

Extension and inversion structures in the Tethys–Atlantic linkage zone, Algarve Basin, Portugal

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Received: 28 July 2015 / Accepted: 22 November 2015 / Published online: 10 December 2015
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Abstract The Algarve Basin is a Meso-Cenozoic sedimentary basin overlying Carboniferous basement, located in the southwestern margin of the Iberian Peninsula. Its structure reveals a protracted tectonic history comprising various pulses of Mesozoic extension followed by Cenozoic compression. This work deals with the structure along the northern margin, where the Mesozoic extensional structures and Cenozoic inversion structures crop out. The strike of the extensional structures ranges from E–W to N–S, as controlled by a shift from Tethyan-dominated extension in the east to Atlantic-dominated extension in the west. Contractural structures are inverted extensional structures, following their same trends. It is argued that the thickness of the Hettangian evaporite layer exerts a strong control on the structural style throughout the basin during the extensional and inversion episodes. The basin is affected by thick-skinned deformation along the northern margin, where salt is thin or absent, basement involved fault systems and short-cut structures. Basinward, as the Hettangian salt thickens, the margin is affected by thin-skinned deformation, with listric and down-to-the-basin growth faults, diapirism and salt-cored detachment folds. The aim was to discuss the key tectonic features, the relevance of salt, and understand the nature, timing, and significance of all these structures in the regional tectonic evolution.

Keywords Algarve Basin · Extensional tectonics · Inversion tectonics

Introduction

The Algarve Basin in the Gulf of Cadiz is a Meso-Cenozoic sedimentary basin located on the southwestern margin of the Iberian Peninsula, north of the Africa–Iberia plate boundary (Fig. 1). Rifting occurred during the breakup of Pangea, associated with the opening of the North-Central Atlantic and Tethys oceans. The Mesozoic sedimentary record of the basin spans from the Late Triassic to the Early Cretaceous, with the main depocenter located in the central part of the offshore Algarve Basin. The basin extends to the offshore as far as 100 km south, as recognized on several seismic surveys. The southern margin of the basin is defined by the Gulf of Cadiz Basement High (GoCBH), a ENE–WSW trending structure with bathymetric relief (Fig. 1). Oceanic lithosphere extends beyond the GoCBH (Sallarès et al. 2011), interpreted to be the westernmost part of the Tethys Ocean (Martínez-Loriente et al. 2013), which has partially been subducted under the Gibraltar Arc (Gutscher et al. 2002).

Two main tectonic phases have been documented for the Gulf of Cadiz and the Algarve basins: a Mesozoic phase dominated by extensional tectonics, and a compressional phase from Late Cretaceous to Quaternary (mainly during Cenozoic), related to the collision between Iberia and Africa (Tortella et al. 1997; Terrinha 1998; Maldonado et al. 1999; Gutscher et al. 2002; Gràcia et al. 2003; Terrinha et al. 2009). Terrinha (1998) developed a detailed tectonic model for the Mesozoic basin onshore, along with a kinematic model for the offshore Cenozoic basin, linked to the geodynamic evolution of the Gulf of Cadiz and the Betic Cordillera. However, the relationship between the onshore Mesozoic basin

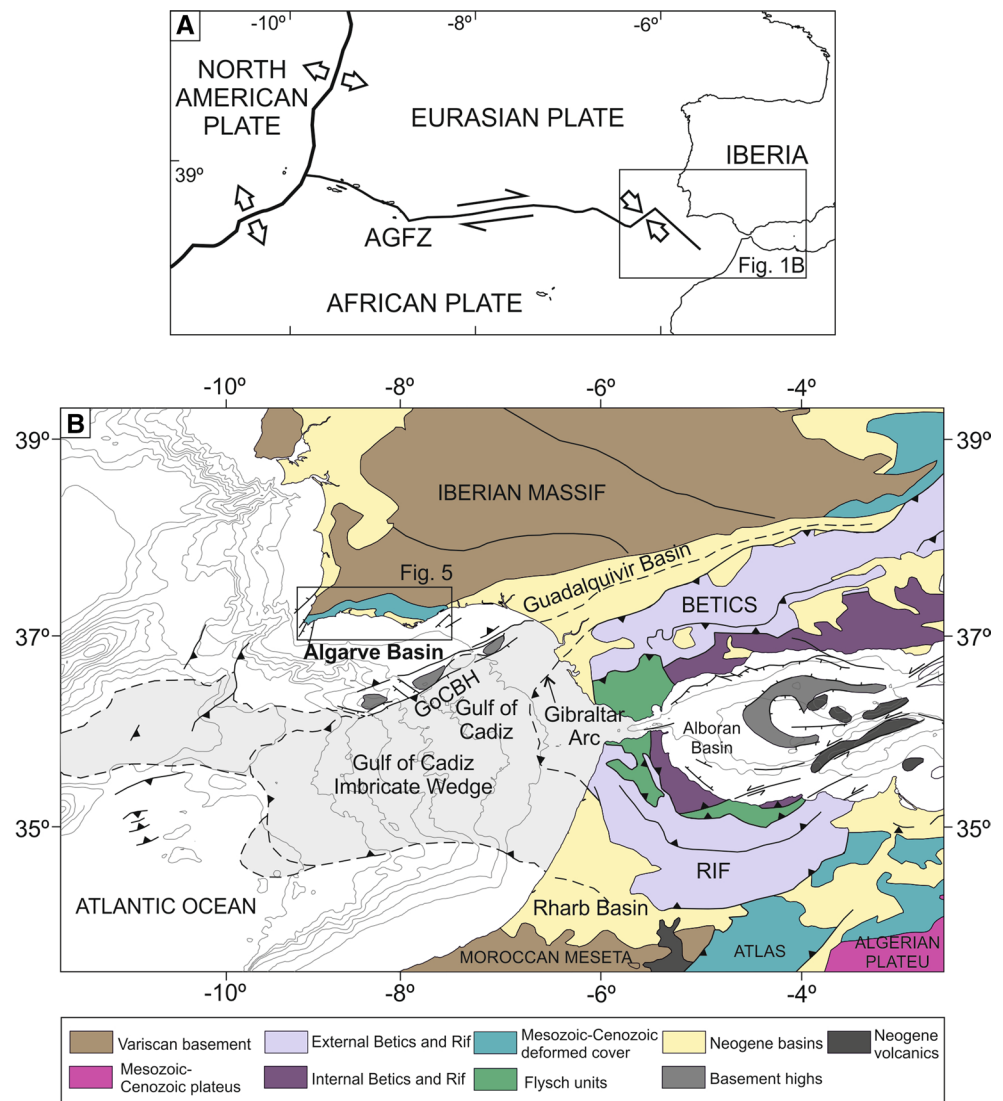
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Fig. 1 **a** Main elements of plate boundaries and relative plate kinematics. *AGFZ* Azores–Gibraltar fracture zone. **b** Geologic map of the Betic–Rif system showing the principal tectonic units and associated Neogene basins (modified from Iribarren et al. 2007). *GoCBH* Gulf of Cadiz Basement High



and its deeper counterparts, in the Gulf of Cadiz and west toward the Atlantic Ocean, has not been fully resolved.

This paper presents a revision of the interpretation of the tectonic architecture of the onshore, northern margin of the Algarve Basin, and its significance in defining the transition between the Tethys and the Atlantic extensional domain. An improved understanding of the Mesozoic extensional systems also sheds light on the relationship between Mesozoic extension and Cenozoic contraction, and the role of the salt in the structural evolution of the Algarve Basin.

Geological setting

Stratigraphy

The stratigraphy of the Algarve Basin presented here (Fig. 2) is defined onshore and offshore by Manuppella (1988),

Terrinha (1998), and Matias (2007). Mesozoic sedimentation starts with red continental alluvial clastics in the Late Triassic (Rhaetian; Fig. 3d). Triassic rocks unconformably rest on low-grade metamorphosed Carboniferous flysch sediments and Permian rocks that were involved in Variscan deformation (Fig. 4). The overlying Hettangian pelite–evaporitic unit is made up of alluvial to shallow lacustrine red shales (Fig. 2), a thin layer of shallow water dolomites, and an evaporitic sequence constituted by halite, anhydrite, and gypsum. At the Hettangian–Sinemurian transition, these units are capped by a volcano–sedimentary complex consisting of basaltic lavas and pyroclastic rocks intercalated with clays and dolomites (Fig. 2). This volcanic event is associated with the Central Atlantic Magmatic Province (CAMP; Martins et al. 2008; Verati et al. 2007) and the ending of the first extensional episode in the Algarve Basin (Terrinha et al. 2002).

Limestones and dolomitic limestones of the Early Jurassic give way gradually to more marly units during the

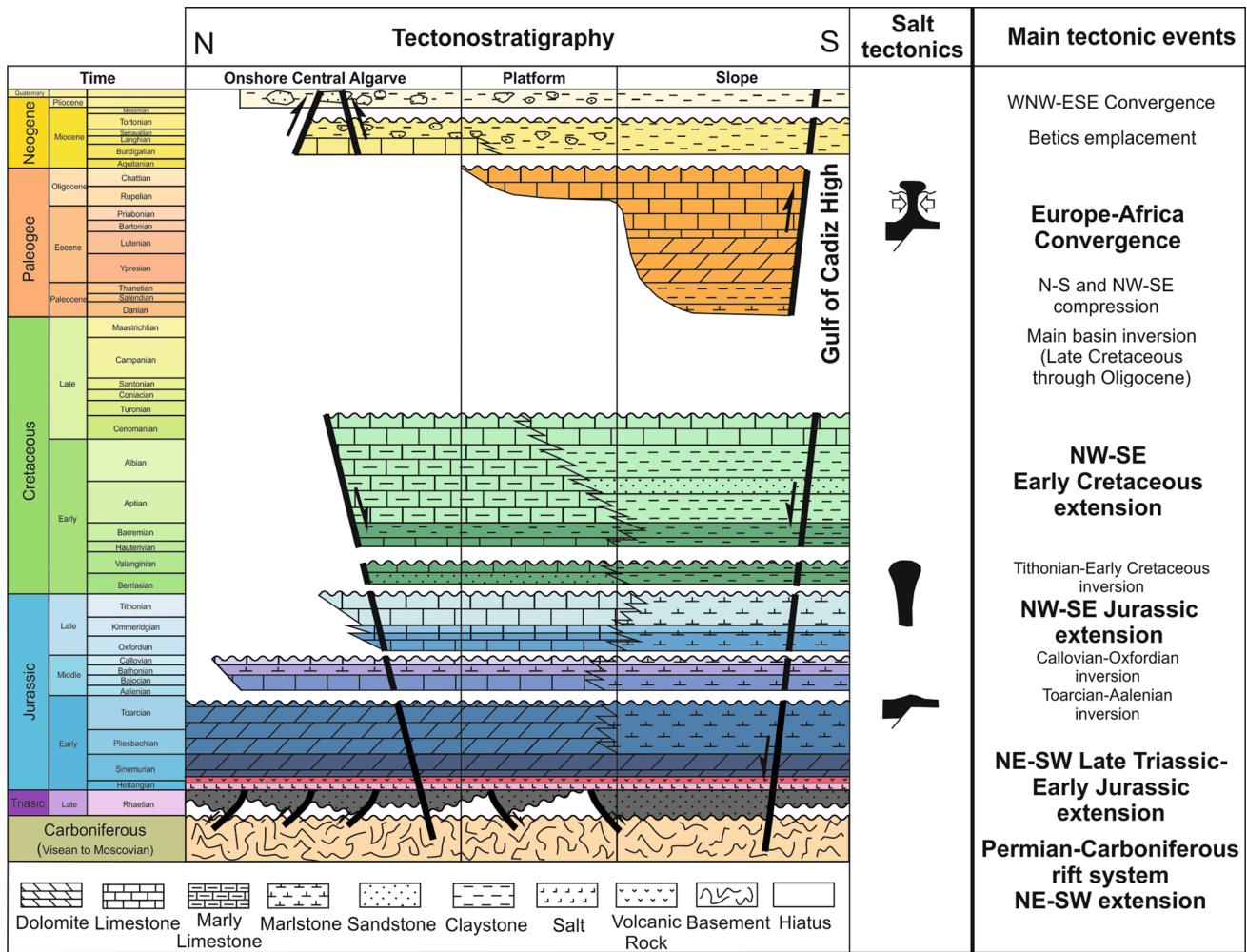


Fig. 2 Simplified stratigraphy of the Algarve Basin with main stratigraphic units and main tectonic events. *Bold type* represents the major tectonic events (adapted from Terrinha 1998; Matias et al. 2011; Fernandes et al. 2013)

Middle Jurassic, and the Late Jurassic consists of limestones (Fig. 2).

The Lower Cretaceous was deposited during the latest phase of extension, after a brief hiatus, and is represented by a mixed carbonate and siliciclastic succession (Rey 1983, 2006, 2009; Fig. 2). The Upper Cretaceous and Paleogene are absent due to uplift during the main phase of basin inversion. Upper Cretaceous rocks are only represented locally by volcanic products such as dikes and sills (Martins 1999; Martins and Munhá 1993) associated with the emplacement of the Monchique alkaline laccolith complex (Miranda et al. 2009). The emplacement age is well constrained to 72 ± 2 Ma by several whole-rock K–Ar and Rb–Sr data (e.g., McIntyre and Berger 1982; Bernard-Griffiths et al. 1997). Sedimentary rocks of Late Cretaceous and Paleogene age have only been described in offshore wells. The Mesozoic rocks of the Algarve Basin are bounded by a regional erosional unconformity, overlain by Neogene

strata (Fig. 3f). Locally, the entire Mesozoic sequence is eroded, setting the Miocene directly on top of the Paleozoic basement. The Miocene is represented by limestones that grade upwards into siltstones and fine sandstones (Pais et al. 2000). These units were karstified and covered by Pliocene to Pleistocene fluvial/marine detrital sediments. The youngest sediments Algarve Basin are lithified Holocene beach sand and dunes, influenced by frequent climatic oscillations and sea level fluctuations (Moura et al. 2007).

Structure and evolution

The extensional evolution of the Algarve Basin starts with rifting in the Mid–Late Triassic along the sinistral transensional boundary between Iberia and Africa. The relative motion of both plates was controlled by the differential movement of Africa with respect to Eurasia and North America, associated with the breakup of Pangea and the



◀ **Fig. 3** Outcrops of the Algarve Basin. **a** Upper Jurassic rollover, located in the hanging-wall of the Algibre Thrust. Normal polarity toward the north. It corresponds to the minor rollover of Fig. 12b. An equivalent image of the outcrop can be explored here: <https://goo.gl/maps/iBnr9Z6NdZJ2>; latitude and longitude: 37.169755N, -8.2552556W. **b** N–S extensional fault affecting the Upper Jurassic in the western sub-basin. Latitude and longitude: 37.063481N, -8.792303W. **c** Bajocian SW-dipping extensional faults fossilized by Bathonian sediments. 37.003903, -8.942807. **d** South-directed thrust affecting the Triassic unit in the margin of the basin. It is analogous to the thrusts in Fig. 10c. An equivalent image of the outcrop can be explored here: <https://goo.gl/maps/rM6USoYiSLM2>; latitude and longitude: 37.2631981N, -8.2932982W. **e** Highly steeped flank of Lower Cretaceous below the Algibre Thrust. See Fig. 12b. Latitude and longitude: 37.164728N, -8.247658W. **f** Erosional unconformity between the Lower Cretaceous and the Miocene, south of the Albufeira diapir. See Fig. 12b. Latitude and longitude: 37.080496N, -8.261459W. **g** Praia do Cilheta outcrop: Oxfordian faulting and an inverted Middle/Upper Jurassic rollover during the Cenozoic. *Red line* faults, *dashed red line* interpreted fault, *white line* bedding plane, *dotted white line* unconformity. Latitude and longitude: 37.008546N, -8.948964W

development of the westernmost Neo-Tethys (Srivastava et al. 1990; Dewey et al. 1989). As a result, a new ENE–WSW trend extensional fault system dominated the basin. Extension lasted into the Early Cretaceous. During this time the structural style of the basin was dominated by extensional faulting and diapirism (Terrinha 1998; Maldonado et al. 1999; Matias et al. 2005).

Four main unconformities or hiatuses can be identified in the Jurassic to Early Cretaceous succession, defining five sedimentary mega-cycles (Fig. 2, Manuppella

1988; Terrinha et al. 2002). These unconformities have been interpreted as episodes of inversion or non-deposition between extensional episodes, based on inversion structures identified onshore and offshore (Terrinha 1998; Lopes 2002) and later defined by Terrinha et al. (2002). The first extensional phase starts in the Triassic and ends in the Sinemurian and is followed by a short period of marine transgression and tectonic quiescence. Subsequent extension is punctuated by three episodes of inversion that occurred in the Toarcian–Aalenian, the Callovian–Oxfordian, and the Tithonian–Berriasian transition. These episodes of tectonic inversion resulted in the partial reactivation of syn-sedimentary extensional faults and the development of small amplitude folds and unconformities. Terrinha et al. (2002) proposed three kinematic models for the inversion episodes: reversal of the shear movement of the Iberia–Africa plate boundary, ridge push, and compression induced by thermal collapse. The last extensional phase took place in the Early Cretaceous and lasted until the Cenomanian. Within this phase there is the presence of a major unconformity, related to a marine regression (Correia 1989), during the Valanginian–Hauteurian in the central-eastern sub-basin, or during the Valanginian–Berriasian in the western sub-basin.

The extensional fault system is compartmentalized by N–S to NW–SE trending faults (Aljezur, Portimão and São Marcos-Quarteira faults, Fig. 5b). These faults controlled changes in the deposition of the Mesozoic units, which thicken eastwards across these faults (Terrinha 1998).

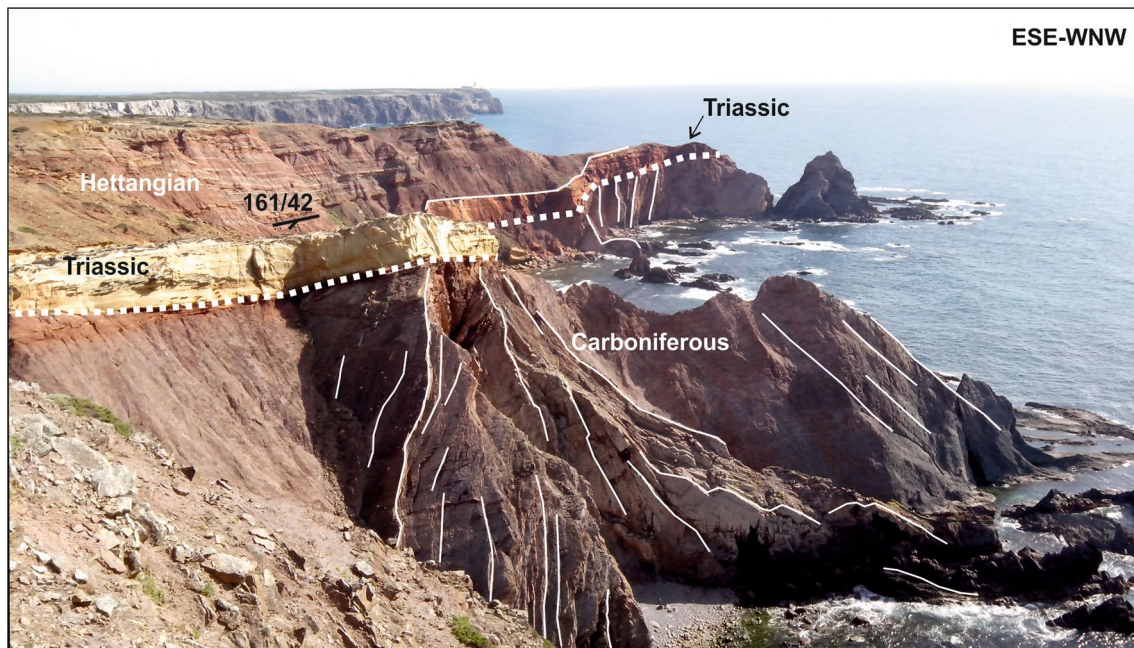


Fig. 4 Praia do Telheiro landscape. Triassic unconformably on top of Carboniferous vertical layers. Notice the south-dipping of the basin margin. *White line* bedding plane, *dotted white line* unconformity. Latitude and longitude: 37.051607N, -8.980471W

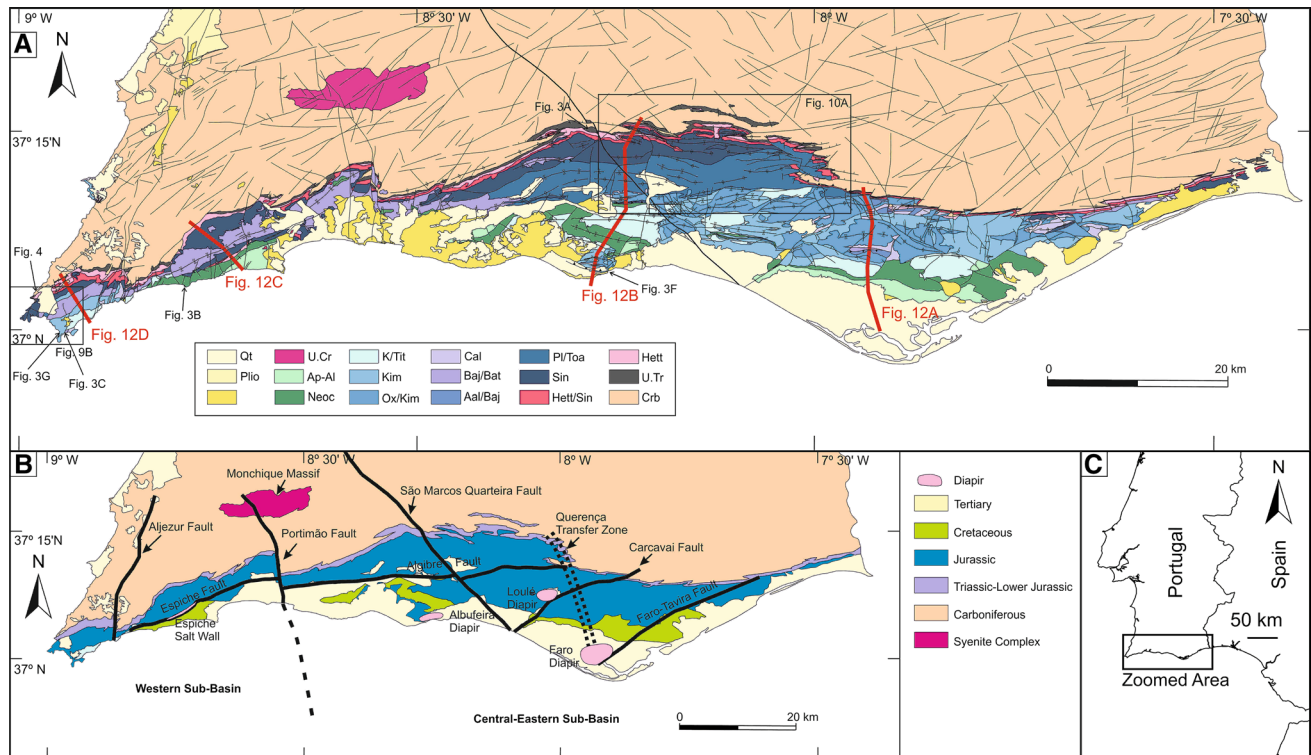


Fig. 5 **a** Study area location and geological map of the Algarve Basin (modified from Manuppella 1992; Terrinha 1998 and Davison et al. 2015). *Qt* Quaternary, *Plio* Pliocene, *Mc* Miocene, *U. Cr* Upper Cretaceous, *Ap–Al* Aptian–Albian, *Neoc* Neocomian, *K/Tit* Kimmeridgian/Tithonian, *Kim* Kimmeridgian, *Ox/Kim* Oxfordian/Kimmeridgian, *Cal* Callovian, *Baj/Bat* Bajonian/Batonian, *Aal/Baj*

Aalenian/Bajocian, *Pl/Toa* Pliensbaquian/Toarcian, *Sin* Sinemurian, *Hett/Sin* Hettangian/Sinemurian, *Hett* Hettangian, *U. Tr* Upper Triassic, *Crb* Carboniferous. **b** Simplified map showing major tectonic features, which have had different behavior since the Late Triassic. **c** Location of the study area

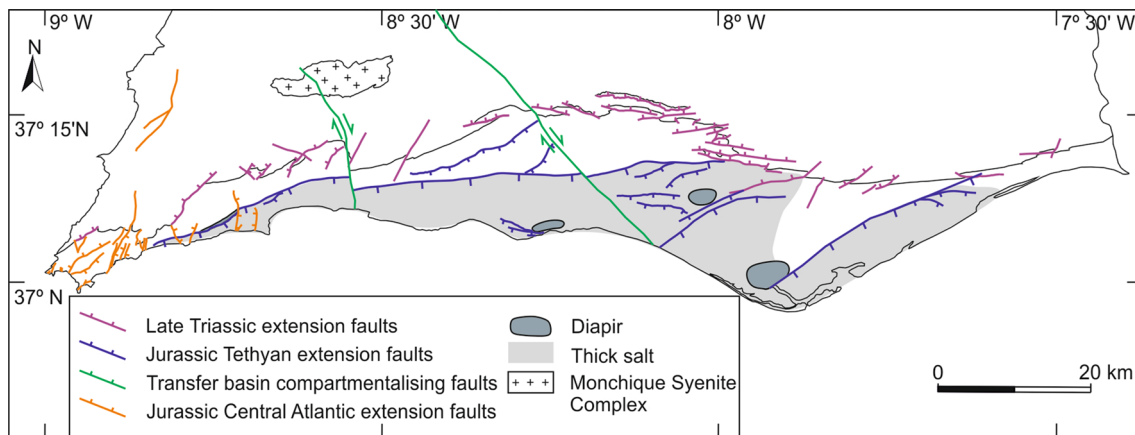


Fig. 6 Mesozoic extensional fault system of the Algarve Basin and the salt distribution. West of the Portimão fault, along the Espiche fault the outcrop is “slay diapir”; At Albufeira the outcropping dia-

pir rock is gypsum; east of the SMQF the diapirs are halite. It seems there is a gradient toward the east from shale thru gypsum/anhydrite to halite; This is also compatible with deepening eastwards

Manuppella (1988) and Manuppella et al. (1988) used the Portimão and São Marco Quarteira faults to define three sub-basins: the western, the Budens-Lagoa/Algoz (central)

and the eastern sub-basins. Nevertheless, in this article, we propose a simpler subdivision into only two sub-basins based on the dominant structural features. We will refer to

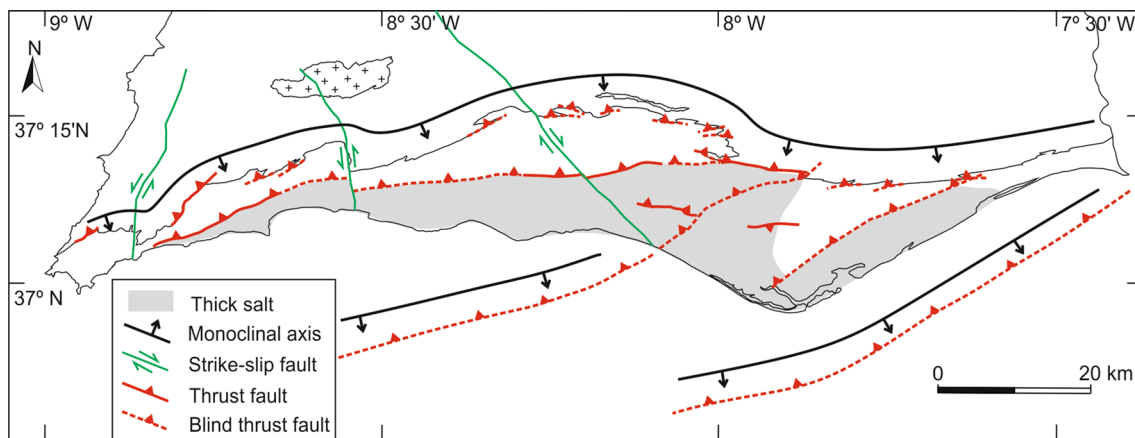


Fig. 7 Late Cretaceous–Cenozoic contractional structures of the Algarve Basin

the western and the central-eastern sub-basins, separated by the Portimão Fault (Fig. 5b). The central-eastern sub-basin is dominated by E–W to ENE–WSW trending extensional faults (Fig. 6), a trend inherited from the Variscan structural grain of the South Portuguese Zone (Terrinha 1998). In the western sub-basin, extensional fault orientation is N–S to NE–SW, parallel to the Atlantic margin of Iberia, cross-cutting some E–W structures that extend from the central-eastern sub-basin. The central-eastern basin and the offshore Algarve Basin are also characterized by Mesozoic salt tectonism of varying intensity (Terrinha 1998; Maldonado et al. 1999; Matias et al. 2005; Figs. 3, 4).

From Late Cretaceous to Quaternary, the basin underwent tectonic inversion due to the convergence between Africa and Iberia. East of the Algarve Basin, convergence led to the formation of the arcuate Betic–Rif mountain belt and the formation of an eastward subduction under the Gibraltar Arc (e.g., Royden 1993; Lonergan and White 1997; Gutscher et al. 2002; Duarte et al. 2011). Basin inversion is characterized by the deformation of ENE–WSW to E–W trending Mesozoic extensional faults (Terrinha 1998; Lopes et al. 2006) and the truncation of these faults by thrusts (Figs. 10b, 11a). Shortening was mainly accommodated by E–W-oriented folds formed by buttressing against extensional faults (Fig. 12b) and south-directed short-cutting of partially reactivated extensional faults. Basin inversion has resulted as well in the reactivation of previously developed salt structures. Diapirs were squeezed against extensional faults to form thrusts (Loulé and Albufeira diapirs, Fig. 12a; Davison et al. 2015). Inversion is also expressed along the basin margin by the general southward dip of the onshore Mesozoic basin. The uplift of the Iberian Peninsula, including the SW Iberian margin, is related to the Cenozoic convergence between Africa and Iberia, which favored the formation of intra-plate mountain ranges (Fernández-Lozano 2012). The recent uplift and

south tilting of the margin basin are registered in the coast by an erosional unconformity between Lower Cretaceous and the overlying south-dipping Miocene (Fig. 3f; Terrinha 1998).

Multi-phase deformation of the Algarve Basin: from extension to inversion

The multi-stage tectonic history of the Algarve Basin presented above has resulted in a complex superposition of extensional and contractional structures (Fig. 6). Firstly, the structural fabric is heterogeneous as it varies with the different extensional phases. This is further complicated by the fact that the Algarve Basin formed as an E–W trending rift basin in the vicinity of the N–S trending north-central Atlantic Ocean rift margin. Tectonic inversion due to the N–S convergence between Iberia and Africa later strongly overprinted many of the extensional structures of the basin (Fig. 7). In this section we aim to discuss the different generations of extensional structures that have been observed in the basin and their role in the extensional history of the basin. In order to do this, we will simplify the history of rifting into two main stages, an early rift stage (Late Triassic to Early Jurassic) and the main rift stage (Early Jurassic to Early Cretaceous), and describe the associated structures prior to inversion (Fig. 6).

Late Triassic to Early Jurassic extension

The present-day northern limit of the Algarve Basin is marked by the outcrop of Carboniferous basement unconformably underlying a generally southward dipping Triassic to Lower Jurassic sequence. This basement–basin unconformity is roughly E–W trending (Fig. 5). Along this margin, extensional faults are preserved (Fig. 6). These faults

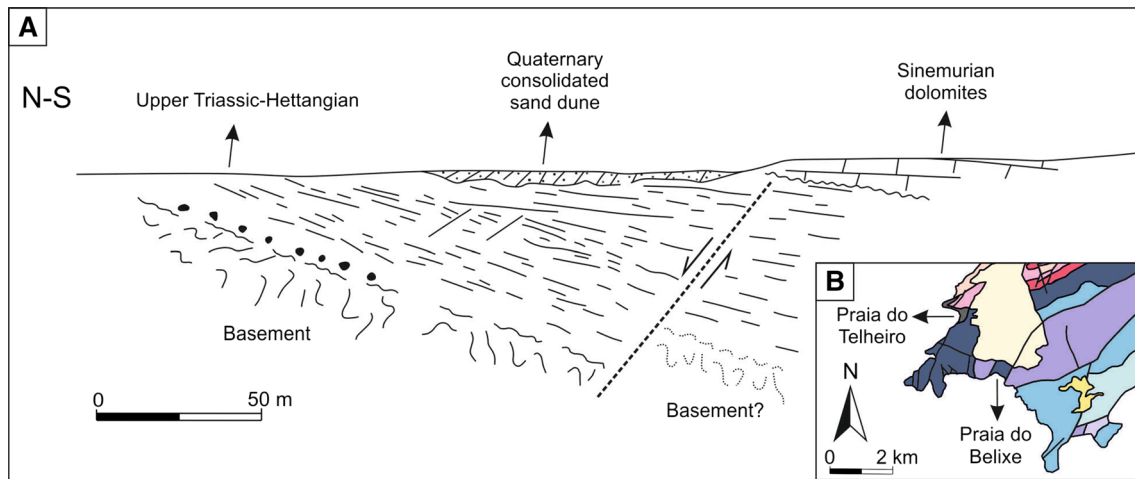


Fig. 8 **a** Triassic–Hettangian growth faults in Praia do Telheiro outcrop. The onlaps of Sinemurian carbonates cover the blind extensional fault and the sedimentary complex of Hettangian age. *Dashed black line* interpreted fault, *dotted black line* interpreted basement

(modified after Terrinha 1998). **b** Location of Praia do Telheiro and Praia do Belixe outcrops. See Fig. 5a for location and legend. Latitude and longitude: 37.051607N, –8.980471W

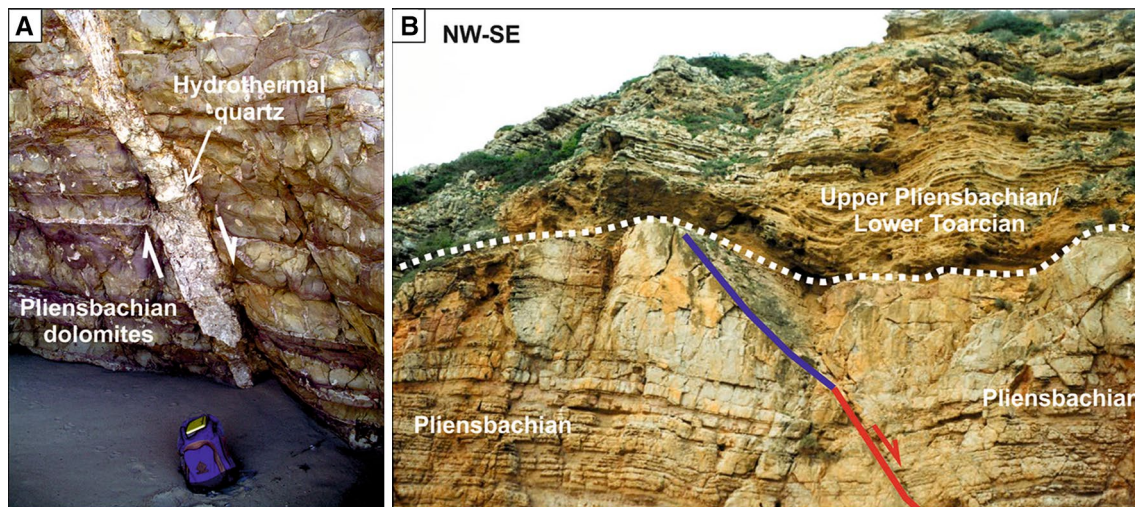


Fig. 9 Praia do Belixe outcrop interpreted photographs. **a** Pliensbachian extensional faults filled with hydrothermal quartz. **b** Extensional faults eroded by intra-Pliensbachian and Early Toarcian unconformities. *Blue line* outcrop splay, *red line* extensional fault. See Fig. 9a for location

are north-dipping, strike E–W to WNW–ESE, and involve basement. They have displacements of tens of meters, juxtaposing Upper Triassic and Lower Jurassic sediments with Carboniferous basement (Figs. 6, 7). This extensional system was active from the Late Triassic to Early Jurassic. The age of the end of deformation can be inferred from the outcrops in Telheiro beach, in the western sub-basin (Fig. 8). Here, a north-dipping fault and its associated half-graben filled with Upper Triassic–Hettangian rocks are covered by Sinemurian sediments. A similar relationship is also seen at an outcrop of Pliensbachian age located at Praia do Belixe (Fig. 9), where syn-sedimentary extensional faults are filled

with hydrothermal quartz (Ribeiro and Terrinha 2007). These syn-sedimentary faults are eroded by intra-Pliensbachian and Early Toarcian unconformities (Fig. 9), attesting for syn-rifting vertical movements of the basin.

These early rifting extensional faults extend a few kilometers north of the present-day limit of Jurassic outcrop, as observed in isolated outcrops of Upper Triassic within the Carboniferous basement (Manuppella 1992, one such example seen in Fig. 10A). This indicates that the present-day northern limit of Jurassic outcrops is not the original limit of the extensional basin; uplift of the basin margin during Cenozoic

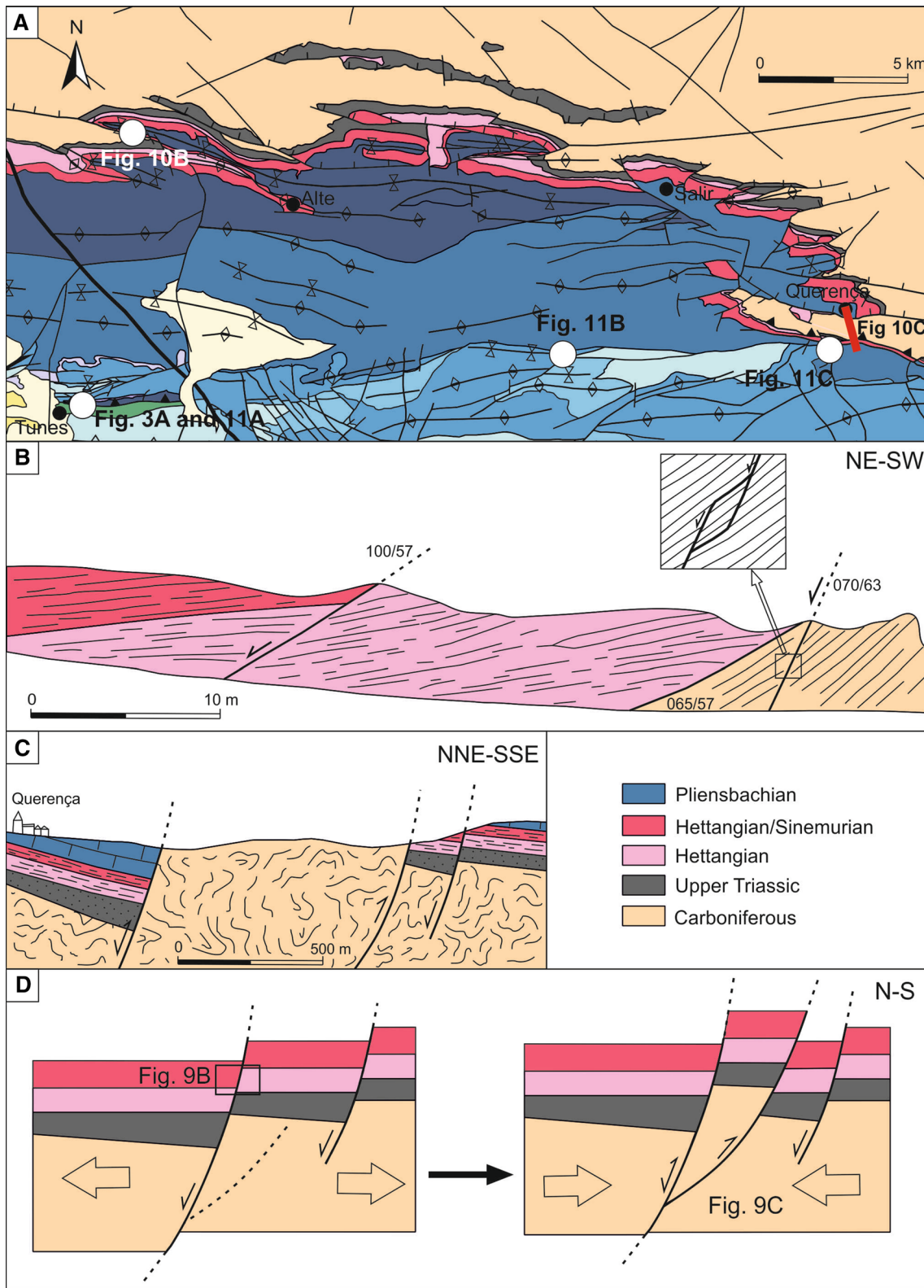


Fig. 10 **a** Geological map with location of outcrops. See Fig. 5a for location and legend. **b** Pico Alto outcrop. An equivalent image of the outcrop can be explored here: <https://goo.gl/maps/GgeYcPvmz2n>. Latitude and longitude: 37.2604932N, -8.2332851W. **c** Querença

cross section. Detail of the extensional fault to the right of the cross section can be explored here: <https://goo.gl/maps/7xf6NRiC2kE2>; latitude and longitude: 37.1832447N, -7.9656067W. **d** Schematic evolution of the basin-basement contact

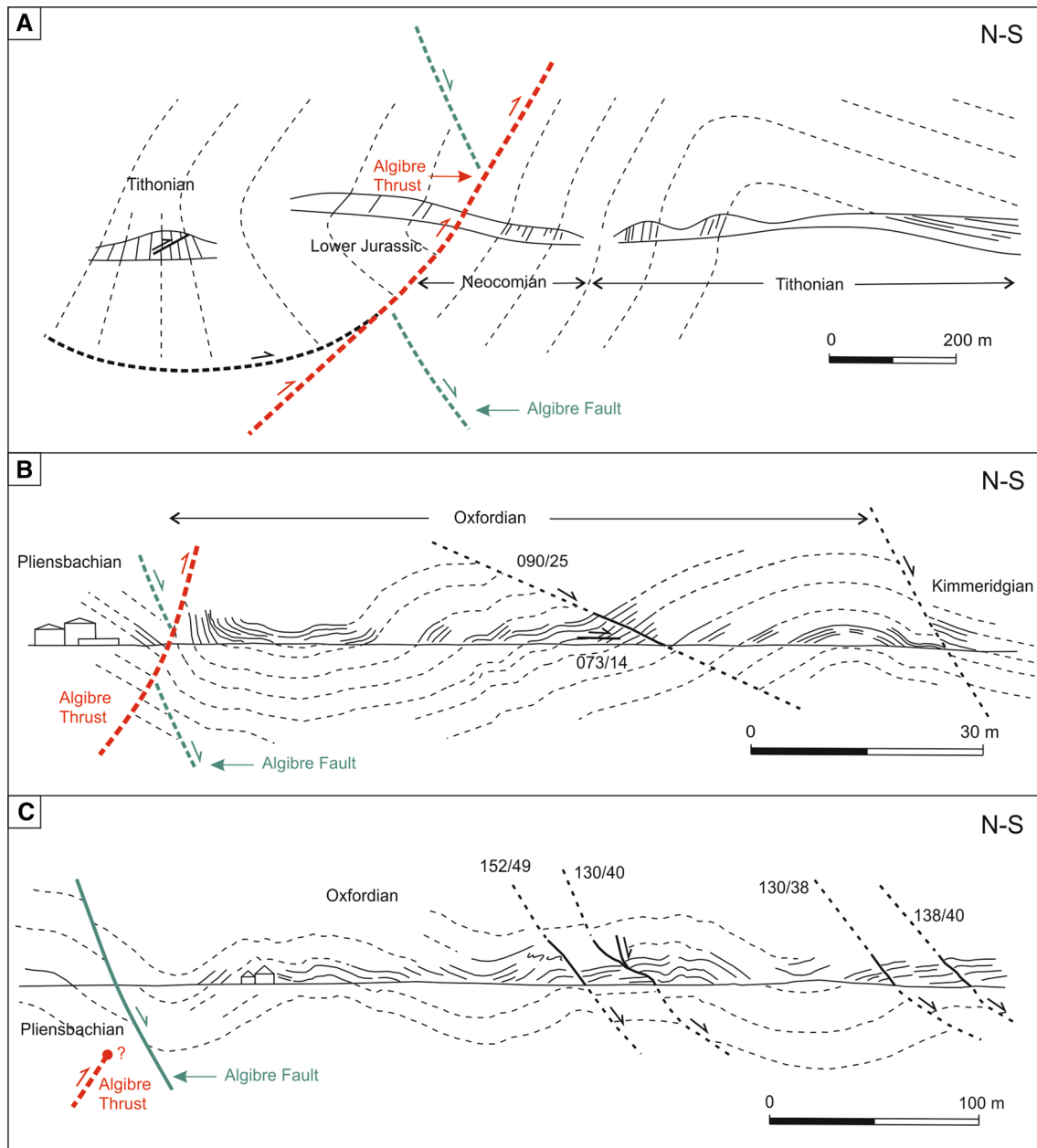


Fig. 11 Key outcrops from W to E showing the Algibre. See Fig. 5a for location. *Solid lines* represents observed outcrop and *dashed lines* represents interpreted bedding and faults. **a** Tunes outcrop. See Fig. 3e for more detail about the rollover structure on the left of the figure. Detail of the highly steeped Tithonian can be explored here: <https://goo.gl/maps/pLdZnp8Dv5x>; latitude and longitude: 37.1621192N, -8.25151W. **b** Ribera de Algibre outcrop. Detail

of the highly deformed Oxfordian in the footwall of the Algibre Thrusts can be explored here: <https://goo.gl/maps/f5XaNB7mmiH2>; latitude and longitude: 37.1830056, -8.0842423. **c** Penedos Altos outcrop. Extensional fault affecting the Oxfordian can be explored here: <https://goo.gl/maps/1phYa221f2m>; latitude and longitude: 37.183179N, -7.9901272W

inversion has removed Jurassic strata to the north of the present outcrop limit.

Uplift of the basin margin imposes a southward regional dip on the Algarve Basin, which means that the Late Triassic—Early Jurassic fault system does not crop out basinward (to the south), as it is covered by the post-faulting

Sinemurian carbonates. However, it is interpreted that this fault system extends south over the entire onshore Algarve Basin. Proof of this is the change in thickness and facies of Hettangian units to the south. Along the northern margin of the basin, this unit is only a few meters thick and dominated by pelites. To the south and to the east, it

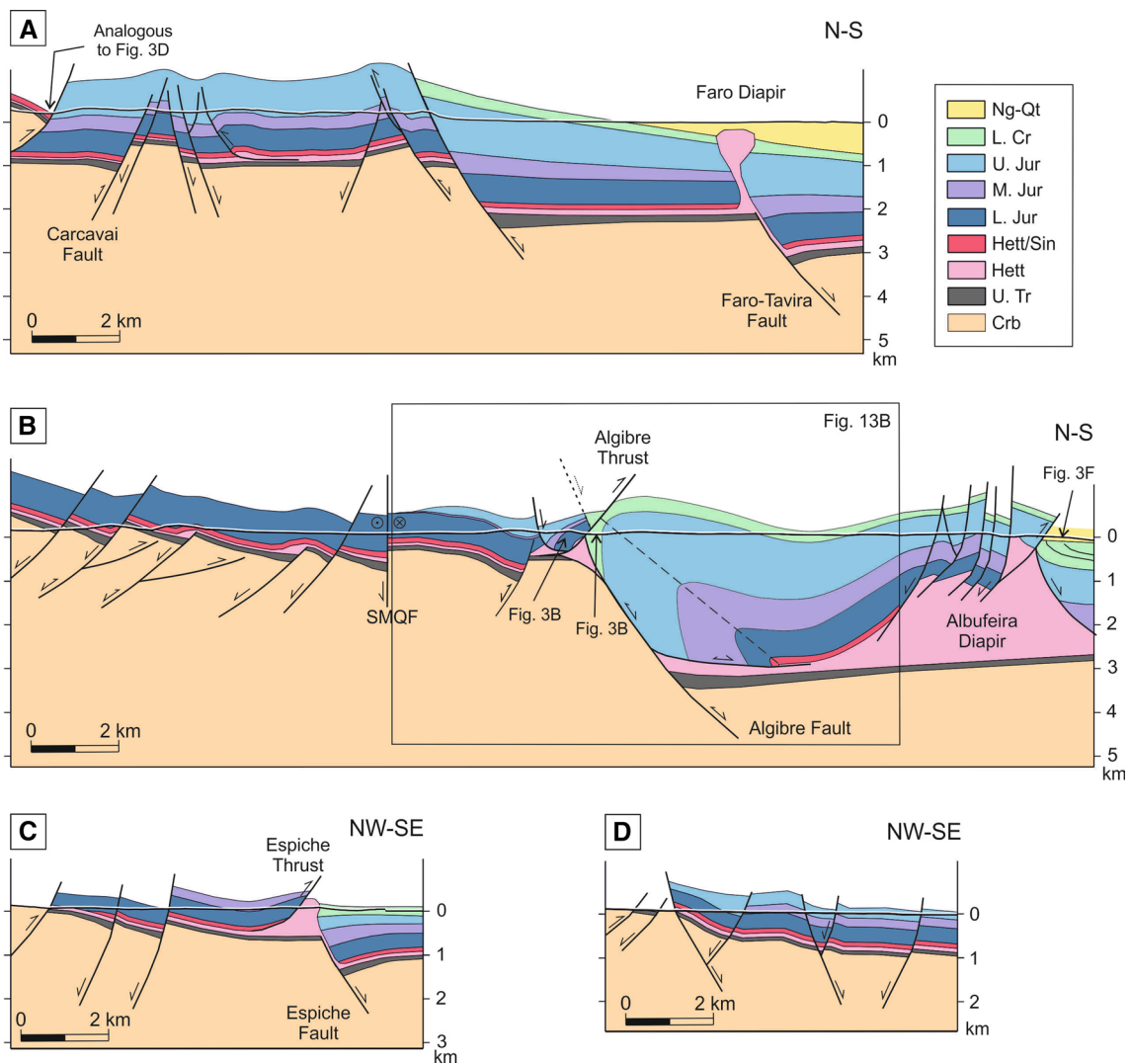


Fig. 12 Cross sections along the Algarve Basin. *Ng-Qt* Neogene–Quaternary, *L. Cr* Lower Cretaceous, *U. Jur* Upper Jurassic, *M. Jur* Middle Jurassic, *L. Jur* Lower Jurassic, *Hett/Sin* Hettangian/Sinemurian, *Hett* Hettangian, *U. Tr* Upper Triassic, *Crb* Carboniferous. See Fig. 5a map for location

becomes thick enough and rich enough in evaporites to feed the Loulé, Albufeira (Figs. 5b, 12b), and Faro diapirs (Figs. 5b, 12a; Terrinha et al. 1990, 1998), or even the allochthonous Esperança salt nappe (Matias et al. 2011). It is interpreted that the increase in subsidence toward the southeast was related to a greater amount of extensional fault activity.

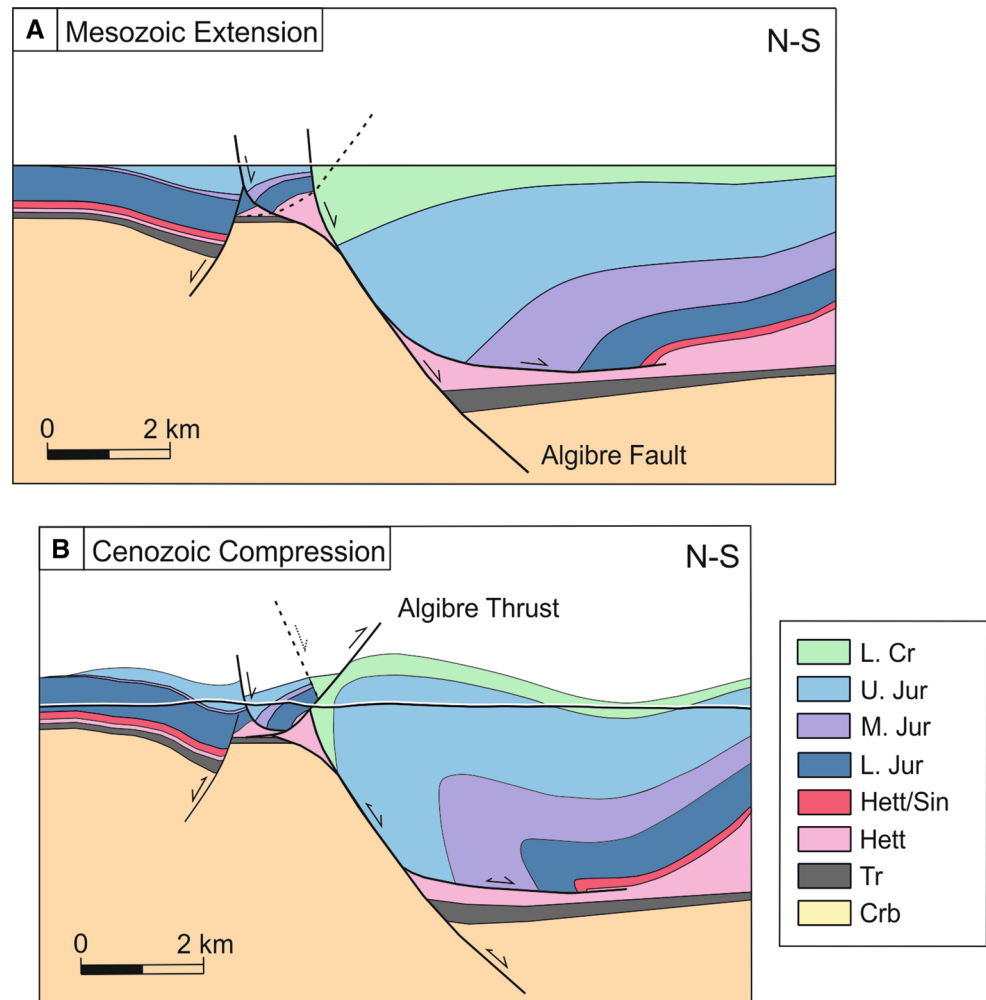
Early Jurassic to Early Cretaceous extension

After a period of tectonic quiescence with regional thermal subsidence during the Sinemurian, extension was recommenced in the Pliensbachian. During this stage there was a clear basinward migration of deformation. This second phase of extension also brought along a change in the

dominant vergence of faults, which changed from being mainly north-dipping in the Triassic–Early Jurassic to south-dipping (basinward dipping) faults. Furthermore, a significant change in style occurred. The initial extensional phase from Triassic to Early Jurassic triggered the formation of closely spaced faults with a limited throw (tens to few hundreds of meters). The orientation and spacing of these faults is interpreted to be related to the reactivation of the north-dipping basement foliation (Vegas 1980). From Pliensbachian, the extension was accommodated along major extensional faults with a greater throw (many hundreds of meters) and spacing, cross-cutting the basement weakness surfaces.

Extension during the Jurassic also led to a focalization of deformation away from the basin margin. Along the

Fig. 13 **a** Restitution of the rollover structure at the end of the Mesozoic extensional phase, in the Early Cretaceous, and **b** the reconstruction of the same structure inverted during the Cenozoic compressional phase. *Ng–Qt* Neogene–Quaternary, *L. Cr* Lower Cretaceous, *U. Jur* Upper Jurassic, *M. Jur* Middle Jurassic, *L. Jur* Lower Jurassic, *Hett/Sin* Hettangian/Sinemurian, *Hett* Hettangian, *U. Tr* Upper Triassic, *Crb* Carboniferous. See Fig. 12 for location



northern margin of the basin, no post-Sinemurian extensional faults can be observed, whereas to the south, significant depocenters of Middle and Late Jurassic are present. The presence of these depocenters is controlled by a set of E–W trending basin-scale faults. These extensional structures are named the Algre, Espiche, Carcavai, and the Faro-Tavira faults (Fig. 5b).

The Algre Fault (Figs. 10b, 11) marks the northern limit of the Upper Jurassic and Lower Cretaceous outcrops. To the north of this fault, the Lower Jurassic carbonates crop out extensively, with pervasive karstification and brecciation inferred to reflect a prolonged phase of subaerial exposure and tectonic quiescence prior to the Mid-Jurassic (which is not karstified). The Algre Fault is also the northern limit of the observed salt-related structures. Mappella (1992), Terrinha (1998), and other authors interpreted the main feature in this area to be the Algre Thrust, an E–W regional south-directed thrust, extending from Portimão to Querença (Fig. 5). However, detailed fieldwork and observations of changes in stratigraphy and structural style across the Algre Fault indicate that this is actually

a complex zone with at least two features: an extensional Algre Fault and a reverse fault, the Algre Thrust.

The Algre Fault is interpreted to be a south-dipping extensional fault bounding a half-graben to the north (Fig. 12b). It is interpreted that the Algre Fault initiated its activity at Late Triassic times, defining the boundary between an area of greater subsidence to the north and an area of thicker evaporite deposition during the Hettangian to the south. When extension restarted in the Middle Jurassic, this fault continued to grow, with faulting and evacuation of Hettangian evaporites resulting in a rollover geometry of Jurassic and Cretaceous beds that thickened against the fault (Fig. 13a). At present, within the hanging-wall of the Algre Fault, the Upper Jurassic and Lower Cretaceous layers form an overturned anticline with northward vergence due to Cenozoic inversion (Figs. 3f, 12b).

The Espiche Fault (Figs. 5b, 9c) is a WSW–ENE structural feature that is also a northern limit for outcrops of Upper Jurassic and thick Lower Cretaceous sediments. It is interpreted as a southeastwards dipping normal fault, overprinted by a southeast vergent thrust, the Espiche Thrust

(Fig. 12c), in which the Lower Jurassic rocks thrust over the Lower Cretaceous sediments. The presence of pelites and evaporites along the fault and their relationships with the adjacent sediments suggest that a salt wall developed along the extensional fault that was subsequently reactivated and squeezed to form a thrust during the pre-Miocene basin inversion (Terrinha 1998). The Espiche Fault is the western continuation of the Algre Fault (Figs. 5b, 10), partly offset by the Portimão Fault. The presence of Middle Jurassic and limited Lower Cretaceous outcrops in the footwall (to the north) of the Espiche Fault indicates that this extensional boundary was not as prominent as the Algre Fault.

The Faro-Tavira fault is an ENE–WSW trending, south-dipping regional extensional fault, parallel to the coast (Figs. 5b, 9a). The Faro-Tavira Fault controls the geometry of the eastern coastline of Faro and marks the northern limit of lower Cretaceous and the uppermost Jurassic (Tithonian) outcrops in the easternmost portion of the basin. Inversion of this fault led to a greater amount of uplift and erosion of this part of the basin (as evident in the greater amount of basement uplift and the vitrinite reflectance data (Fernandes et al. 2013). There is only one documented salt structure north of the Faro-Tavira fault, the Faro diapir. This diapir is interpreted to have developed in the footwall of the Faro-Tavira fault by evacuation of salt in its hanging-wall depocenter (Fig. 11a).

The last of the major extensional faults in the onshore basin is the Carcavai Fault zone. It is an ENE–WSW trending structure extending from the basement outcrop NE of the Loulé diapir, and at least 150 km into the offshore, south of Portimão (Fig. 5b; Noiva 2009; Carvalho et al. 2012). During the Upper Jurassic this fault acted as an extensional fault down throwing to the SE, while in its northeast termination, it is a NW dipping extensional fault (Terrinha 1998; Fig. 12a). This fault is not a major paleogeographical boundary, and it is interpreted to have formed as a structure relaying throw between the Algre and the Faro-Tavira faults and acting as locus of growth for the Loulé diapir. During basin inversion, the fault was reactivated in contraction, and the Loulé diapir was squeezed (Terrinha et al. 1990 and Terrinha et al. 1994b; Davison et al. 2015).

In contrast to the dominant E–W trend of extensional faults in the central-eastern sub-basin, the general structural pattern of the western sub-basin is dominated by NNE–SSW to N–S trending normal faults (Figs. 2f, 6). Nonetheless, E–W to NE–SW normal faults, which are more common further east, are still present (such as the Espiche Fault). The presence of these two, almost perpendicular sets of faults indicates the interference of two different regional extensional systems. On the one hand, E–W-to-NE–SW faults are related to Tethyan rifting. N–S to NE–SW faults,

on the other hand, are associated with extension along the proto-Atlantic rift from Early to Late Jurassic, an orientation consistent with that observed further north along the western Portuguese margin (Alves et al. 2002; Montenat et al. 1998; Soto et al. 2012). Extension on these two differently oriented fault systems also seems to have shifted in time from the Tethyan domain system in the Early Jurassic to the Atlantic domain system in the Late Jurassic (Terrinha 1998).

Middle Jurassic to Early Cretaceous extension was responsible for the main phase of salt tectonism documented in the area (Lopes et al. 2006; Matias 2007; Terrinha et al. 2009; Matias et al. 2011). Other than the evidence for salt movement in the footwall of the Algre Fault, extrusive salt diapirs in the onshore also occur; the Espiche, Loulé, Albufeira, and Faro diapirs (Terrinha et al. 1990; Terrinha 1998), associated with the main E–W-striking extensional faults. Salt diapirism is not reported north of the Algre Fault due to the almost complete absence of evaporites in the Hettangian, which highlights the relevance of the Algre Fault as a relevant paleogeographical basin boundary since the Late Triassic. The diapirs and salt structures of the onshore Algarve basin have all been reactivated during tectonic inversion (Davison et al. 2015).

Oblique, basin compartmentalizing faults

The Algarve Basin is dissected by several regional-scale faults (Portimão, SMQF, Aljezur; Terrinha 1998), which are parallel to the Late Variscan thrusts documented in the Carboniferous basement in the South Portuguese Zone and the Iberian Pyrite Belt (Arthaud and Matte 1977; Manuppella 1992; Terrinha 1998) and acted mainly as transfer faults compartmentalizing the Algarve Basin during Mesozoic extension. During Cenozoic inversion, many of these faults were reactivated as strike-slip features (Fig. 5b; Barreto et al. 2015).

The Portimão Fault strikes roughly N–S (Fig. 5b). This fault is interpreted to have acted as transfer fault during the Mesozoic. As mentioned above, the Portimão Fault separates the Algarve Basin into two sub-basins, the western and the central-eastern sub-basins, each of which has extensional faults with different trends. The two sub-basins are also characterized by having different depositional environments and thickness of sediments throughout the Jurassic and the Lower Cretaceous (Manuppella et al. 1988; Correia 1989 and Terrinha 1998). During the Early to Middle Jurassic, both sub-basins are dominated by hemipelagic sedimentation. The main difference between both basins during this time is a greater sediment thickness in the central-eastern sub-basin which is in excess of 1000 m in contrast with less than 500 m in the western sub-basin. The central-eastern sub-basin also records intervals of more

confined sedimentation and even an event of uplift and sub-aerial erosion, represented by a Callovian erosion unconformity and depositional hiatus that lasted until the Late and Middle Oxfordian in the Algarve and Lusitanian basins (Terrinha et al. 2002).

During the Late Jurassic, the differentiation on sedimentation between the two sub-basins increased, with thicknesses varying from 200 m in the west to more than 1600 m in the east. Despite the larger amount of subsidence, the eastern sub-basin developed internal compartments and important lateral facies differentiation, especially in the Late Oxfordian to Early Kimmeridgian. From the upper Kimmeridgian and through the Lower Cretaceous, the sedimentary environment becomes uniform throughout the sub-basin with the generalized development of internal platform facies. In contrast with the western sub-basin, where the Lower Cretaceous presents a marine-like facies and a thickness up to 500 m, it presents continental and littoral facies, reaching a thickness of roughly 1500 m (Terrinha 1998).

Present-day activity is also observed on the Aljezur Fault (Fig. 5b), a N–S trending left-lateral strike-slip fault in the western sub-basin that also controls the position of a submarine canyon across the continental shelf and slope. The Aljezur Fault extends around 60 km northwards into the Variscan basement where it controls the formation of Miocene grabens (Terrinha et al. 2009). However, there is no evidence that this fault was active during Mesozoic extension.

The SMQF is the third of the major compartmentalizing faults of the Algarve Basin (Fig. 5b). This fault extends from the non-rifted Paleozoic basement into and across the Algarve rift and post-rift Basin. Inspection of the geological maps and field work shows that the SMQF was active since Triassic through Quaternary times, i.e., during extensional and compressional tectonics. Palain (1976) showed how this fault affected the distribution of the clastic Triassic–Hettangian facies and thickness. It has also been reported that the onshore occurrence of salt diapirs is common on the hanging-wall of the SMQF (e.g. Terrinha et al. 1999). Various works (e.g., Manuppella 1988 and Manuppella 1992) showed that the thickness of the Jurassic and Cretaceous hanging-wall (i.e., northeast of the fault) are considerably thicker than the foot-wall sequences.

This argues in favor of the role of a transfer fault for the SMQF during rifting (Fig. 6), creating a hanging-wall block with higher subsidence and sub-basin development, important salt basins, and thicker sedimentary sequences.

While in the non-rifted basement and Triassic clastics the SMQF is mapped as a discrete fault, in the Jurassic carbonate sequences of the hanging-wall, the SMQF forms a diffuse deformation corridor that materializes as a series of dextral strike-slip transpressive duplexes, some of them

deeply rooted in the pelite–evaporite complex, as shown by sheared gypsum mylonites squeezed out along faults parallel to the SMQF. At the Triassic–basement contact the discrete dextral offset is visible (Fig. 5a) as well as the up-thrown displacement of the northeastern hanging-wall block.

Finally, east of the SMQF, the Querença margin would have acted as an extensional transfer zone during the Mesozoic (Fig. 5b) along with the Carcavai fault zone, connecting the Algibre and the Faro–Tavira faults. The Querença zone was later reactivated as a lateral ramp structure in the inversion system, relaying the basin margin basement monocline (Fig. 7).

Late cretaceous to Quaternary inversion and shortening

The main effect of shortening and basin inversion in the onshore Algarve Basin is the broad southward tilt of the basin. This regional tilt is related to basin-scale deformation and uplift of the basement during the Cenozoic (Fernández-Lozano 2012), most probably associated with the presence of a south-directed basin-scale thrust, rooting into the basement. Tilting and uplift related to this structure are responsible for the regional southward dip of Mesozoic beds and the complete absence of Neogene and Quaternary deposits over most of the onshore Algarve Basin. There is also evidence for at least one other contraction-related monocline in the basin, which causes a step in the offshore bathymetry in the west (along offshore segment of the Carcavai fault) and controls the location of the present-day coastline further to the east (Fig. 7). This basement-involved monocline was probably located along a basement step of extensional origin which focussed the folding during the Alpine contraction.

It is interpreted that at this basin-scale, and along the northern margin of the basin where Hettangian evaporites are almost absent, Cenozoic inversion reactivated pre-existing discontinuities in the Carboniferous basement. As a result, the regional thrusts formed with ENE–WSW trend and dipping to the north. This trend is related to the reactivated fabric, which is probably the pervasive Variscan-age foliation of the meta-sedimentary basement, which is known regionally to dip toward the north and crops out along the northern margin of the basin (Vegas 1980). The foliation is documented to be reactivated in multiple south-directed thrusts within the outcrop of the South Portuguese Zone and the northern margin of the Algarve Basin (Soriano Clemente 1996; Terrinha 1998). In some cases, this caused the partial reactivation of pre-existing Triassic faults and the formation of shortcuts (Fig. 10d), and in others it led to the formation of monoclines with no evident rupture (Fig. 7), but completely deforming the overlying Mesozoic cover and its associated faults.

At a more local scale, a number of thrusts and contractional structures have been unambiguously documented in the area. These include the Algibre Thrust (Fig. 12b), short-cuts that affect the Triassic half-grabens along the northern margin of the basin (Figs. 7, 10), and multiple buttressing structures along the Algibre Fault (Fig. 12b).

Perhaps the best defined contractional structure is the inversion of the Algibre fault and its associated thrust. During Cenozoic inversion, the hanging-wall of the Algibre Fault was detached above the Hettangian evaporites and folded by buttressing against the Algibre Fault footwall, producing E–W trending tight detachment folds (Fig. 11) and tightening and overturning the Algibre rollover (Figs. 12b, 13b). The inversion structure is further complicated by the presence, locally, of a south-directed thrust that places Lower and Mid-Jurassic rocks on top of the Early Cretaceous (Figs. 11a, 12b), rooting into the salt of the footwall.

The example of the Algibre Fault illustrates how the pattern of basin inversion was influenced by the presence of a thick Hettangian salt unit. This unit only presents thicknesses in excess of a few tens of meters to the south of the Espiche–Algibre–Faro–Tavira corridor. To the south of this corridor, deformation during shortening was dominated by decoupling between basement deformation and deformation of the Mesozoic cover. This decoupling is evident for both the abundant buttressing structures in the hanging-wall of the Algibre Fault (Figs. 11, 13b), which detach within the Hettangian evaporites, and in the reactivation of diapirs throughout the basin. On the other hand, north of the Espiche–Algibre–Faro–Tavira corridor, shortening structures propagate from the basement through the Mesozoic units above without any decoupling (Figs. 11, 12). In summary, evaporites played a key role in defining two different structural styles during inversion of the basin: one dominated by thick-skinned thrusts where salt is very thin and one dominated by decoupling of the Mesozoic cover above the basement where salt deposits were originally thicker.

Conclusions

1. The Algarve Basin is interpreted to have formed mainly as the consequence of N–S-to-NW–SE-directed extension (in present-day orientation) that is consistent with extension along the westernmost end of the Tethys. The related E–W to ENE–WSW fault trend dominates the central-eastern sub-basin.
2. The influence of Atlantic domain extension is observed in the western sub-basin of the Algarve Basin. In this sub-basin, the dominant trend of extensional faults is NE–SW to N–S.

3. The Algarve Basin is the result of the interaction between two major phases of Mesozoic extension (Triassic–Early Sinemurian and Pliensbachian–Early Cretaceous) and one phase of Alpine compression (mainly Cenozoic). Minor extension prevailed through the earliest extensional phase, which is characterized by north-dipping faults, whereas faults with greater throw generated during the second extensional phase are predominantly southward dipping. Extensional structures were inverted during the Cenozoic as south to south-east-directed structures throughout the basin accompanied by buttressing on the major extensional faults.
4. Extension played a key role in defining the location of evaporite deposition, which was greater to the south of the Algibre–Espiche and Faro–Tavira faults. In turn, evaporites played a key role in differentiating two structural styles during basin inversion from north to south. The northern margin of the basin (evaporite poor) is dominated by thick-skinned deformation in both extension and inversion. Southward, the basin records thin-skinned deformation above the evaporites in both extension and inversion, decoupled above the deeper basement-rooted structures.
5. This basin is a great example of reactivation of structures: Both extensional faults and basin compartmentalizing faults formed along previously existing Variscan structures. These structures were in turn reactivated during inversion of the basin, which also caused the reactivation of Variscan-age fabrics in contraction.

Acknowledgments This study was funded by Repsol Exploración (Madrid) and partially financially supported by the SALTECRES project (CGL2014-54118-C2-1-R). Adrià Ramos thanks Repsol Exploración for his PhD grant. The authors thank Ian Davison and an anonymous reviewer for thorough and helpful suggestions and comments. We also acknowledge Midland Valley for the academic software license used for cross-sectional construction.

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