major lithospheric boundaries throughout Iberia using methodologies such as deformable plate tectonic reconstructions and numerical models may be a more advantageous approach moving forward to address problems related to Iberian plate kinematics. Integrating results calculated by deformable plate models with observations from independent data sets and numerical models is important to understand the development of present-day crustal structure associated with lithospheric heterogeneities and depth-dependent deformation. Considering the current state of deformable plate modeling capabilities, these phenomena are not easily understood using deformable plate models alone.

6. Conclusions

The deformable plate tectonic models presented in this work have provided insight into the plate kinematic evolution of the Bay of Biscay-Parentis rift system. A comparison of deformable plate models with previously published and newly presented gravity inversion results, and interpretations from regional seismic and well data, provided a good metric for investigating the evolution of the Bay of Biscay. The main findings of this work include:

1. Oblique extension and strain partitioning prior to the opening of the Bay of Biscay were largely influenced by the independent plate kinematics of the Landes High and its interplay with the Ebro Block. As suggested by previous studies using alternative methodologies and data sets, the preferred plate kinematic model suggests that models proposing subduction in the Pyrenees or pure strike-slip motion along the North Pyrenean Fault are very unlikely
2. Deformable plate models that include the Landes High produce a region of thinned crust centered within the Parentis Basin, analogous to that observed present day. Thus, the formation of the Parentis Basin is considered to be largely dependent on the Landes High kinematics

3. Based on the deformable modeling results presented, the Ebro Block is interpreted to have minimal impact on the deformation experienced within the Bay of Biscay in contrast to its significant influence eastward within the Pyrenean realm
4. Deformable plate models that consider the Le Danois High as a rigid independent continental block appear to overestimate the amount of regional deformation experienced along the North Iberian margin as a result of its independent kinematics. Moreover, continental blocks similar in size to that of the Le Danois High ($\sim 3,000 \text{ km}^2$) appear to be at the limit of continental block sizes that should be included within deformable models built in GPlates
5. Major lithospheric boundaries such as the Ventaniella Fault and Armorican Shear Zone appear to have played a significant role in rift segmentation and shaping the present-day crustal architecture of the Bay of Biscay. It is likely that these lithospheric boundaries follow inherited/preexisting Variscan and Late Carboniferous–Early Permian structural trends
6. More generally, as opposed to obtaining more detailed oceanic magnetic anomaly constraints and assessing their impact on the orientation of rigid tectonic plates, considering the independent kinematics of continental blocks and their impact on the deformation experienced along the Iberia–Eurasia plate boundary represents an alternative approach moving forward to develop a more detailed understanding of strain partitioning along the Iberia–Eurasia plate boundary

Data Availability Statement

Data used to perform gravity inversions are available through Andersen (2010), Divins (2003), Smith and Sandwell (1997), Muller et al. (1997), Sandwell and Smith (2009), and Tugend et al. (2014). Archiving of GPlates data files used to create deformable plate models can be found in the Mendeley Data repository at <https://www.doi.org/10.17632/k3kp22yxs7.1>

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