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Tectonic evolution of the Malaga Basin (Alboran Sea): insights from its sedimentary infill

Evolución tectónica de la Cuenca de Málaga (Mar de Alboran): visión a partir del relleno sedimentario

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ABSTRACT

The Malaga Basin is a subbasin of the Alboran Sea Basin, which in turn represents the backarc of the Gibraltar Arc System. It is a half-graben which shows a very complete Miocene to Holocene sedimentary sequence. In order to determine the 3D tectonic framework of this half-graben, we interpreted a grid of multichannel seismic commercial profiles, to constrain its geodynamic evolution. A map of the lower to middle Miocene structures that occurred during the rifting events as well as structures generated or reactivated in compression during Tortonian times shows striking differences regarding the structural style from the northern to the southern flank of the Malaga Basin and also along strike of this half-graben. Moreover, our results point that the tectonic inversion and compressional deformation within the sedimentary infill ceased by end of the Messinian, which contrast with the southern and eastern areas of the Alboran Basin.

Key-words: *Malaga Basin, Alboran Sea, tectonic inversion, multichannel seismic, basin evolution.*

RESUMEN

La cuenca de Málaga es una subcuenca de la Cuenca del Mar de Alboran, que a su vez representa el retro arco del Sistema del Arco de Gibraltar. Se trata de una semifosa cuya secuencia sedimentaria del Mioceno hasta el Holoceno se encuentra muy completa. Para determinar la arquitectura tectónica en 3D de esta semifosa se han interpretado una red de perfiles sísmicos comerciales de sísmica multicanal, lo que permite determinar su evolución geodinámica. El mapa resultante, que incluye estructuras formadas en el Mioceno Inferior y Medio correspondientes a la etapa de rift, y estructuras generadas o reactivadas en compresión durante el Mioceno Superior muestra notables diferencias en el estilo estructural entre los flancos septentrional y meridional de la Cuenca de Málaga. Además, nuestros resultados muestran que la inversión tectónica que afecta al relleno sedimentario en la cuenca de Málaga cesó a finales del Messiniense, hecho que contrasta con lo que se observa en zonas más meridionales y orientales de la Cuenca del Mar de Alboran.

Palabras clave: *Cuenca de Málaga, Mar de Alboran, inversión tectónica, sísmica multicanal, evolución de cuenca.*

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Introduction

The geodynamic evolution of the Gibraltar Arc System, which closed to the West the Mediterranean orogenic system, is very complex and remains a matter of debate. In this scenario, the Alboran Basin, situated in a back-arc position, is a key element to understand the evolution of the whole Gibratar Arc System, which also includes the Betic-Rifean mountain belt and the Gulf of Cadiz accretionary wedge (inset of Fig. 1).

The timing of the main events in the Neogene tectonic evolution of the Alboran Sea was established by Comas *et al.* (1999) and is generally used as a model for the whole basin. Nevertheless, the Alboran Basin is made of several sub-basins (op.cit.). A remarkable diachronism in terms of deformational events has been observed onshore (e.g. Crespo-Blanc *et al.,* 2007). Accordingly, similar diachronism may be expected in the back-arc position, and it is feasible that each of the sub-basins shows particular characteristics in terms of subsidence, kinematics and tectonic evolution. For this reason more regional studies need to be done offshore. In this paper we present the architecture of the Malaga Basin, which represents the north-western branch of the West Alboran Basin (Comas *et al.,* 1999). It is a NE-SW oriented half-graben that extends from East of Gibraltar Strait to approximately the 4ºW meridian (100 km long, Fig. 1). In this contribution we refine the age of the structures observed in this basin, in particular those associated with the Miocene rifting and the later compressional deformation.

Suades *et al.* (2012) analysed the top of the basement of the Malaga Basin, meanwhile in this paper we focus on its infill. For this study we use a dense grid (around 2km side) of commercial multichannel seismic profiles oriented NNW-SSE and ENE-WSW. This grid covers the area mapped in figure 1 and is also shown in Suades *et al.* (2012; Fig. 1). The seismic profiles were analysed using Kingdom Suite software in order to generate the 3D basin architecture.

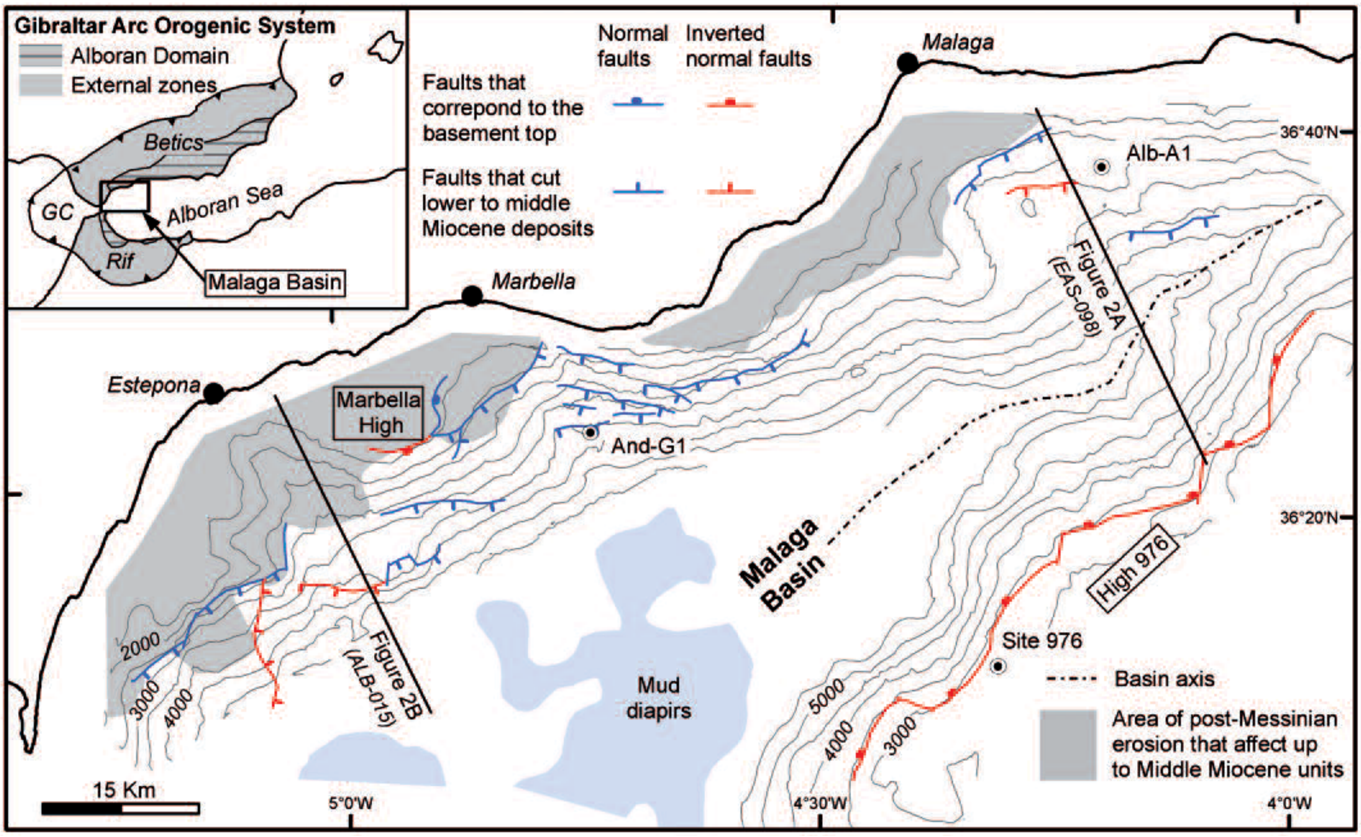

Fig. 1.- Structural sketch of the Malaga Basin showing the main faults affecting lower to middle Miocene deposits (units IV and V). Fault traces correspond with the top of the fault scarps. Top basement contour lines every 500 msec. (TWTT). Inset: location of the Malaga Basin and main domains of the Gibraltar Arc System. GC: Gulf of Cadiz accretionary wedge.

Fig. 1.- Esbozo estructural de la Cuenca de Málaga mostrando las fallas principales que afectan los depósitos del Mioceno inferior y medio (Unidades IV y V). El trazado de las fallas se corresponde con el inicio del escarpe de falla. Líneas de contorno de la superficie de Basamento cada 500 mseg. El recuadro muestra la localización de la Cuenca de Málaga así como los dominios principales del sistema del Arco de Gibraltar. GC: prisma de acreción del Golfo de Cádiz.

Geological setting

The extensional evolution of the Alboran Basin took place from very Late Oligocene onwards and lasts until Lower Tortonian (27-9 Ma; Comas *et al.,* 1999). The rifting affected the internal zones of the Gibraltar Arc System known as the Alboran Domain, a post-metamorphic nappe stack whose main complexes are now bounded by brittle extensional detachments (García-Dueñas *et al.,* 1992). The Alboran Domain is now partially emerged due to a contractive reorganization from Upper Miocene (9 Ma) onwards (inset of Fig. 1). Commercial wells (Alb-A1 and And-G1, Fig. 1) and results from ODP Site 976 show that these metamorphic complexes form the basement of the sedimentary sequences in the western Alboran Sea basins (Comas *et al.,* 1999, and references therein).

Comas *et al.* (1999) established that the sedimentary cover of the Alboran Sea, and in particular the Malaga sub-basin (Martínez del Olmo and Comas 2008), is build up by six major seismostratigraphic units, bounded by major unconformities. The onset of deposition begins with unit VI, Burdigalian, eventually upper Aquitanian, in age. It is an overpressured olistostromic and clay unit responsible of the shale diapirism observed in the deepest parts of the basin (Fig. 1). Unit VI, together with units V (Langhian to lower Serravallian) and IV (upper Serravallian to lower Tortonian) represent the syn-rift sequence of the basin. The R3 unconformity separates the main-rift sequences from units III and II (late Tortonian and Messinian). On top of them, a common major erosional unconformity is observed (M reflector), which is mainly associated with post-Messinian erosion following the Mediterranean salinity crisis. Finally, the Pliocene to Quaternary unit I capes the Miocene sedimentary cover. In this paper, the same seismic sub-division has been adopted (Fig. 2).

Basin architecture and tectonic structures

The overall geometry of the Malaga Basin is well depicted by the basement contour map (Fig. 1 in Suades *et al.,* 2012). It is a narrow and deep half-graben, NE-SW oriented that swings to a NNE-SSW direction towards the West, following the curvature of the Gibraltar Arc. It is limited to the North by the actual shelf and to the South by the basement high called High 976. From the top-of-basement surface, Suades *et al.* (2012) shown a strong asymmetry between the graben flanks and differences in terms of shape, topographic gradient, and scarp alignment from the eastern to the western part of the basin. Similar differences are also observed in the sedimentary architecture of the Malaga Basin that led us to differentiate between the eastern and the western sectors. The boundary between both areas is situated approximately 10km East of the And-G1 well (Fig. 1). Two seismic lines rep-

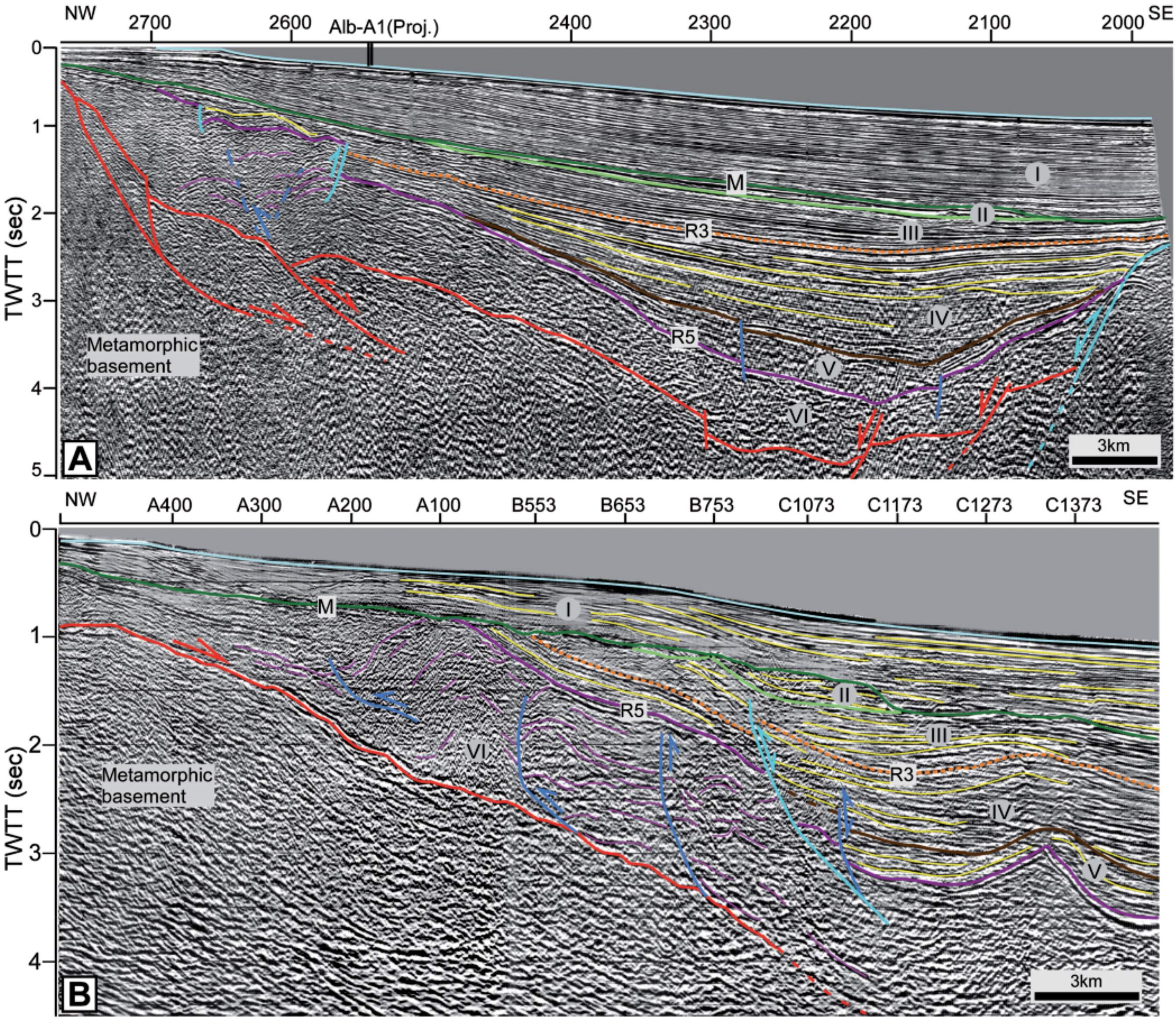

Fig. 2.- Interpreted seismic profiles of the Malaga Basin (location in figure 1). Units are according to Comas et al. (1999). Reflectors are drawn in purple for unit VI and in yellow for the rest of the sedimentary sequence. A) Line EAS-098 showing the seismic architecture of the north-eastern part of the basin. B) Line ALB-015 showing the flank North at south-western sector. Faults represented in the map of figure 1 are coloured in light-blue.

Fig. 2.- Perfiles sísmicos interpretados de la Cuenca de Málaga (localización en la figura 1). Unidades según Comas et al. (1999). Los reflectores están marcados en rosa para la unidad VI y en amarillo para el resto de la secuencia sedimentaria. A) Línea EAS-098 mostrando la arquitectura símica de la parte Nord-Este de la cuenca. B) Línea ALB-015 del flanco norte en el sector Sud-Oeste. Las fallas en azul claro son las que están representadas en el mapa de la figura 1.

resentative of the relationships between the sedimentary sequence and the structures of the basin are presented in figure 2.

The dip-line crossing the eastern sector of the basin shows both graben flanks (Fig. 2A). The southern flank is characterized by a set of faults whose footwall corresponds to the basement High 976 and by the lack of significant faults affecting units V and IV. Sedimentary wedges drawn by unit IV (between shot points 2200 and 2100) reveal the sin-sedimentary activity of this basement normal-faulting. In the northern flank, the lack of important normal faults affecting the sedimentary infill stands out. The main faults are located on top of the basement and may correspond to extensional duplexes. Along this segment of the graben, it is also noticeable the important angular unconformity observed on top of unit VI (around shot point 2400). The maximum thickness of units V and IV roughly coincides with the basin axis drawn by the top-of-basement surface. By contrast, unit VI shows a thickness increase towards the northern flank probably caused by local compression from the shale tectonics that affected this over-pressured unit (Fig. 2A). Deformation of beds in units III and IV around shot point 2600 denotes that this compression remains until the late Miocene, at least (Fig. 2A). Tectonic inversion of normal faults bounding the footwall of the High 976 is also shown in this profile (around shot point 2000).

The dip-line crossing the western part of the graben (Fig. 2B) shows two normal faults affecting units VI to IV (around shot point C1073), which have been reactivated in compression. It is noticeable that the amount of inversion on those faults is small as the cut-off observed in the R3 reflector is less than 200msec. Such inversion had to occur during Upper Miocene times and stopped before the Messinian as unit II is not deformed and its internal reflectors draw a progressive onlap. The geometry of the reflectors inside unit VI reveals reverse faulting in this unit that may be in part triggered by shale tectonics. These faults are rooted on top of the basement, which corresponds to an extensional detachment originated during the rift stage. The M reflector shows that post-Messinian erosion was very important in the western part of the profile.

The map of figure 1 shows that in the northern flank faults affecting units V and IV are more abundant towards the West. In addition, there is more variability in fault directions. Note that normal faults labeled as affecting lower to middle Miocene deposits in this map were traced according their projection upon the observable fault scarp at depth. Near Marbella High these normal faults are mainly NE-SW and WNW-ESE directed coinciding with a basement-top escarpment. A few faults trending N-S and E-W are also found. Most of these faults have listric geometry and root on top of unit VI or along the basement-top surface (Fig. 2). Sometimes the basement-top also shows evidences of active faulting during deposition of units V and IV. This is the case of the fault at the top of Marbella High following roughly a NE-SW orientation (Fig. 1). It must be taken into account that in the northern flank the post-Messinian erosion has removed an important amount of Neogene deposits that prevents the preservation of structures that may have affected the middle to upper Miocene sequences.

Miocene tectonic evolution: discussion

The architecture of the Malaga Basin shows that the Syn-rift sedimentation started at Early Miocene with the deposition of unit VI (Burdigalian, eventually upper Aquitanian; Martínez del Olmo and Comas, 2008). The main unconformity between this unit and the remaining Miocene sediments and the fact that this unit becomes thicker towards the NW (northern flank) suggest that the counter fault which bounds the southern flank of graben to the SE may have had a minor role during the deposition of unit VI. From shot point 2150 to 2560 (Fig. 2A), the sedimentary wedge included between R5 and R3 reflectors is the response of a significant normal fault movement along the counter fault. However, the present-day organization of the strata from shot point 2150 to the SE denotes that it was modified by later uplifting of the High 976.

The main rifting episode that controlled the sedimentary infill of the Malaga Basin occurred from Langhian to Lower Tortonian (units V and IV). During this time interval, in the eastern part of the basin, most of the extension was accommodated by both the low-angle detachment on top of the basement of the northern flank and its counter fault that bounds the High 976 (Fig. 2A). In the western part of Malaga Basin, the northwestern flank shows extensional structures (now partially inverted) that affected both the basement and the whole Miocene infill (Fig. 2B).

The contractive reorganization in the Malaga Basin, occurred after the formation of R3 unconformity (intra-Tortonian in age), and did not cause significant deformation of the sedimentary infill. Indeed, there is no deformation of the Plio-Quaternary beds and only minor tilting is observable in the late Tortonian/Messinian beds, associated with discrete, minor faulting. In fact, upper Miocene reflectors (units II and III) are titled but usually a progressive unconformity can be observed onlapping unit VI (Fig. 2B). This can be explained by uplifting of the northern flank and eventually concomitant shale tectonics (Comas *et al.,* 2012). This contrast with what is observed in other areas of the Alboran Basin where compression is still ongoing and is the cause of noticeable folding and faulting affecting the post-R3 Late Tortonian to Holocene sequence (e.g. Martínez-García *et al.,* 2011).

Conclusions

1) We confirmed that the accumulation of unit VI occurred in the early stages of the rift on a shallower and wider basin than the one observed nowadays.
2) The deformation resulting from the extension during Langhian to Lower Tortonian was different in each sector of the Malaga Basin. For the eastern sector, extension was accommodated by a major basement counter fault (High 976 fault) while the northern flank probably rotated as the hanging wall. In the western part the extension was accommodated also by internal faulting within the Miocene cover. Those faults show a much more complex pattern than the one observed for the eastern part.
3) The compressional deformation in the Malaga Basin started at Upper Tortonian and seems to have ceased before the Plio-Quaternary.

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