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# FROM FIELD DATA TO LITHOSPHERIC-SCALE MODELS GOING THROUGH ANALOGUE EXPERIMENTS: THE GIBRALTAR ARC SYSTEM REVISITED IN THE LIGHT OF THE EXTERNAL ZONES STRUCTURAL EVOLUTION

*De los datos de campo a los modelos litosféricos pasando por experimentos analógicos: el Sistema del Arco de Gibraltar revisitado a luz de la evolución estructural de las zonas externas*

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**Abstract:** *We present the most relevant results of our research group concerning the structural and kinematic evolution of the Gibraltar Arc System external zones. Field data permitted us to evidence that the main shortening deformation took place during the Early and Middle Miocene. This main shortening is followed by a Late Miocene to Holocene tectonic event which tightened the Western Gibraltar Arc (NNW-SSE directed compression). In the westernmost part of the arc, strain partitioning took place during both events of deformation as shortening with radial transport direction is coetaneous with arc-parallel extension accommodated by arc-perpendicular normal faults and arc-oblique strike-slip faults. The Late Miocene to Holocene arc tightening is associated with vertical axis rotations of blocks whose dimensions reach a few hundreds of kilometers, clockwise in the Betics and counterclockwise in the Rif. These data permit us to infer that the deformation mechanism of the external zones situated in the Western Gibraltar Arc is that of a progressive arc that we were able to simulate in analogue model laboratory. They also allow us to determine that the most probable lithospheric-scale model for the Gibraltar Arc System tectonic evolution is that of a retreating subduction slab, with progressive increasing of the arc curvature and coeval lengthening and extension of the upper plate.*

**Keywords:** *Gibraltar Arc System, strain partitioning, progressive arc, analogue modelling, retreating subduction slab.*

**Resumen:** *Se presentan los resultados más relevantes de nuestro grupo de investigación en las últimas décadas referentes a las zonas externas del Sistema orogénico del Arco de Gibraltar. Los datos de campo nos permiten mostrar que el evento de acortamiento principal -con el consiguiente despegue de las secuencias sedimentarias de sus zócalos respectivos- tuvo lugar durante el Mioceno Inferior y Medio. Fue seguido por un evento tectónico que apretó el arco desde el Mioceno Superior hasta el Holoceno (compresión de dirección NNE-SSW). En la parte más occidental del arco, ambos eventos fueron caracterizados por una partición de la deformación en la que la formación de pliegues y cabalgamientos con un transporte aproximadamente radial alrededor del arco fue coetánea a una extensión paralela al arco, a su vez acomodada por fallas normales perpendiculares al arco y sistemas conjugados de fallas en deslizamiento. El apretamiento del Mioceno Superior al Holoceno está asociado a rotaciones de eje vertical de bloques, horarias en las Béticas y anti-horarias en el Rif, bloques que tienen dimensiones del orden de unos pocos centenares de kilómetros. El conjunto de datos nos permite inferir que el mecanismo de deformación de las zonas externas situadas en la parte occidental del Sistema del Arco de Gibraltar es la de un arco progresivo que hemos sido capaces de reproducir en nuestro laboratorio de modelización analógica, con un diseño innovador de la mesa de experimentación. Nos permite también afirmar que el modelo más probable a escala* *litosférica del Sistema orogénico del Arco de Gibraltar es el de una zona de subducción con retroceso de la losa subducida, asociado tanto a un aumento de la curvatura del arco como al alargamiento y extensión de la placa superior.*

***Palabras clave:*** *Sistema del Arco de Gibraltar, partición de la deformación, arco progresivo, modelos analógicos, retroceso de la losa subducida.*

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## Introduction

Since the pioneer work of Argand (1924), who documented the sinuous character of the whole Alpine-Himalayan system from the Mediterranean to SE Asia, the Gibraltar Arc orogenic System (GAS), which represents its westernmost segment and one of the most protruded arcs on Earth (Macedo and Marshak, 1999; Faccenna *et al.*, 2004; Platt *et al.*, 2013; Fig. 1), has puzzled the geologists. This is due not only to its overall arcuate geometry -which posed several fundamental questions on its development (see review on arc formation by Marshak, 2004)-, but also to the seemingly contradictory observations of a young extensional marine basin surrounded by an arcuate fold-and-thrust belt (Horvath and Berkhemer, 1982). In the GAS, the Alboran Basin is enclosed by the Betic mountain belt north of the Gibraltar Strait and the Rif to the south. The accretionary prism present in the Cádiz Gulf completes the GAS to the west (Fig. 1).

The geodynamic evolution of the GAS, straddling the modern Africa–Eurasia plate boundary, is intimately linked with the very slow and broadly N-S to NW-SE Neogene convergence of the African and European tectonic plates (*e.g.*, Dewey *et al.*, 1989; Mazzoli and Helman, 1994). Andrieux *et al.* (1971), who evoked the westward escape of a “sub-plate” during this convergence, were the first authors to include the plate tectonic concept in a geological model of the GAS. Since the publication of this paper, and particularly from the end of the eighties of the last century, the tectonic evolution of the GAS has been a highly topical subject and many geodynamic models have been proposed in order to explain its protrusion and the coeval evolution of the Alboran Basin. Three of them can be considered as reference models: a) extensional collapse of an earlier collisional orogen caused by convective removal of a thickened lithospheric root (Platt and Vissers, 1989); b) delamination of an over-thickened continental lithosphere (García-Dueñas *et al.*, 1992; Seber *et al.*, 1996; Calvert *et al.*, 2000); and c) back-arc extension in the overriding plate of a retreating subduction zone (Royden, 1993; Lonergan and White, 1997), associated with the fragmentation of the subducting plate in small, narrow slabs which retreat outward, producing large-scale rotation of the flanks, shaping the arc (Faccenna *et al.*, 2004). Note that the first of these competing reference models was published thirty years ago, the year of the creation of the Tectonic Commission of the Geological Society of Spain.

At the time of their formulation, these lithospheric-scale models were mainly based on geophysical data and/or on the recently -at that time- revealed structure and kinematics of the low-angle normal faults associated with crustal thinning that affected the GAS internal zones (Aldaya *et al.*, 1984; García-Dueñas *et al.*, 1986, 1992; García-Dueñas and Martínez-Martínez, 1988; Galindo-Zaldívar *et al.*, 1989; Balanyá and García-Dueñas, 1991; García-Dueñas and Balanyá, 1991; Jabaloy *et al.*, 1992). Nevertheless, these competing models have very different implications in terms of strain partitioning (type, timing and distribution of the resulting structures, kinematic indicators, structural pattern, etc.) within each of the domains involved in the GAS, in particular in the external zones. At that time, the latter were well known in terms of stratigraphy and sedimentology (see review by Vera *et al.*, 2004) but only few structural data were available at 1:50,000 geological maps (MAGNA series) and very few PhD Theses, most of them old (*e.g.*, García-Dueñas, 1967; Didon, 1969; Bourgois, 1978; Sanz de Galdeano, 1973; Blankenship, 1992). Accordingly, in order to acquire an integrated view of the tectonic evolution of the GAS, an analysis of the structures and kinematics of the GAS external zones was necessary, a task that our research group performed during the last fifteen years, essentially through detailed mapping and field work. Besides, in order to address the problem with a complementary methodology, we recently developed upper crustal-scale analogue models, which permitted us to look into the progressive deformation of the fold-and-thrusts belts that were reproduced in the laboratory and to compare these results with the natural cases that surround the Gibraltar Arc.

The main objective of this paper is to revisit the aforementioned lithospheric-scale, geodynamic models of extensional collapse, delamination or retreating subduction in the light of the data concerning the structural evolution of the GAS external zone. We will also try to couple the lithospheric processes with the available field data, an unbreakable assignment of the members of the Tectonic Commission. For this purpose, we first highlight the key results of our research group related to the GAS external zones, not only based on field geology but also on analogue modeling. Then, we frame these data within the three main evolution models proposed until now, by revising what a convective removal, delamination or retreating subduction model represents in terms of deformation, timing and kinematics in the upper crust. This will permit us to test and refine these lithospheric-scale models.

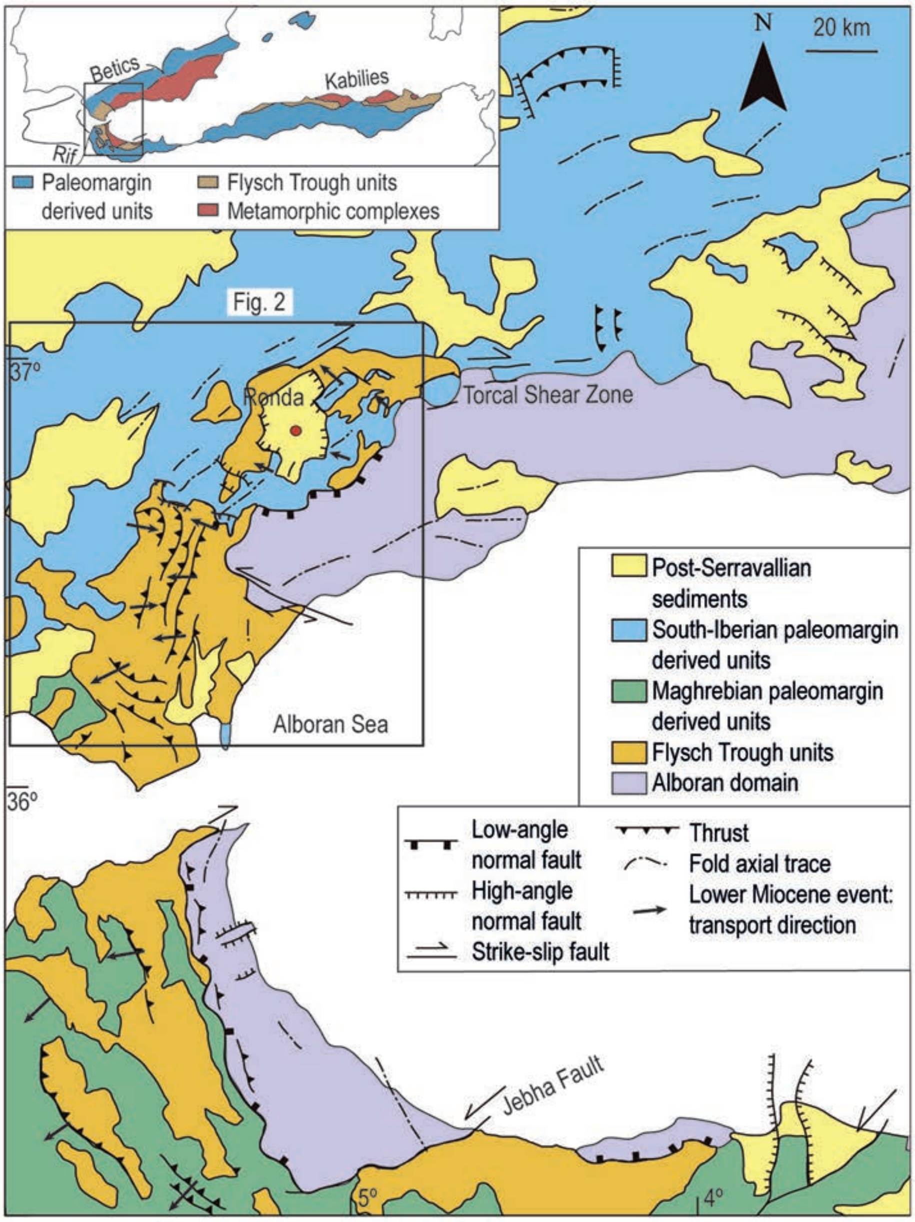


**Fig. 1.-** Main tectonic domains of the Betic-Rif orogen (localized in the inset). Inset: Tectonic map of the westernmost Mediterranean.

## Tectonic setting of the Gibraltar Arc System external wedge

The external wedge of the GAS is composed of distinctive tectonic units whose accretion occurred due to the westward migration of the Alborán Domain -*i.e.*, the hinterland of the GAS- and that took place during the Miocene. These external units belong to both the South Iberian paleomargin (in the Betics) and the Maghrebian paleomargin (in the Rif) domains as well as to the Flysch Trough Complex (Fig. 1).

The Alborán Domain is located in the inner part of the GAS and has been classically defined as a stack of three different tectonometamorphic terranes (from bottom to top, the Nevado-Filábride, Alpujárride and Maláguide complexes). They are mainly composed of Paleozoic rocks that experienced a polyphasic Paleogene to Miocene deformation and metamorphism, including a high pressure-low temperature (HP-LT) event (*e.g.*, De Jong, 1991; Tubía and Gil Ibarguchi, 1991; Azañón *et al.*, 1997). Nevertheless, recent works have interpreted the lowermost complex -the Nevado-Filábrides- is part of the Iberian Paleomargin domain, subducted beneath the Alborán crustal domain during the Neogene (Booth-Rea *et al.*, 2015). The Alborán Domain experienced vulcanism and pervasive back-arc extension during the Miocene, therefore coeval to the external wedge accretion, giving rise to the Alborán Basin at the concave side of the on-shore GAS (Comas *et al.*, 1999; García-Dueñas *et al.*, 1992).

The Flysch Trough Complex is tectonically overthrust upon the paleomargin derived units and emplaced beneath the Alborán Domain. It is mainly formed by Lower Cretaceous to Lower Miocene turbiditic sequences of siliciclastic rocks, interpreted to have been detached from a deep-seated basement, eventually oceanic, forming an accretionary prism in front of the Alborán Domain (Dercourt *et al.*, 1986; Durand-Delga *et al.*, 2000). They are better represented in the western GAS, where they exhibit a typical thin-skinned tectonic style essentially developed during Middle Miocene times (Luján *et al.*, 2003a, b, 2006).

The paleomargins derived units, the Subbetic-Prebetic and the external Rif north and south of the Gibraltar Strait, respectively, are located at the bottom of the external wedge and are made up of Mesozoic–Paleogene sedimentary rocks that roughly define a transgressive sequence and detached from their Hercynian basement (Chalouan and Michard, 2004; Vera *et al.*, 2004). Nevertheless, they show differences when the northern and southern branches of the GAS are compared. In the Betics, the detachment level is associated with Triassic rocks, which include mainly evaporites. Evaporite-rich formations show important lateral thickness variations, reaching maximum values (more than 1 km) in the western Betics. The Jurassic rocks are dominated by limestones and dolostones, whereas marls and marly limestones are significant in the Cretaceous. On the contrary, the basal detachment in the Rif is characterized by Triassic clayed formations and the Jurassic-Cretaceous section shows scarce limestones or dolostones, being instead dominated by lutites (Chalouan and Michard, 2004).

In plan-view, the GAS describes several salients and recesses, which contribute to draw second-order arcs (Fig. 1), according to the terminology of Macedo and Marshak (1999). Our research focuses on one of them, the Western Gibraltar Arc (WGA), located in the hinge zone of the GAS (Balanyá *et al.*, 2007) and defined by both the tectonic boundary of the Alborán Domain and the external wedge structural trend. The WGA presents specific lithological, structural and geophysical features that differ from those observed eastward (Balanyá *et al.*, 2007, 2012; Crespo-Blanc, 2007; Crespo-Blanc *et al.*, 2007). The salient-recess transition of the WGA is accomplished by E-W to ENE-WSE strike-slip dominated transpressive zones, dextral in the Betics (the Torcal shear zone; Barcos *et al.*, 2011; Balanyá *et al.*, 2012; Díaz-Azpiroz *et al.*, 2014; see also below) and sinistral in the Rif (the Jebha fault zone; Leblanc and Olivier, 1984; Platzman *et al.*, 1993; Chalouan *et al.*, 1997).

The shortening structures that define the external wedge of the WGA, mainly folds and thrusts, exhibit presently radial transport directions, diverging towards the foreland around 90º in the area of Figure 1 and up to 120º when the whole system is taken into consideration, according to the reviews of Balanyá *et al.* (2007) and Crespo-Blanc *et al.* (2016). From the Early Miocene to the Quaternary, orthogonal shortening of the external wedge occurred coupled with arc-parallel extension, the latter accommodated by both, arc-perpendicular normal faults and arc-oblique strike-slip faults. Although arc-parallel extension seems to have reached the Alborán Domain outer tectonic boundary, the Alborán Basin was mainly generated by arc-orthogonal, extension of the Alborán Domain (Comas *et al.*, 1999; Balanyá *et al.*, 2012).

Our structural and kinematic analysis focused on the strain partitioning affecting the western external Betics, which belong to the northern branch of the WGA.

## Structure and kinematics of the external wedge of the Western Gibraltar Arc

### *Early and Middle Miocene main shortening*

The main shortening deformation recorded in the western external Betics took place during the Early and Middle Miocene, when the Subbetic units and the Flysch Trough units stacked, pushed from behind by the metamorphic units of the hinterland, that is the Alborán Domain. At that time, they acquired their distinctive main structural pattern and deformational style (Figs. 2 and 3, respectively; Crespo-Blanc and Campos, 2001; Luján *et al.*, 2006; Balanyá *et al.*, 2007; Expósito *et al.*, 2012).

The Flysch Trough units are mainly deformed by imbricate thrust systems and emplaced on top of the paleomargin derived units (Fig. 3A; Luján *et al.*, 2006). This brittle structural style contrasts with the more ductile deformation exhibited by the immediately underlying paleomargin-derived Subbetic units. Indeed, the Cretaceous to Paleogene multilayer carbonate rock sequence of the Subbetic is deformed by asymmetric W to NW-vergent folds, detached from the underlying Jurassic dolostone and limestone formations (Fig. 3B; Expósito *et al.*, 2012). They are metric to decametric folds whose geometric and kinematic features change along transport directions, as a consequence of a decreasing shear deformation toward the foreland. These contrasting structural styles have been interpreted as the result of overthrust shearing produced by an overriding mass (the Flysch Trough units) in a multi-décollement setting (Fig. 3C; Expósito *et al.*, 2012). Simultaneous arc parallel extension was accommodated by highly distributed structures, decimeter to centimeter scale. These are mainly calcite veins normal to the fold axis, and brittle

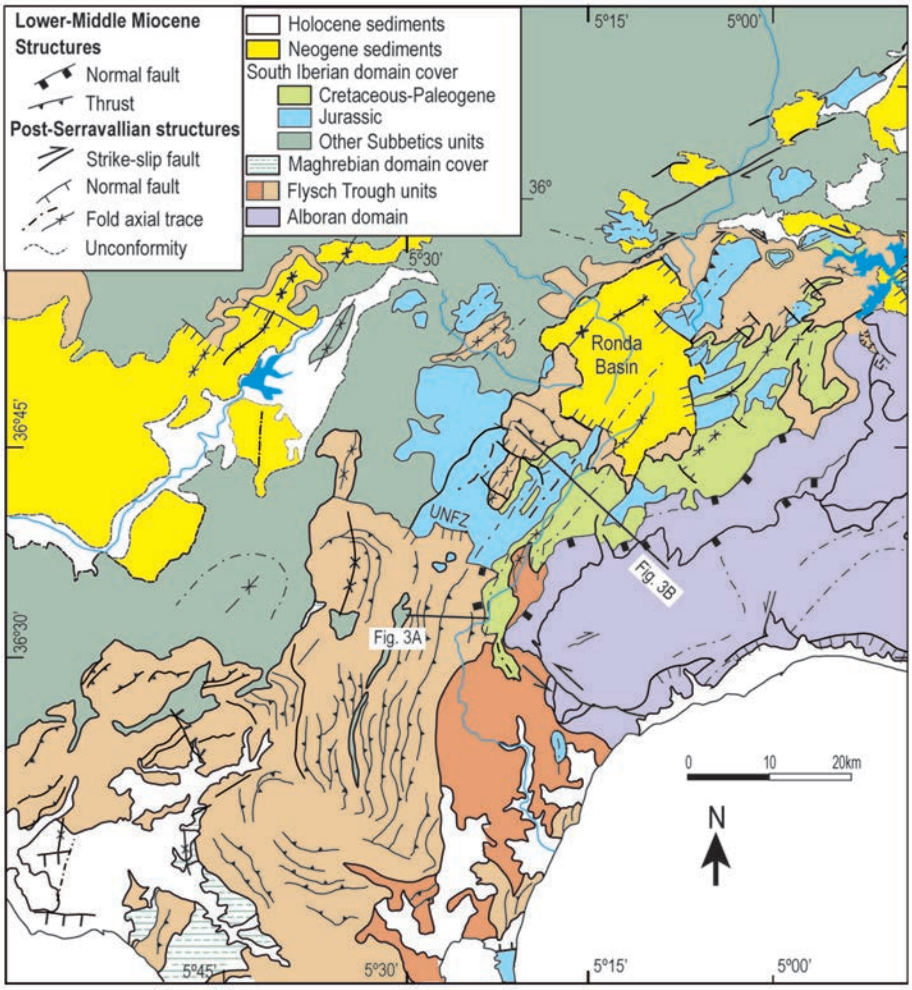


**Fig. 2.-** Structural and kinematic map of the Western Gibraltar Arc (localized in Fig.1). UNFZ: Ubrique Normal Fault Zone.

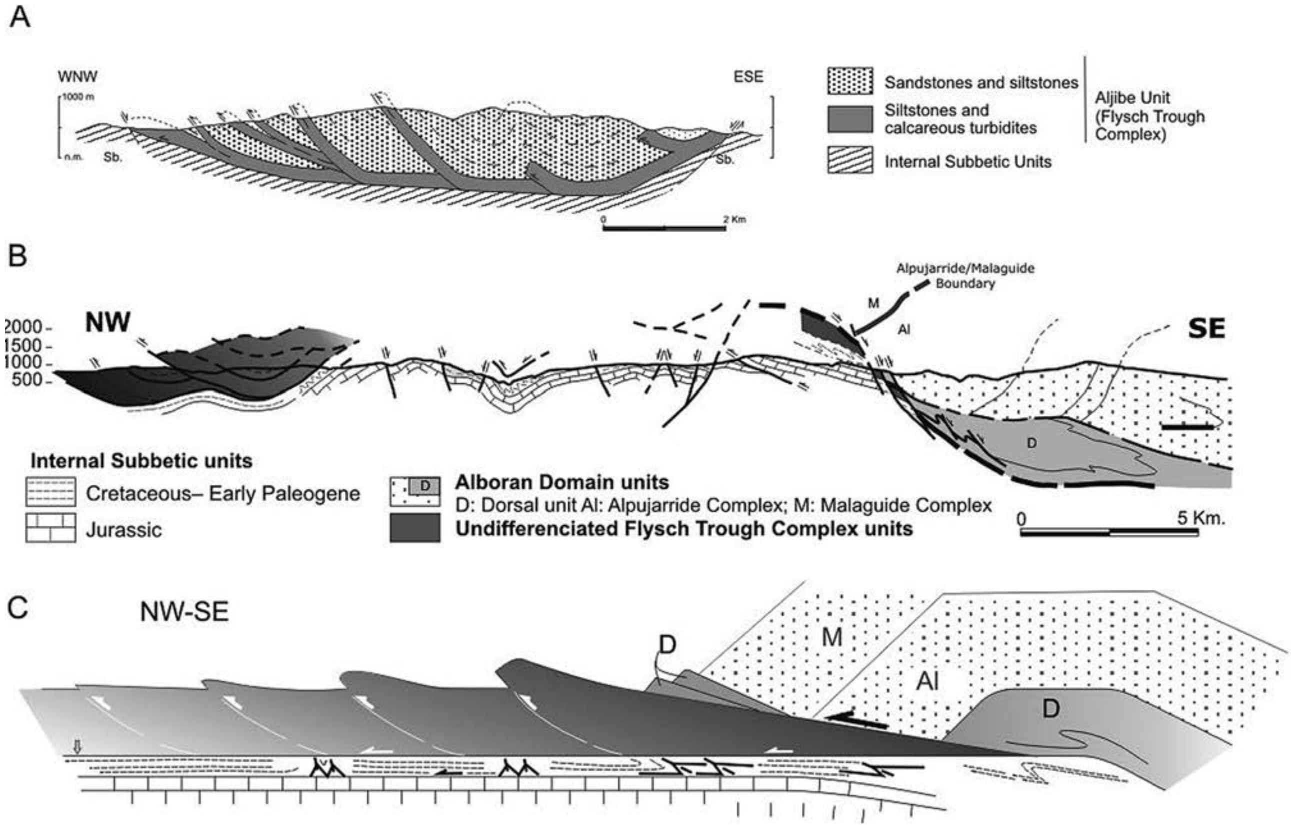


**Fig. 3.-** A,B. Geological cross sections in the external zone of the western Gibraltar Arc (according to Luján *et al.*, 2006 and Expósito *et al.*, 2012, respectively; localization in Fig. 2). In cross-section B, observe the structure interferences. C. Simplified model showing the structural decoupling developed during the Early–Middle Miocene tectonic evolution of the Western Gibraltar Arc.

to brittle-ductile shear zones that appear on both fold limbs and frequently with an en-échelon distribution. The intersection with the fold axis of these shear zones forms an angle of 45 to 55º. These distributed structures produced arc parallel stretching coetaneous with the main shortening, and was estimated by Balanyá *et al.* (2007) between 0.15 and 0.25 (beta value).

*Late Miocene to Present compressive event: strain partitioning and relief segmentation*

A NNW-SSE-directed compressive event took place after the Early to Middle Miocene main shortening. It is a second deformation event that generated a tectonic re-organization of the whole Western Gibraltar Arc. In terms of kinematics and strain partitioning modes that developed during this second event, two main structural domains can be distinguished within the westernmost external Betics (Fig. 2). The first one is the frontal fold and thrust belt located in the arc hinge, which results from fan-like, arc-suborthogonal convergence. It is partitioned into outward verging shortening structures and along-strike extensional structures that operated at least until the Holocene and most of them are probably still active (Balanyá *et al.*, 2012; Jiménez-Bonilla *et al.*, 2015, 2017). The second is the Torcal shear zone, a strongly partitioned transpressive zone which acts as a salient-recces transition, active from Late Miocene to Holocene (Fig. 1).

In the Betic fold-and-thrust belt located in the arc hinge (Fig. 2), in both the Subbetic and Flysch Trough units, the post-Serravalian contractional deformation follows the same strain partitioning mode that operated during the main deformation event. SW-NE-directed kilometric-scale upright folds and associated reverse faults are superposed to the Lower to Middle Miocene structures (see for example the refolded thrusts of Fig. 3B; Crespo-Blanc and Campos, 2001; Expósito *et al.*, 2012). This deformation event shape the current conformable relief exhibited by the westernmost Betics, that is, ranges and valleys which correspond respectively to antiforms and synforms of the second event, occupied respectively by Jurassic limestones and dolostones of the Subbetic units and Flysch Trough units.

Post-Serravalian arc-parallel extension in the arc hinge was localized in map-scale, discrete, arc-orthogonal normal fault zones and, to a lesser extent, in arc-oblique strike-slip fault zones (Balanyá *et al.*, 2007; Jiménez-Bonilla *et al.*, 2015, 2017), which differ from the distributed extension related to the main deformation event. The normal faults are mainly steeply dipping structures that accommodate significant vertical throws producing a remarkable along-strike relief segmentation of the SW-NE ranges (enhanced by the lack of fold axis cylindricity). This segmentation is particularly conspicuous in two sectors of the frontal Betics: a) the high-angle fault that bounds the Flysch Trough units and the Subbetic units in the westernmost external Betics, with vertical throws up to 1170 m (the Ubrique Normal Fault Zone of Jiménez-Bonilla *et al.*, 2017), which cuts a Lower to Middle Miocene, middle-angle normal fault localized along the same boundary (the Colmenar fault of Luján *et al.*, 2000), and marks a sharp SW-ward topographic drop of the Betics ranges (up to 400 m height); and b) the intramontane Ronda Basin, limited by conjugated, basin-ward dipping faults, that interrupt the arcuate topographic relief (Jiménez-Bonilla *et al.*, 2015, 2017). As a whole, these arc-parallel extensional structures achieved low stretching values (0.04–0.08: Jiménez-Bonilla *et al.*, 2015), although the overall extension in the frontal external Betics is probably greater. Indeed, it is difficult to estimate the stretching associated with the Ronda Basin opening but it should be higher as the basement structures seem to omit the Jurassic and Cretaceous units under the basin infill (Ruiz-Constán *et al.*, 2010).

The Torcal shear zone (TSZ) is defined by a conspicuous, 70 km long, up to 8 km wide dextral transpressive deformation zone (Figs. 2 and 4; Barcos *et al.*, 2011; Balanyá *et al.*, 2012; Díaz-Azpiroz *et al.*, 2014). It marks a salient-recess transition of the outer Alboran Domain boundary characterized by a rough E-W lineament of several disconnected, en-échelon arranged topographic highs, formed during the sub-vertical uplift generated by the highly oblique convergence. Transpression is dated essentially as Late Miocene to Quaternary according to overprinting criteria, age of deformed rock units, geomorphic indices and earthquakes data (Balanyá *et al.*, 2012; Barcos *et al.*, 2012; Díaz-Azpiroz *et al.*, 2014). Detailed structural mapping, kinematic analysis of the main structures and comparison of the TSZ geometry with analytical and analogue models suggest that transpressional deformation at the central sector of the TSZ is compatible with an obliquity angle ranging from 15 to 35º (angle between the simple shearing direction and the strike of the shear zone; Barcos *et al.*, 2011, 2012, 2015, 2016; Díaz-Azpiroz *et al.*, 2014). Multi-scale deformation partitioning within this transpressive zone produced unevenly distributed sectors with specific structural patterns that accommodated the dextral movement and link both branches of the Subbetic fold-and-thrust belt, with a N-S structural pattern in the central Betics immediately north of the TSZ, and NE-SW-directed in the western Betics immediately south of the TSZ (*e.g.*, domains dominated by triclinic transpression or monoclinic pure shear transpression, see full description in *op. cit.*).

### *Kinematic evolution of the Western Gibraltar Arc external wedge: main deformation events*

The kinematic features described above allow us to state two distinct deformational events, which contribute to the structural evolution of the WGA external wedge and shape the arc. The first one is represented by the structures responsible for the stacking and main deformation of the units that form this wedge mostly developed during Early and Middle Miocene (Balanyá *et al.*, 2007) and must have grown already as a progressive arc, as suggested by the development of distributed arc-parallel stretching coeval to wedge shortening. The second one occurred essentially from Late Miocene to Holocene. The structures that operated during this time interval, coherent with geomorphic and seismic data, produced tightening of the plan view curvature of the WGA. It increased its protrusion grade, leading to its current shape (Balanyá *et al.*, 2012; Barcos *et al.*, 2015; Crespo-Blanc *et al.*, 2016; Jiménez-Bonilla *et al.*, 2015, 2017). This significant post-Serravalian protrusion towards the west of the WGA is essentially accomplished by lateral displacement at the two salient-recess transition zones, the afore-mentioned dextral Torcal shear zone and the sinistral Jebha fault in Morocco (Fig. 1; Chalouan *et al.*, 1997).

Crespo-Blanc *et al.* (2016) established the time relationships between available paleomagnetic data and the two tectonic events that contribute to the external wedge structuration. A detailed study of these relationships in the whole Gibraltar Arc from 2ºW to the west, either in the paleomargin-derived units or in the foredeep basins on top, permitted to show that the second Late Miocene to Holocene event is concomitant with vertical axis rotations of blocks, clockwise in the Betics and counterclockwise in the Rif. The dimension of these blocks is around a few hundreds of kilometers. During the last 9 Ma, differential rotation between these two blocks reached up to 65º, and it is still active (Crespo-Blanc *et al.*, 2016). Based on the restoration of the late Miocene to Holocene vertical-axis rotations, a 9 Ma paleotectonic reconstruction was proposed by these authors. It shows how the post-9 Ma rotations modified drastically the arc geometry, with a progressive lengthening of the arc and coetaneous protrusion towards the west.

## Contribution of analogue modelling

Scaled analogue models provide insights into the progressive development of fold-and-thrust belts, extensional or strike-slip fault systems (see reviews of Liu *et al.*, 1992; McClay, 1990; and Dooley and Schreurs, 2012, respectively). Despite their limitations, these experimental and very visual templates provide a unified picture of the evolution of fault systems with considerable spatial and temporal detail.

Our research group gets interest in such methodology since 2002, when collaboration with the Analogue Modelling Laboratory located in Roma Tre University led us to model the influence of 3D variations in the rheological properties of décollement rocks on the structural architecture of a growing thrust wedge. At that time, the investigated natural case was the Flysch Trough units (Luján *et al.*, 2003a, b). As the great potential of physical models became clear for us, we created an Analogue Modelling Laboratory in Granada University. Since then, the progressive deformation and strain partitioning of different Subbetic fold-and-thrust systems have been scaled and modeled in that laboratory (*e.g.*, Crespo-Blanc and Pérez-Ramos, 2002; Crespo-Blanc and Navarro, 2004; Crespo-Blanc and Gálvez, 2008; Crespo-Blanc, 2008; Crespo-Blanc and Suades, 2011; Crespo-Blanc *et al.*, 2012).

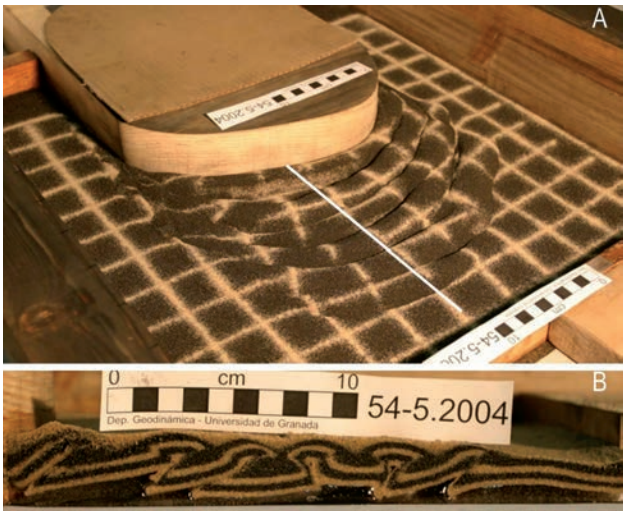


**Fig. 4.-** A. Arcuate fold-and-thrust belts formed above a viscous detachment in front of a rigid backstop (Crespo-Blanc and González-Sánchez, 2005). B. Cross-section of the same model (line on figure A). Graphic scales: 10 cm.

In particular, we were interested in modelling arcuate fold-and-thrust belts such as the Gibraltar Arc external zone. Crespo-Blanc and González-Sánchez (2005) simulated the progressive development of folds and thrusts when a rigid backstop with different geometries, moving along a straight translation path, indented an initial sandpack situated above either a brittle or viscous layer (Fig. 4). The results, in term of cross-section, are very similar to the Subbetic fold-and-thrust belt. However, models and natural case showed significant geometric and kinematic differences in map view. Firstly, deformation affected only the frontal part of the indenter whereas the lateral deformation zone around the indenter was very narrow, whereas the Subbetic and Flysch units are deformed around the whole arc. Furthermore, the model wedge showed a relatively simple structural association in contrast with the complex strain partitioning exhibited by the Gibraltar Arc external zone, which includes an outward radial thrusting coeval with normal and strike-slip fault systems (particularly localized in its lateral zones) that cause arc-parallel stretching, and individualized blocks that rotated significantly clockwise or counterclockwise in the right or left arc limbs, respectively (see previous paragraphs). Accordingly, these discrepancies between the natural case of the Gibraltar Arc external wedge and the models required a different experimental setting.

Our working hypothesis for the Gibraltar Arc external wedge was that of a progressive arc, that is the external fold-and-thrusts developed in front of an indenter (the Alboran Domain internal zones) that moved towards the foreland (the Subbetic and Flysch units) with an increasing protrusion grade and a curvature ratio which diminished with time (see review in Crespo-Blanc *et al.*, 2016). Therefore, we designed an experimental setting with a plastic strip pushed-from-behind in its apex by a screw attached to a motor drive (Figs. 5 and 6). We obliged this strip to go through a rigid, fixed gate (the wood battens left and right of the plastic strip in the upper part of the photographs of Figs. 5 and 6), which represents the chord line of our experiment arcs (*sensu* Macedo and Marshack, 1999). As the plastic strip was deformable, its curvature ratio progressively diminished and its protrusion grade increased. At the same time, it was sufficiently rigid to push and deform the initial parallelepiped. A full description of the experimental apparatus and the analogue material properties for a scaling factor of 2 x $10^5$ can be found in Jiménez-Bonilla *et al.* (2016, submitted).

With this innovative design, we simulate the progressive arching of a thin-skinned, external fold-and-thrust belt, such as that which surrounds the Gibraltar Arc. Indeed, we reproduced at small scale: 1) the rheological column with a silicone layer (the Triassic evaporites-rich formation) overlaid by sand (the post-Triassic brittle sedimentary sequence); 2) the progressive protrusion of the backstop (the internal zones) into the initial parallelepiped (the external zones); 3) the lengthening of the backstop boundary (the internal-external zone boundary); and 4) the limb rotation (the progressive arching), associated with the increase of surface behind the backstop (the back-arc area). In this paper we summarize the results of the most representative model of the series made in our laboratory (Model 4-1 of Jiménez-Bonilla *et al.*, submitted). The initial parallelepiped was very large in order to reduce border effects (100 cm x 65 cm), and the basal layer of silicone and the overlying sand thicknesses were 0.5 cm and 1.5 cm, respectively.

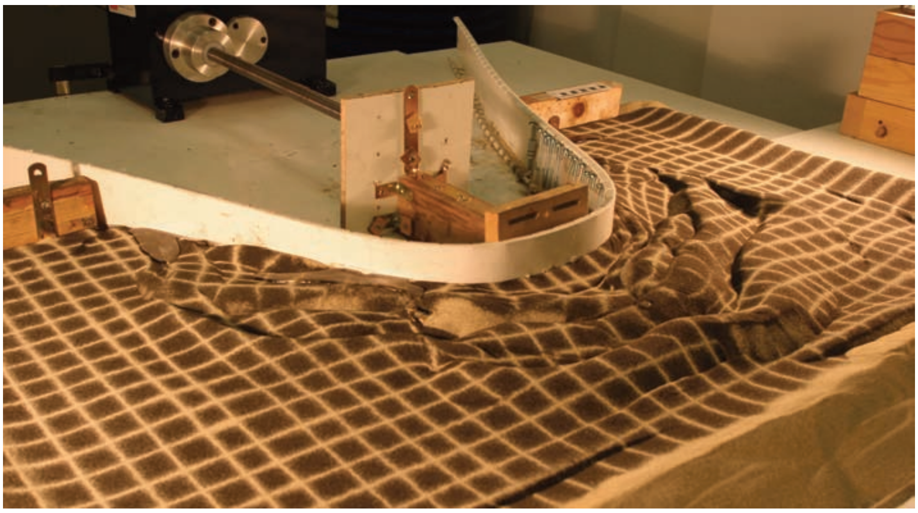

**Fig. 5.-** Oblique photograph of the final deformation of a sandpack floored by silicone in front of a backstop that indent it with an increasing protrusion grade and diminishing curvature ratio. Observe the configuration of the experimental apparatus and the motor drive which push-from-behind the apex of the plastic strip, which permits to simulate a progressive arc (Experiment of Jiménez-Bonilla et al, submitted). Side of the grid sieved on the experiment: 3cm.

Photographs of the experiment at different stages are presented in Figure 6. At the onset of deformation, the radial outward shortening in the parallelepiped was accommodated by thrusts, normally with foreland vergence, interconnected by transfer zones; these structures bound a block situated to the left of the symmetry axis of the experiment (Fig. 6A). This block began to rotate clockwise due to the differential displacement of the backstop which pushed-from-behind the sand-silicone initial parallelepiped. This block is relatively homogeneous as it can be deduced from the grid geometry on top of it. At this deformation stage, a strike-slip fault appeared, running from the central part of the fold-and-thrust belt to the frontal boundary of the parallelepiped (Fig. 6A). As shortening increased, the deformation front propagated toward the foreland with nucleation of curved thrusts and backthrusts (Fig. 6B). Differential displacements along the thrusts led to the vertical axis rotations of the earlier structures, eventually producing their regime change. In particular, this is the case for the vertical transfer zones situated in the flanks of the arc, and their regime can vary from pure strike-slip to either transpressive or transtensive. At the stage of Figure 6B, structures of different types induced the individualization of various blocks that later on suffered clockwise or counterclockwise vertical-axis rotations (observe the grid geometry variation from Fig. 6A to Fig. 6C), depending on their location in the left or right flank of the backstop, respectively. At the completion of the experiment, the grid marker rotations diminished progressively from *ca.* 60–70º in the limbs of the backstop down to 0º in its apex. These vertical-axis rotations were accompanied by lengthening of the wedge front. This along-strike lengthening resulted in arc-parallel extension, mainly accommodated by conjugated strike-slip faults and/or transtensive transfer zones (Fig. 7A). Millimetrical spaced normal faults, mostly oriented subperpendicular to the backstop boundary also contributed to arc-lengthening (Fig. 7B). Squeezed buoyant silicone pierced the sand layer, preferentially along transtensive structures.

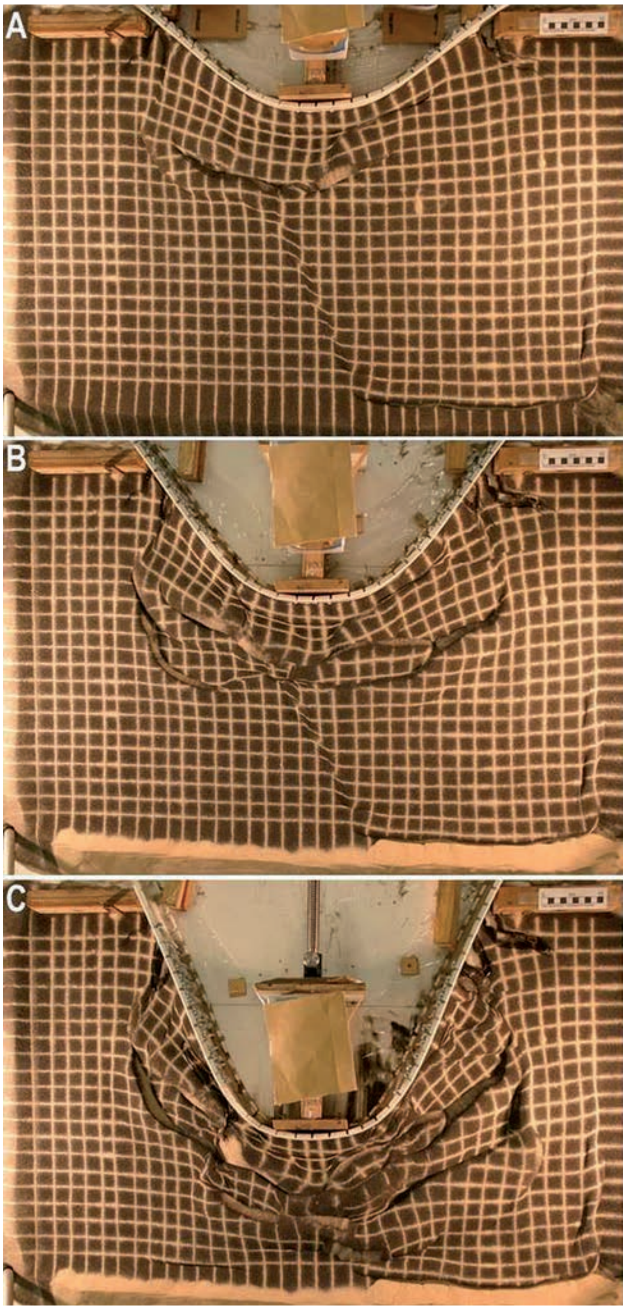


**Fig. 6.-** A–C. Representative photographs of the progressive deformation of the same experiment as in Figure 5. Observe the development of different structures evidenced by the displacement of the grid and the topography of the model, which highlight thrusts, backthrust and folds (spotlights situated in the lower right and left corners of the experiments, generating tangential light). Side of the grid sieved on the experiment: 3cm.

The final stage of the model is a highly arcuate fold-and-thrust belt characterized by foreland and hinterland-verging thrusts and folds, segmented by transpressive and trantensive transfer zones and conjugate strike-slip faults which generated arc-parallel lengthening and played a crucial role on the along-strike segmentation of the fold-and-thrust belt (Figs. 5 and 6C). This arcuate belt shows salient and recesses and is formed by blocks that underwent clockwise or counterclockwise vertical-axis rotations. Jiménez Bonilla *et al.* (submitted) show that throughout the experiments, the kinematic vectors display a radial pattern swinging roughly 90º from one part to the other of the backstop symmetry axis, resulting in oblique thrusting.

### From structural data in the external zones to lithospheric-scale models: a discussion about the expected strain partitioning

The main results reached by our research group in the external fold-and-thrust belt of the Gibraltar Arc System for the last fifteen years, some of which were summarized in the previous paragraphs, permit us to outline the key kinematic features that characterize its westernmost external wedge. These are: 1) outward radial thrusting nearly orthogonal to the regional structural trend; 2) arc-parallel stretching which affect the fold-and-thrust belt, associated with the development of large-scale strike-slip dominated fault zones in the lateral parts of the arc; and 3) large vertical-axis rotations of opposite sense on each arc limb. This leads us to consider the Gibraltar Arc a case of progressive arc (*sensu* Weil and Sussman, 2004). In addition, the per-


**Fig. 7.-** A. Detail photograph of the right part of the final stage of the same experiment as in Figure 5. Observe the thrusts and backthrusts in the lower part of the photograph which generate shortening across the arc and the conjugate strike-slip faults, which contribute to the lengthening of the arc; FTT, strike-slip fault evolving to a transtensive transfer fault towards the backstop. B. Detail photograph of the central part of the experiment. Observe the millimetric-scale array of normal faults, subperpendicular to the fold-and-thrust and the backstop boundary (within the rectangles).

formed analogue models successfully simulate these main kinematic traits by imposing a backstop, which progressively protrudes and increases the length of its outer boundary. This backstop behavior simulates the changing shape and area increase of an extending domain in the inner part of the arc, that is, the Alboran Basin basement of the natural case, which crustal thickness dropped to 14 km during the Neogene (Comas *et al.*, 1999).

As mentioned in the introduction section, three main types of lithospheric-scale conceptual models could be considered to explain the Gibraltar Arc/Alboran Basin couple. The model of the convective removal of a lithospheric root (Platt and Vissers, 1989), the first that offered a lithospheric-scale interpretation to explain the synchrony between the Miocene contractional arc and the Alboran extensional basin, entails the extensional collapse (radial spreading) of a previous (Paleogene) orogen supposed to be located in the current Alboran Sea position. Nevertheless, updated geologic and geophysical data show that several major features of the GAS tectonic evolution are in disagreement with the requirements and/or implications of this model, symmetrical and fixed with respect to the lithospheric root. They are essentially: 1) the high E-W asymmetry of the arc; 2) the large amount of westward migration of its contractional front (> 300 km from the Early Miocene; García-Dueñas *et al.*, 1992); and 3) the presence below the Alboran Sea of an eastward-dipping slab identified by tomography (Spakman and Wortel, 2004; Faccenna *et al.*, 2004).

Accordingly, we focus our discussion on orogenic arc models that imply a westward migration of the couple extension (in the rear)-contraction (in the front) and therefore are asymmetrical. Concerning these types of models, it is worth to note that either an eastward-dipping subcontinental mantle delamination (García-Dueñas *et al.*, 1992; Seber *et al.*, 1996; Calvert *et al.*, 2000) or a westward retreating subduction (Royden, 1993; Lonergan and White, 1997; Faccenna *et al.*, 2004) have similar kinematic implications. In both cases, it is expected that the contractional front migrates towards the west while it acquires an arcuate shape. Additionally, the tomographic views beneath the Gibraltar Arc -this is also the case of the Calabrian Arc- show that the slab stops and flattens at *ca.* 660 km (Spakman and Wortel, 2004), thus pointing to a high viscosity contrast at the base of the upper mantle. Meanwhile, an expanding extensional back-arc basin developed on the overriding lithospheric domain. However, as new data based on seismic wave form analysis (Bokelmann and Maufroy, 2007; Bokelmann *et al.*, 2011) identified a possible oceanic nature of the eastward-dipping slab imaged beneath the Gibraltar Strait (Spakman and Wortel, 2004), we suggest to discard a model of subcontinental mantle delamination.

With these premises, the model of retreating subduction could be the best candidate in terms of lithospheric-scale model. Such tectonic process has been modeled in laboratory (Faccenna *et al.*, 2001; Funiciello *et al.*, 2008; Meyer and Schellart, 2013) and we will try to couple these experiments with the structural and kinematic data from the Gibraltar Arc fold-and-thrust belts we presented. Both the analogue models and the field data show common key characteristics: the progressively increasing arc curvature and the coeval lengthening and extension of the upper plate. Results derived from one-plate, free subduction analogue models indicate that high viscosity ratios between lithosphere and sublithosphere mantle systematically lead to the development of a retreating subduction with a subducted slab that flattens at depth along the upper-lower mantle discontinuity together with trench retreat, trenchward subducting plate motion, and a concave trench curvature (Faccenna *et al.*, 2001; Funiciello *et al.*, 2008; Meyer and Schellart, 2013). In the case of free subduction analogue models (narrow subducting plate below a narrow overriding plate; Meyer and Schellart, 2013), the progressively increasing arc/trench curvature also takes place without the action of external forces, being the result of the subduction roll-back process itself, probably due to toroidal flow at the lateral ends of the subducting slab. Moreover, because trench retreat velocity is higher than the overriding plate velocity at its trailing edge, widespread extension develops in the upper plate. Extension increases from the lateral parts of the plate to its symmetry axis, and the higher displacement along the symmetry axis of the upper plate drives trench arching. This displacement pattern is similar not only to backarc natural cases, but also to our analogue modelling, where the progressive protrusion and lengthening of the experimental backstop is associated with an area increase in its concave side. This implies that if an accretionary prism would have developed at the plate boundary, it should mimic the progressive trench curvature. Due to the probable strain decoupling between the deformed synorogenic sediments and the more rigid two plates, arc-parallel stretching is expected to happen in a similar way as in our own analogue experiments, which simulate the deformation at upper structural levels of the GAS. In both cases, a progressive lengthening and tightening of the backstop outer boundary systematically lead to the outward radial thrusting, large-scale fold-and-thrust belt segmentation and opposite block rotation on each side of the arc.

## Summary and conclusions

Our research group collected for the last fifteen years a series of structural and kinematic data, which permit to characterize the tectonic evolution of the external wedge of the Gibraltar Arc orogenic System in its westernmost part. The main shortening deformation took place during the Early and Middle Miocene; it is followed by a tectonic event which tightened the western Gibraltar Arc (NNW-SSE-directed compressive event) and that took place from Late Miocene to Holocene. The main shortening has been interpreted as the result of overthrust shearing produced by an overriding mass in the multi-décollement setting. Both events of deformation followed the same strain partition mode, that is, shortening with radial transport direction towards the foreland (swinging around 120º) and an arc-parallel extension accommodated by arc-perpendicular normal faults and arc-oblique strike-slip faults. The Late Miocene event is associated with vertical axis rotations of blocks, clockwise in the Betics and counterclockwise in the Rif.

These data permit us to infer that the deformation mechanism of the external zones situated in the western Gibraltar Arc is that of a progressive arc. Through an innovative design of an experimental apparatus in our analogue model laboratory, we were able to simulate such tectonic situation and investigate its progressive deformation. The analogue modelling results and the natural case study of the Gibraltar Arc are very similar in terms of structures, strain partition mode and kinematics.

These results all together suggest that the lithospheric-scale model most coherent with our data is that of a retreating subduction zone, associated with both back-arc extension in the overriding plate and fragmentation of the subducting plate in small, narrow slabs which retreat outward, producing large scale rotation of the arc flanks. Such model permits to link deep Earth dynamic processes with near-surface geologic processes.

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