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Gravitational dismantling of the Miocene mountain front of the Gibraltar Arc system deduced from the analysis of an olistostromic complex (western Betics)

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ABSTRACT

A mélange complex seals the internal-external zone boundary of the western part of the Gibraltar Arc orogenic belt and constitutes a key element to establish milestones of the Betic-Rif tectonic evolution. The blocks and olistoliths embedded in this mélange provide constraints on the geological history of the main tectonic units involved in the Miocene mountain front. We mapped and analysed the blocks and olistoliths included in this mélange in order to understand its age and genesis, which have long been a matter of debate. The relationships of this mélange La Joya Olistostromic Complex (LaJOC) with the basement units together with the high variability of the block lithologies suggest a sedimentary origin for this mélange. Two large-scale olistoliths retain their original structure prior to their emplacement in the LaJOC Basin. The sedimentological and structural analysis allowed us to correlate these olistoliths with the folded and thrust sequence belonging to the Miocene Betic-Rif accretionary prism (Flysch Trough units), and to constrain the age of deposition of the La Joya Olistostromic Complex. The age of the matrix of the mélange deposits is poorly known because of the lack of in-place fauna. Indeed, the formation of the inherited fold-and-thrust structure of these olistoliths is well-known in the western Betics. Accordingly, the LaJOC should have been deposited during middle Miocene times and the blocks and olistoliths included within the mélange would derive from the gravitational dismantling of the Gibraltar Arc mountain front. The data presented help us to understand the formation of reliefs and basins in the western part of the Gibraltar Arc orogenic system.

KEYWORDS **Gibraltar Arc. Betics. La Joya Olistostromic Complex. Olistoliths structure. Gravitational dismantling.**

INTRODUCTION

Mélange complexes are widespread in the Alpine Mediterranean orogenic belt and can be found in very different geological settings (*e.g.* Jeanbourquin, 1994 for the Alps; Nemcok and Nemcok, 1994 for the Carpatians; Lucente and Pini, 2008 for the Apennines; Okay *et al.*, 2010 for the Anatolian range; Cavazza and Barone, 2011 for the Calabrian Arc; Alonso *et al.*, 2006 for the Iberian Variscan Massif). Because of its structureless and chaotic appearance, the origin of these mélanges is not easy to determine and the processes from which they derive, sedimentary or tectonic, are often subject of discussion (Camerlenghi and Pini, 2009; Festa *et al.*, 2010).

This type of complexes crops out in the Gibraltar Arc orogenic system, the westernmost link of the Alpine

Mediterranean orogenic belt; and is a well-known case of back-arc extensional collapse simultaneous with compression in the external part of the arc (Fig. 1; *e.g.* García-Dueñas *et al.*, 1992). In particular, north of the Gibraltar Strait, mélanges have been described in the Betic external zones, either included in the paleomargin-derived fold-and-thrust belt units (Subbetic units of Fig. 1; Comas *et al.*, 1978; López Olmedo *et al.*, 1988) or in the foreland basin deposits (Guadalquivir Complex of Fig. 1; Vera *et al.*, 2004; and Gulf of Cadiz Complex; Medialdea *et al.*, 2004). In both cases, these mélanges show an olistrostromic character.

Another mélange complex is situated in the boundary between the internal (Alborán Domain) and external zones along the transition between the central and western Betics (essentially between meridians 4º and 5ºW, Fig. 1). Its position made well worth its study in order to decipher and correlate the tectonic pulses in this boundary, and its origin was a matter of debate during the 70's and 80's (Peyre, 1974; Bourgois, 1978; Olivier, 1984; Balanyá and García-Dueñas, 1986; Martín-Algarra, 1987). These studies were based on limited outcrops. In this paper, we provide a comprehensive analysis of this mélange complex and we shed light on its nature, origin and emplacement. We characterized the type of boundary with the underlying units, and studied the stratigraphy and structures of the embedded blocks. In particular, we focused on the analysis of large-scale blocks as the tectonic structures preserved within these blocks permitted to determine their source area and to establish time relationships with the main tectonic events that took place during the Gibraltar Arc mountain front evolution at Miocene times.

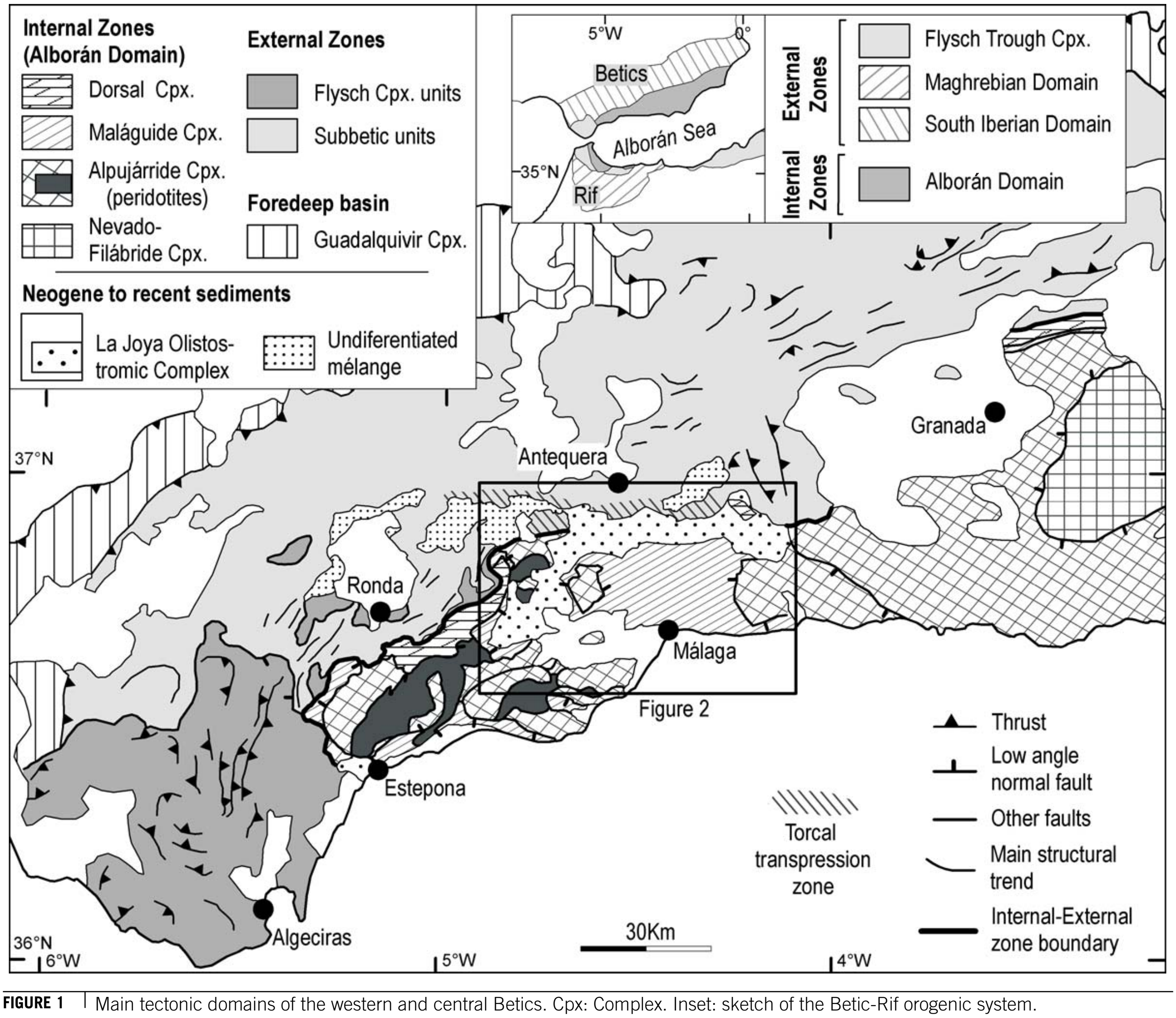

FIGURE 1 | Main tectonic domains of the western and central Betics. Cpx: Complex. Inset: sketch of the Betic-Rif orogenic system.

GEOLOGICAL SETTING

The Gibraltar Arc orogenic system

The Gibraltar Arc orogenic system bounds the Mediterranean to the west. The main units involved are the following (Fig. 1):

i) The Alborán Domain, in the hinterland, is formed by the metamorphic internal zones. It is subdivided into several complexes, which from bottom to top are: the Nevado-Filábride (not present in the western Betics), the Alpujárride, the Maláguide and the Dorsal complexes (Fig. 1). The Alpujárride Complex is composed of a Paleozoic metapelitic-metapsammitic sequence and Triassic carbonate rocks. The Alpujárride Complex is made up by units of variable metamorphic grade (Adra,Salobreña and Herradura units in the study area, Azañón and Crespo-Blanc, 2000; Fig.2). Peridotite slices can be found in between the uppermost units (Sánchez-Gómez *et al.*, 1996). The Maláguide Complex consists of a Paleozoic sequence of low metamorphic grade made up of phyllites and carbonates, in turn overlain by a non-metamorphic cover of mainly Triassic red conglomerates and sandstones accompanied by scarce Jurassic to Eocene carbonates (*e.g.* Cuevas *et al.*, 2001). The Dorsal Complex (Durand-Delga and Foucault, 1967) is mainly composed by Triassic to Neogene sedimentary non-metamorphic rocks with a predominance of carbonated series. It is an imbricate thrust sequence that crops out discontinuously along the internal-external zone boundary, tectonically sandwiched by the other units of the Alborán Domain on top and the external zones at the bottom (Balanyá, 1991).

ii) The Flysch Trough Complex consists of Cretaceous to lower Miocene clastic rocks imbricated in thrust stacks and emplaced over the South Iberian and Maghrebian paleomargin-derived units (Fig. 1; Didon, 1969; Luján *et al.*, 2006). The Oligocene to Miocene sediments of the Flysch Trough Complex were deposited in the accretionary prism which underlined the western Mediterranean subduction zone (Faccenna *et al.*, 2004). Based on the presence of sandstones or greywackes in the Aquitanian sediments (Aljibe or Algeciras formations respectively), three main units have been described in this complex (Aljibe, Algeciras and Bolonia units; Didon, 1969). The Predorsal units crop out along the internal-external zone boundary and are included in the Flysch Trough Complex. Predorsal units are characterized by dismembered slices of Jurassic to lower Miocene rocks (Fig. 2; Durand-Delga, 1972; Olivier, 1984). The calcareous Jurassic rocks show a strong affinity with the Dorsal Complex whereas the Cretaceous to Neogene sequence is similar to the aforementioned Flysch Trough Complex units. The Predorsal units are structurally sandwiched between the Alborán Domain on top and the other Flysch Trough Complex units below.

iii) The Subbetic units represent the detached cover of the South Iberian paleomargin. They are composed by sedimentary rocks of ages generally ranging from Triassic to Cretaceous, although the sedimentary record extends up to the Neogene (Vera, 2000). The detached cover of the Maghrebian paleomargin is represented by the External Rif.

The Gibraltar Arc orogenic system formed mainly during Miocene times because of the westward migration of the Alborán Domain that acted as a backstop. The movement of the Alborán Domain with respect to the external zones produced the detachment of the cover rocks from the Flysch Trough Complex and the South Iberian and Maghrebian paleomargins. These rocks detached from their basement currently form the fold-and-thrust belt of the Gibraltar Arc external wedge (Balanyá and García-Dueñas, 1988). The study area corresponds to the westernmost part of the Gibraltar Arc (west of 4º30'W, Fig. 1). There, the Flysch Trough Complex and the Subbetic units form the external fold-and-thrust belt whose structural trend mimics the Gibraltar Arc curvature (Fig. 1). The formation of this fold-and-thrust belt took place during Burdigalian and/or Serravalian times (Crespo-Blanc and Campos, 2001; Crespo-Blanc and de Lamotte, 2006; Luján *et al.*, 2006; Balanyá *et al.*, 2007). In the central part of Figure 1, the continuity of the structural trend is cut off by a dextral transpression zone which mainly affected the Subbetic units (Barcos *et al.*, 2011, inclined hatching in Fig. 1; Torcal transpression zone of Balanyá *et al.*, 2012). The transpressional regime and associated uplift were active, at least, between the late Miocene and the Quaternary and probably their activity begun in middle Miocene times.

While compression was taking place along an orogenic front migrating towards the external zones, rifting was active in the back-arc of the Gibraltar Arc and various systems of low-angle normal faults affected the Alborán Domain (Fig. 1; García-Dueñas *et al.*, 1992; Comas *et al.*, 1999). In the study area (Fig. 2), these structures mainly present a top-to-the-SW transport direction north and east of the city of Málaga (Alonso-Chaves and Orozco, 1998; Booth-Rea *et al.*, 2003), whereas west of the city a centripetal tectonic transport towards the arc is observed (from SSE to SE directed; Balanyá, 1991; García-Dueñas *et al.*, 1992). The interval age during which these fault systems were active is considered to be early Burdigalian-Serravallian (op. cit.).

After these main orogenic episodes of folding and thrusting coeval with the extension, the western Gibraltar Arc area was affected by a contractive episode from Tortonian to Recent (García-Dueñas *et al.*, 1992; Comas *et al.*, 1999; Rodríguez Fernández *et al.*, 1999). This triggered the formation of open folds and high-angle fault systems.

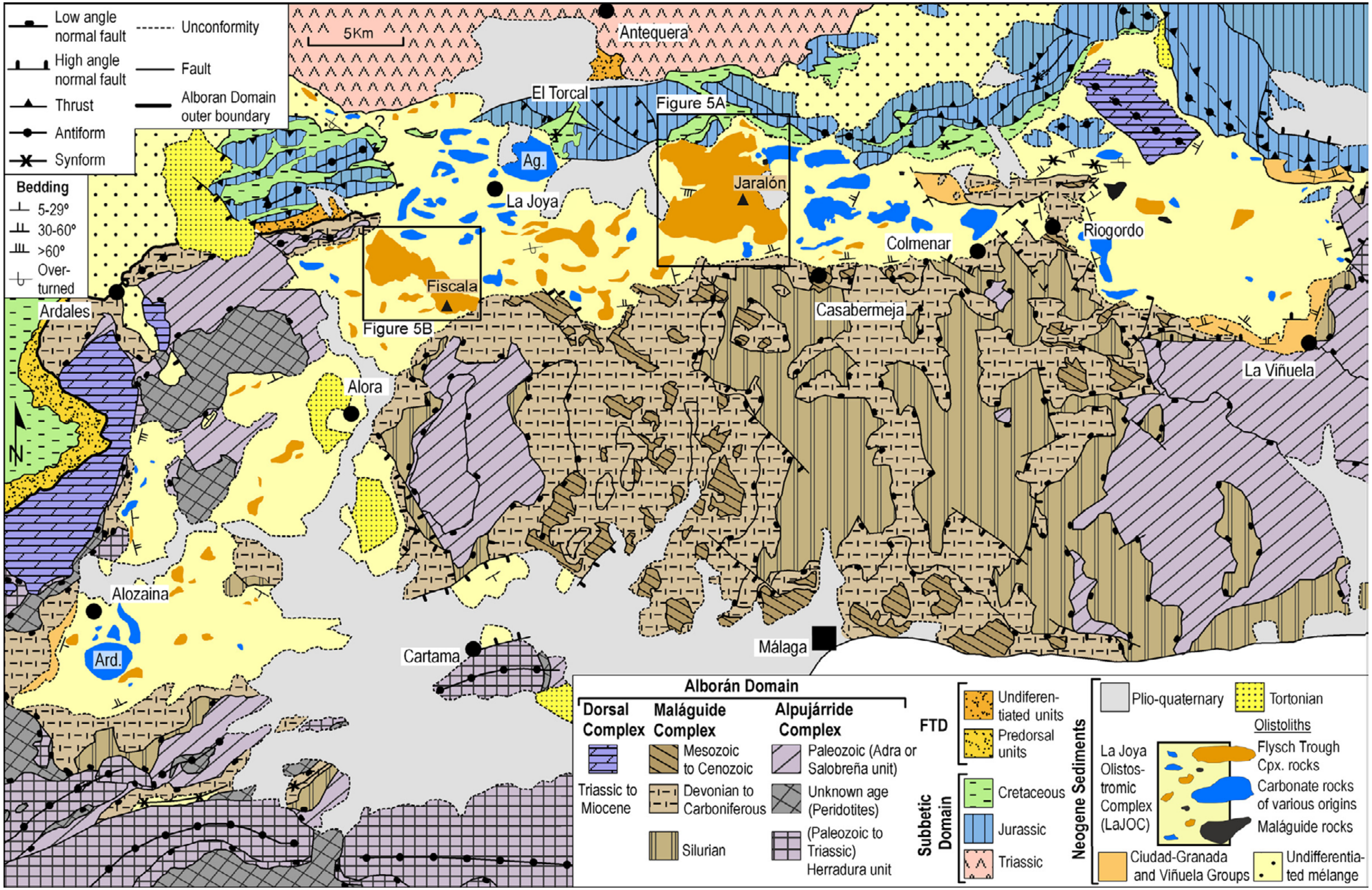

FIGURE 2 | Structural sketch of the La Joya Olistostromic Complex (location in Fig. 1). Modified from Balanyá *et al.* (2012), Martín-Algarra *et al.* (2004), Booth-Rea *et al.* (2003), Cano Medina and Ruiz Reig (1982), Barba Martín *et al.* (1979), Chamón Cobos *et al.* (1976). FTD: Flysch Trough Domain units; Ard: Cerro de Ardite olistolith; Ag: Cerro del Águila olistolith.

Miocene deposits in the study area

The extensional processes that affected the Alborán Domain contributed to its subsidence and to the deposition of Miocene sediments unconformably over the metamorphic complexes (Comas *et al*., 1992; García-Dueñas *et al*., 1992). Whereas offshore the sedimentary record is fairly continuous during Miocene times (Jurado and Comas, 1992), only scattered outcrops of the same time interval are present onshore.

In the western Betics, the Ciudad-Granada and La Viñuela groups represent the first sedimentary record (see review in Serrano *et al*., 2007) and testify the initial stages of the Alborán Domain rifting (García-Dueñas *et al*., 1992). Both groups outcrop in the studied area (Fig. 2) and are characterized by initial deposits of breccia or conglomerate with clasts that derived from the nearby Alpujárride and/or Maláguide metamorphic rocks (Serrano *et al*., 2007). The marls that overlie the breccias were dated as Aquitanian to early Burdigalian (González-Donoso *et al*., 1983; Martín-Algarra, 1987; Aguado *et al*., 1990; Durand-Delga *et al*., 1993; Serrano *et al*., 2007). The Ciudad-Granada and La Viñuela groups onlap the Alborán Domain and seal some of the extensional fault systems related with the rifting episode, as observed in the eastern part of Figure 2 (10km SSE of Riogordo; Alonso-Chaves and Orozco, 1998). It must be stressed that, locally, hydraulic brecciation associated with some low-angle normal faults could have favoured the supply of the breccias from La Viñuela Group (Suades and Crespo-Blanc, 2010). Analogous sediments, supplied in turn by clasts from the Subbetic Domain (Santana formation of Mathis (1974) in Barba Martín *et al*., 1979), occur north of La Viñuela village (Fig. 2). They are presently verticalized, even overturned and thrusted by the Jurassic limestones of the Subbetic Domain.

A mélange complex overlies the Ciudad-Granada and La Viñuela groups as well as the Alborán Domain metamorphic rocks and the Subbetic units. It is characterized by turbiditic sediments alternating with chaotic deposits. The latter are a mixture of blocks of diverse sizes, ages and lithologies embedded in an argillaceous matrix. The block-in-matrix appearance is characteristic of both tectonic and sedimentary mélanges (tectosomes and olistostromes, respectively; Cowan, 1985; Camerlenghi and Pini, 2009; Festa *et al*., 2010). This complex crops out along two main sectors (Fig. 2): a northern one that follows an E-W depression along the internal-external zone boundary, and a western one, NNE-SSW-directed and located over the Alborán Domain units. A very narrow outcrop is also present 10km SSE of Alozaina, pinched between the Alborán Domain units (García-Dueñas *et al*., 1992). Finally, small outcrops of this formation occur near the locality of Estepona (Fig. 1; Balanyá, 1991). This mélange complex is the subject of this study and will be decribed in detail in the next section.

Finally, a few outcrops of near-horizontal conglomerates, sandstones and calcarenites dated as Tortonian are present in the studied area (Fig. 2; see López-Garrido and Sanz de Galdeano, 1999 and references therein).

Previous work on the mélange

The mélange complex that we describe in this paper received several names in the past, because of its enigmatic origin, undetermined age, chaotic appearance and poor outcrops. Previous works were mainly based on small, limited areas being the most important ones listed in Figure 3. The lack of in-place fauna within the mélange complex made an accurate dating difficult. However, the paleontological studies of Peyre (1974), Bourgois (1978), Feinberg and Olivier (1983), González-Donoso *et al*. (1987) and Martín-Algarra (1987) indicated that it cannot be older than early Burdigalian (as indicated by resedimented planktonic foraminifera), which is nonetheless consistent with the fact that the mélange lies over the La Viñuela Group (Balanyá, 1991).

The origin and emplacement processes of the mélange complex have also been a matter of debate. Peyre (1974), who focused his studies on the northern outcrops, defined two main units in the mélange according to the degree of disturbance of the matrix: the Colmenar Flysch, transgressive over the Alborán Domain, and the so-called Tectonosedimentary Complex, in turn thrusted over the Colmenar Flysch. He also considered the large-scale blocks of the mélange either as tectonic windows or klippes. Bourgois (1978) held again the term of Tectonosedimentary Complex and defined two units, the "Neonumidian" and "Argiles à blocs". He defined them west of the Ronda Basin (Fig. 1), and included in both units any flysch type unit with a supposed chaotic structure of sedimentary klippes embedded in a clay matrix. He exported this model to the western sector of the mélange and considered the sector as part of the "Tectonosedimentary Complex", which would have been emplaced tectonically over the Alborán Domain.

By contrast, Olivier (1984) considered this mélange complex as Predorsal units, which would represent part of the dismembered Flysch Trough units, also overthrusted on the Alborán Domain. This author interpreted the blocks as tectonic slices which would have lost their internal continuity. Martín-Algarra (1987) considered both processes, tectonic and gravitational, to explain the origin

	Defined Units	Age of deposition	Method	Genetic interpretation
Peyre (1974)	Tectono-sedimentary Complex	Lower Burdigalian	Fauna	Tectono-sedimentary Complex
	Flysch de Colmenar	Aquitanian		sedimentary unit
Bourgois (1978)	Neonumidien / Argiles à blocs	Burdigalian	Fauna/ super-position criteria	Tectono-sedimentary Complex
Olivier (1984)	Predorsal	Lower Burdigalian	Fauna	Backthrust (dismantled)
Martín-Algarra (1987)	Arcillas Variegadas	Lower Burdigalian	Fauna	Tectonic unit resedimented
	Numidoide			Sedimentary unit
Balanyá (1991)	Alozaina Complex	Upper Burdigalian	super-position criteria	Sedimentary Complex
This work	La Joya Olistostromic Complex	Langhian to Serravallian	Olistoliths corre-lation	Olistostromic sedimentary Complex

FIGURE 3 | Schematic chart that summarises the main points of previous works on the La Joya Olistostromic Complex, as well as this work.

of the mélange cropping out in the western part of the northern sector. In his opinion, the "Arcillas Variegadas s.s." would correspond to Flysch Trough units tectonically emplaced over the Alborán Domain, later dismantled and resedimented; whereas he considered the so-called "Numidoide" as autochthonous and deposited during active tectonics. In this scenario, large-scale blocks can either have an intrabasinal origin, or be individual tectonic units.

Finally, Balanyá and García-Dueñas (1986) and Balanyá (1991) used the term of Alozaina Complex to define the mélange deposits cropping out in the southwesternmost sector as well as in the isolated outcrop of Estepona (Fig. 1). For these authors the mélange derived from the gravitational dismantling of mainly Dorsal and Predorsal units over the Alborán Domain.

The works of the aforementioned authors deserve several considerations. First of all, it must be stressed that even if this complex contains turbiditic deposits, the use that most of the cited authors made of the term "Flysch" contributed to generate confusion. Indeed, the term is not appropriate as this mélange complex is not a unit of the Flysch Trough Complex, in the sense that it did not belong to its paleogeographic domain (accretionary prism associated with the western Mediterranean subduction zone during Miocene times). Moreover, petrographical similarities with some of the sequences of the Flysch Trough Complex units were observed in blocks or olistoliths embedded in this complex. On the other hand, some authors (Peyre, 1974; Martín-Algarra, 1984) considered the large-scale blocks as individual tectonic units, encouraging the characterization of a great number of tectonic units (*e.g.* Barba Martín *et al.*, 1979).

In this work, we consider the mélange as a single and differentiable complex, although we recognize that it could be made up of several subunits.

We offer for the first time an overall view of it, from the village of Alozaina in the west, to the village of La Viñuela in the east (Fig. 2). We agree with the overall concept of gravitational dismantling of Balanyá and García-Dueñas (1986). However, we think that the term Alozaina Complex has to be abandoned, because it has already been used for the Alozaina Formation, a local formation of the Ciudad-Granada Group, cropping out near the village of Alozaina (Bourgois *et al.*, 1972) and stratigraphically situated below the mélange. Accordingly, we propose the term of La Joya Olistrostromic Complex (LaJOC) to refer to this mélange complex. La Joya is a small village located at the intersection of the two sectors of this complex, and the term "olistrostromic" will be justified in the next section.

MAIN FEATURES OF THE LA JOYA OLISTOSTROMIC COMPLEX

At outcrop scale, we have not found any evidence characterizing the contact between the LaJOC and the underlying units (Alborán Domain, Flysch Trough Complex and Subbetic Domain) as a mechanical contact, but in spite of its poor exposure, we could see that is a sedimentary unconformity. This does not agree with the thrust interpretation that can be found in the national geological maps of Spain (Chamón Cobos *et al.*, 1976; Barba Martín *et al.*, 1979; Cano Medina and Ruiz Reig, 1982). At map scale, it can be observed how the low-angle normal faults bound the Alpujárride and Maláguide complexes and are always sealed by the LaJOC (Fig. 2). The few available measurements in the stratified levels of the LaJOC show that it strikes generally parallel to the contact with the Alborán Domain, and dips gently to moderately towards the centre of both the northern and western sectors of the LaJOC (Fig. 2). This would indicate two main, very smooth, E-W and NNE-SSW trending folds, respectively. On the other hand, the contact between the LaJOC and the Subbetic Domain is generally masked by scree deposits issued from the erosion of the Subbetic carbonate rocks. When observed, this contact is either a high-angle fault or a stratigraphic unconformity (Figs. 2; 4A). Finally, late high-angle normal faults, trending mainly NW-SE, affect the LaJOC-Alborán Domain unconformity near the villages of Riogordo and Alora (Fig. 2). They belong to the same late fault system that affects the Alborán Domain.

The LaJOC is characterized by chaotic units (mélanges with blocks floating in a matrix) intercalated with well-layered stratified levels. In the field, the matrix of the mélange units and the stratified levels usually correspond to the low-relief cultivated areas and show characteristic colours that range from brown-tobacco to ochre (Figs. 4A, B). By contrast, the large blocks that belong to the mélange units are easily differentiable and appear mainly on top of hills (Fig. 4B). Because of the poor outcrops, it was not possible to differentiate between the stratified levels and the exposure of mélange units in the map of Figure 2, although they can be distinguished at outcrop scale (in ravines or along road trenches).

The stratified levels are mainly constituted by turbiditic clays and marls (Fig. 5A) interbedded with scarce, thin and rhythmic levels of fine-grained sandstones. The marls are usually rich in silica and present a conchoidal fracture. Scarce folds are observed, though their origin is still unclear (sedimentary slumps or tectonic folds). Nevertheless, N and NE of the village of Riogordo, near the boundary with the Subbetic Domain, the whole sequence is folded, verticalized and/or even overturned. Accordingly, some of the observed folds may be tectonic in origin.

Regarding the chaotic units, the matrix that supports the blocks is also comprised of marls and clays but in this case with a disrupted aspect. The latter are characterized by anastomosed smoothly undulated surfaces, forming pseudobedding (scaly fabric according to Vannucchi *et al.*, 2003), generally subhorizontal or dipping slightly (Figs. 5B, C, D).

Blocks and olistoliths are all those bodies that are embedded or floating within the chaotic matrix, being the olistoliths all those blocks of more than 4m in length (see Dunbar and Rogdger, 1957). In general, the blocks are isolated. They are isometric with sharp borders and are supported by the matrix (Fig. 5C). Sometimes, blocks are elongated, lens-shaped, and may be folded (Fig. 5D).

The contact of the olistoliths with the matrix is not observable everywhere but, in most cases it is sub-horizontal and the olistoliths seem to "float" on the matrix (Fig. 4B, C). For this reason, Peyre (1974), Barba Martín *et al.* (1979) and Olivier (1984), among others interpreted some of them as tectonic klippes. Other olistoliths are embedded in the matrix, forming large-scale lens structures (Fig. 5E). Usually, they preserve their internal structure, but they can be also disrupted or fractured. The LaJOC contains a large number of olistoliths and many of them are big enough to be mapped (Fig. 2). Their distribution is not homogeneous: they are very abundant in the northern sector, and scarcer in the western one.

The blocks and olistoliths have been classified according to their lithology. Three main groups are present (Fig. 2):

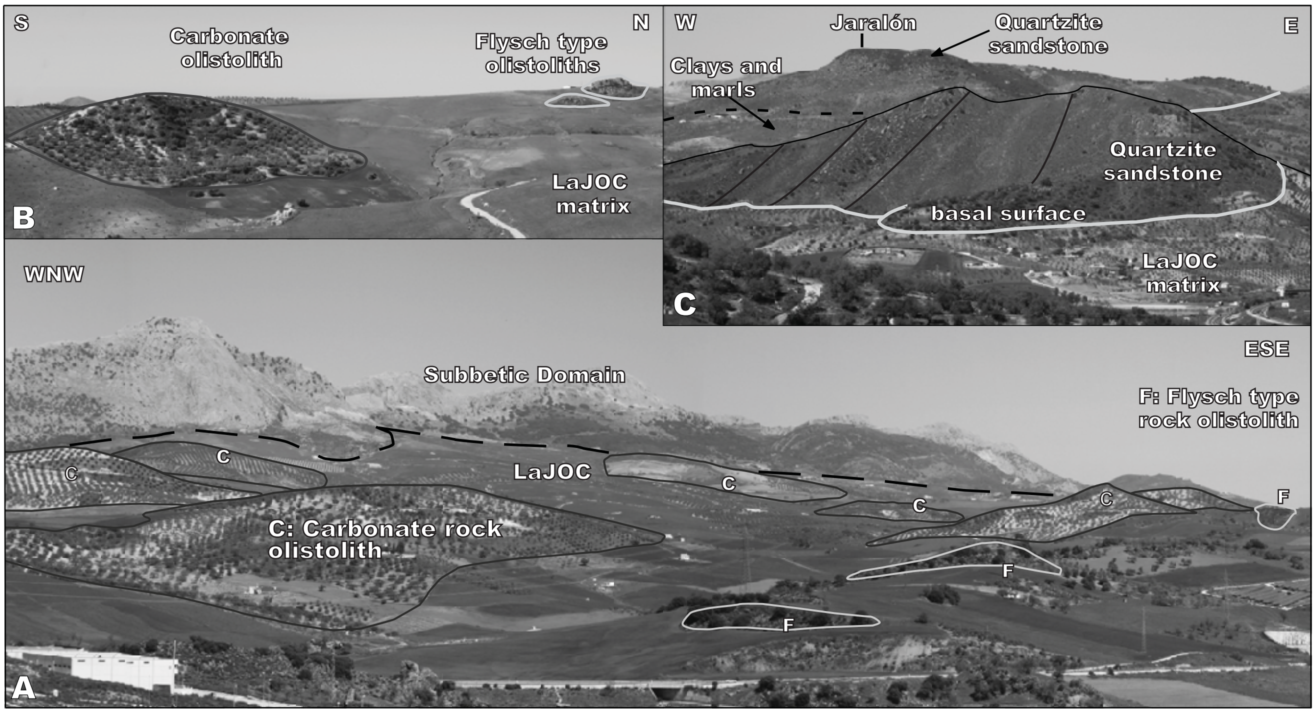

FIGURE 4 | Field photographs of the La Joya Olistostromic Complex (LaJOC). A) General view of the LaJOC northern sector taken from Casabermeja, facing ENE. C: Carbonate rock olistolith, F: Flysch type rock olistolith. B) View of two olistoliths with a positive relief "floating" on the matrix (5km NW of Colmenar). C) View of the Jaralón olistolith. Note beds of quartzite sandstone cut abruptly by the basal surface.

i) A first group includes all those blocks and olistoliths composed mainly by unmetamorphosed carbonate rocks. They can proceed from the Subbetic Domain, the Predorsal, the Dorsal, or even from the Maláguide cover. Some of them have been dated and their ages mainly range from Jurassic to Paleocene, although some can be as young as Miocene (Peyre, 1974; Bourgois, 1978). The biggest olistoliths of this group are those from the "Cerro del Aguila" hills (Peyre, 1974), situated SW of El Torcal (Ag. in Fig. 2). Martín-Algarra (1987) and Alcalá-García *et al.* (2002) correlated them either to the Predorsal units or the Subbetic Domain. Another large olistolith crops out in the "Cerro de Ardite" hill, situated 2km south of Alozaina (Ard. in Fig. 2). It shows an overturned Jurassic to Eocene sequence and has strong similarities with the Predorsal units (Bourgois, 1978; Olivier, 1984).

ii) The second group is poorly represented and is comprised of Silurian to Devonian shales and Permian to Triassic red clays and conglomerates from the Maláguide Complex.

iii) The blocks and olistoliths of the third group are made of rocks that can be directly correlated with the Flysch Trough Complex rocks (Figs. 2; 5E; 6). The most common rocks are mature quartzite sandstones with a high degree of roundness and grain sorting. The grain size varies from one block to another, ranging from fine to very coarse. Another type of rock is a less mature and finer grained greywacke with abundant mica. These two types of sandstones can be correlated with the Aquitanian formations present in the three main units of the Flysch Trough Complex: while the quartzite sandstones are analogous to the sandy levels of the Aljibe Formation (which belongs to the Aljibe unit), the greywackes can be correlated with the Algeciras Formation (Algeciras unit; Fig. 6A; Didon, 1969). Finally, an intercalation of both types of sandstones can be observed in an olistolith (Fig. 6B), similiar to the Bolonia unit (Didon, 1969). Moreover, there are other unconsolidated sediments which do not form isolated blocks and can only be distinguished in the large-scale olistoliths, alternating with the sandstones (Fig. 6). They are characterized by marls, clays and carbonates that Peyre (1974) dated as Eocene to Oligocene in the olistolith situated 3 km WNW of Casabermeja (Fig. 2). This succession of sandstones and unconsolidated sediments shows strong similarities with what is know in the Flysch Trough Complex as the "Serie de Base", a Palaeocene to Oligocene calciturbiditic sequence (Esteras *et al.*, 1995 in Luján *et al.*, 2006).

LARGE-SCALE OLISTOLITHS

The two largest olistoliths from the LaJOC are located on top of the hills of Jaralón (5km NW of Casabermeja village) and Fiscala (8km NNE of Alora) (Figs. 2; 6A, B). The Jaralón olistoliths is 25km^2 in area and 450m in height (with respect to its base), and Fiscala olistoliths is 13km^2 in area and 250m in height. Both olistoliths can be correlated with the sedimentary sequences of the Flysch Trough Complex. Peyre, 1974; Cano Medina and Ruiz Reig, 1982; Olivier, 1984 and Martín-Algarra, 1987 considered the olistoliths as tectonic units either nappe or klippe.

A map and a cross-section of the Jaralón hill olistolith is shown in Figures 6A and D. It shows an imbricated thrust sequence composed by Aljibe and Algeciras type rocks, *i.e.* quartzite sandstones alternating with marls and clays ("Serie de base" sequence) and greywackes, respectively. It trends approximately E-W and the thrust sequence dips generally gently towards the N or the S (see cross-section in Fig. 6D). In the southern part of the olistolith, the whole imbrication depicts an arcuate geometry and the trend turns from E-W and NW-SE to N-S. The basal surface contact between the structured olistolith and the matrix runs almost horizontal. Accordingly, the olistolith seems to be "floating" on the matrix and its bedding is cut by the basal contact (see Fig. 4C and the cross-section in Fig. 6D), that does not show kinematic indicators.

The olistolith that crops out in the Fiscala hill shows decametric to hectometric alternation, characteristic of the Bolonia unit, of Aljibe type quartzite sandstones and fine-grained Algeciras type greywackes (Fig. 6B). The Fiscala olistolith forms a NW-SE trending synform plunging towards the NW. The strata that draw this synform are in a normal position. On top of this Aquitanian sequence, an Eocene to Oligocene marly-argillaceous sequence is observed, equivalent to the "Serie de base" sequence. It points to the presence of a thrust of unknown kinematics which separates the Bolonia unit at the bottom and the "Serie de base" sequence on top. As in the Jaralón olistolith, the base of the Fiscala olistolith shows a flat geometry cutting all the previous thrust imbrications (Fig. 6D). Late high-angle, ENE-SSW faults, cut the olistolith and the matrix.

DISCUSSION

Nature and genesis of the La Joya Olistostromic Complex

The LaJOC is mainly characterized by the presence of very heterogeneous blocks in terms of litology and size. These blocks are dispersed in a matrix where a stratigraphic succession can not be established. As a matter of fact, only partial sections have been measured (Peryre, 1974; Martín-Algarra, 1987). According to Camerlenghi and Pini (2009) and Festa *et al.* (2010) among others, the LaJOC description broadly coincides with the current concept of mélange, in a descriptive sense. For these authors, the origin of a mélange can be associated either with tectonic processes (fault-related), sedimentary processes (due to gravitational falling or sliding into a basin), or diapirism. In our study area, this latter process can be ruled out as it would require the existence of overpressured shales or evaporites in the metamorphic Alborán Domain basement. In addition, if the mélange was the result of diapirism a prevalence of basement metamorphic blocks would be expected. These rocks would be eroded during the ascension of the diapir, which is not the case. To distinguish between tectonic and sedimentary origins, outcrop-scale detailed textural analyses are needed (see Camerlenghi and Pini, 2009). Unfortunately, the poor quality of the outcrops exclude the possibility to make this type of analysis. Nevertheless, the following criteria led us to favour a sedimentary origin.

FIGURE 5 | Outcrop views of the La Joya Olistostromic Complex. A) Well-layered turbiditic beds with conchoidal fracture. B) Mélange matrix with scaly fabric. C) Isolated block in the mélange matrix. D) Block shaped in a closed fold. E) Lenticular flysch type olistolith within the matrix.

First, the contact between the LaJOC and its basement can be interpreted as a sedimentary unconformity, and the LaJOC indistinctly overlies the internal (Alborán Domain) and the external (Subbetic and Flysch Trough fold-and-thrust belt) zones. Indeed, LaJOC seals the low-angle normal faults related to the Alborán Domain rifting (Fig. 2). Concerning the blocks and olistoliths of the LaJOC, they range in age from Permo-Triassic to Aquitanian, all older than the matrix (at least early Burdigalian). This and the fact that they show a wide range of lithologies, including Flysch Trough rocks which are not present in its surroundings, point to an exotic sedimentary origin for the blocks and olistoliths. Moreover, in tectonic mélanges, blocks frequently show an elongated, boudin-like geometry and their preferential orientation results in pseudo-bedding (Cowan and Pini, 2001; Bettelli and Vannucchi, 2003). This is not generally observed in our case study.

If the mélange were tectonic in origin, we would expect an alignment with a major tectonic structure. This is true for the northern sector, where the LaJOC outcrops along the boundary between the internal and external zones and could be related with the fault zone between both. Nevertheless, along the western sector, the LaJOC crops out entirely over the Alborán Domain, where the major tectonic structures (essentially low-angle normal faults) do not affect it. The scaly fabric observed in the matrix of the mélange units (Figs. 5B, C, D) is typical of tectonic mélanges, but this kind of fabric can also occur in sedimentary mélanges. It can be produced, at the base of large olistostromes (see Camerlenghi and Pini, 2009),

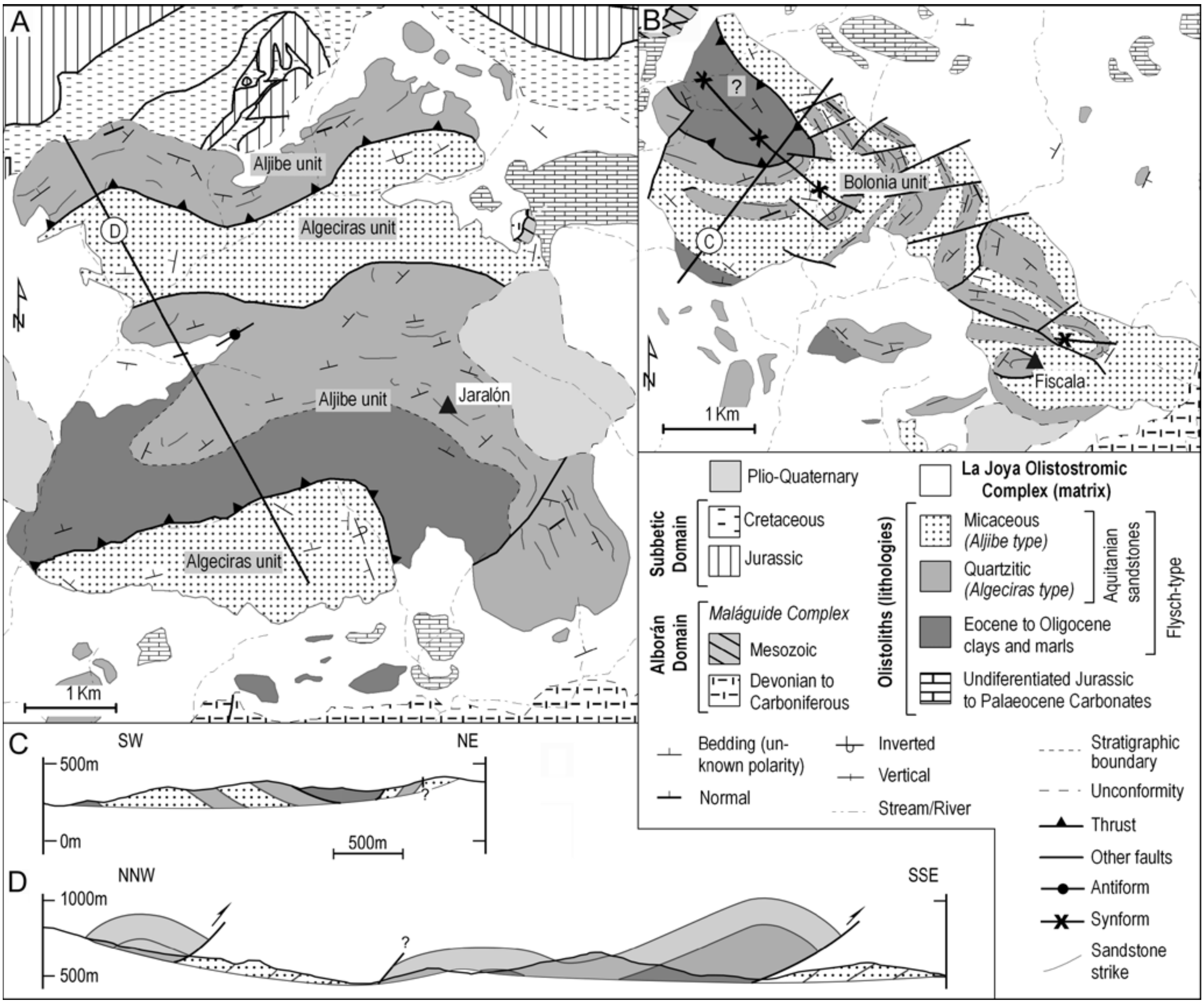

FIGURE 6 | A) and B) Geological maps of Jaralón and Fiscala olistoliths, respectively (see location in Figure 2). Olistolith lithologies are listed in the legend and their correspondence with the Flysch Trough Domain units is indicated on the map. C and D) Cross-sections of Fiscala and Jaralón olistoliths, respectively.

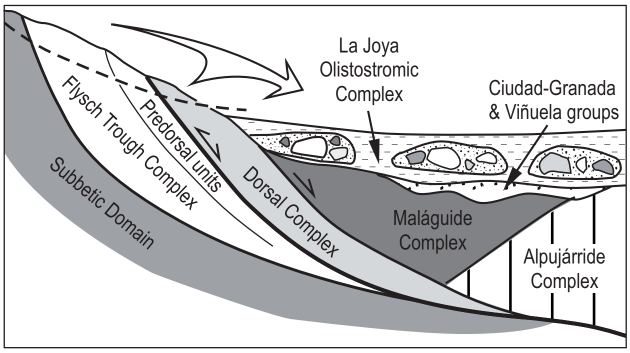

FIGURE 7 | Sketch illustrating the geometry of the main tectonic complexes, the relative position of the LaJOC Basin and the mode of emplacement of the olistoliths.

either by compaction (by burial and/or dewatering) or late tectonics (Flores, 1959; Vannuchi *et al*., 2003; Lucente and Pini, 2008).

Emplacement of the large-scale olistoliths

The folds and thrusts imbricate structures described in the Jaralón and Fiscala olistoliths are similar to those observed in the Flysch Trough Complex units (Luján *et al*., 2006; Crespo-Blanc *et al*., 2010). Peyre (1974), Olivier (1984) and Martín-Algarra (1987), considered these olistoliths as tectonic units. According to them, the olistoliths would have been emplaced through a backthrust from the Flysch Trough Complex over the mélange, which, in turn, would have thrust the Alborán Domain. Nevertheless, in the northern branch of the Gibraltar Arc, the Flysch Trough Complex units are always situated structurally below the Alborán Domain (Crespo-Blanc and Campos, 2001; Luján *et al*., 2006). Even if this is the case for the emplacement of these olistoliths, this tectonic process cannot explain the presence of blocks and small olistoliths of the same lithology dispersed in the matrix. Moreover, the lack of mechanical contacts along the base of the large-scale olistoliths and the fact that their lower boundary does not correspond to a basal thrust, as it cuts all the thrusts located in the interiors, are not coherent with the backthrust hypothesis (although they could be out-of sequence thrusts). Accordingly, we consider that the Fiscala and Jaralón hills are formed by olistoliths, that were already structured when they were gravitationally emplaced within the LaJOC.

Figure 7 schematically illustrates the LaJOC deposition and the emplacement of the olistoliths. We propose that the LaJOC was supplied by the erosion and gravitational dismantling of the tectonic units involved in the mountain front, that was growing coetaneously with the development of the external zone fold-and-thrust belt. By that time, the Alborán Domain was already affected by back-arc rifting and subsidence. Accordingly, it should have been at lower topographic level than the mountain front, which would have favoured the gravitational transport of the olistoliths initially located in a more external position over the Alborán Domain. As for the Jaralón and Fiscala olistoliths, they derive from the deformed Flysch Trough Complex, structurally located between the Subbetic and the Alborán domains (Balanyá and García-Dueñas, 1988; Crespo-Blanc and Campos, 2001). In the case of the Ardite olistolith, it derives from an overturned Predorsal unit.

Age of the La Joya Olistostromic Complex and relationships with the evolution of the Gibraltar Arc

The structural analysis of the large-scale olistoliths suggests a middle Miocene age for the LaJOC (Fig. 8). Indeed, the uppermost deposits of the Flysch Trough Complex fold-and-thrust belt have been dated as lower Burdigalian for the Aljibe unit (Esteras *et al*., 1995 in Luján *et al*., 2006) and upper Burdigalian for the Algeciras unit (De Capoa *et al*., 2007). Consequently: i) the main shortening and thrusting of these units should have taken place from late Burdigalian onwards (Luján *et al*., 2006; Crespo-Blanc *et al*., 2012), and ii) the presence of two already deformed Flysch Trough Complex olistoliths implies that sedimentation in the LaJOC probably began around the boundary between early and middle Miocene.

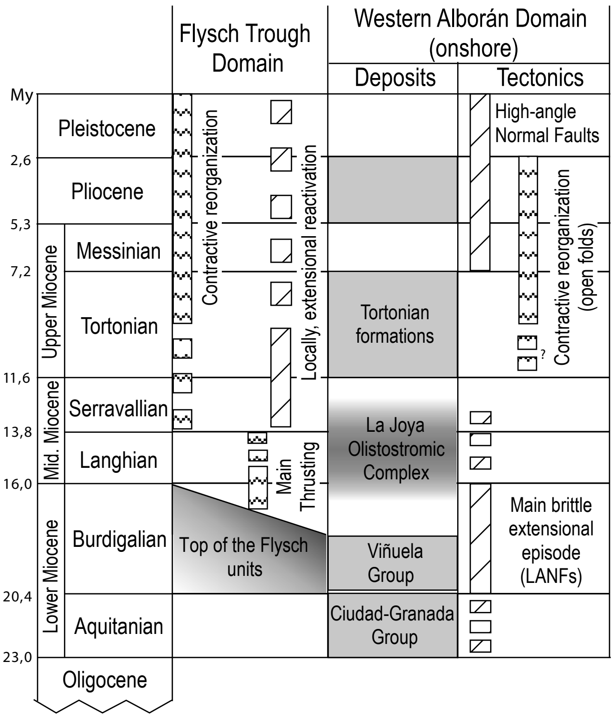

FIGURE 8 | Chronologic chart of the tectonic evolution of the Flysch Trough Domain and western Alborán Domain during Miocene times. Ages of tectonic processes and sedimentary deposits constrain the deposition of the La Joya Olistostromic Complex.

Its deposition could have extended up to Serravallian times, since LaJOC is sealed by Tortonian calcarenites and conglomerates.

Geological mapping of LaJOC showed that the low-angle normal faults that affected the Alborán Domain, associated with the Miocene extension, are sealed by the LaJOC (Fig. 2). In addition, Suades and Crespo-Blanc (2010) showed that hydraulic brecciation related to some of these low-angle normal faults supplied Malaguide detritus to the breccia deposits of La Viñuela Group (Aquitanian to early Burdigalian in age), situated stratigraphically below the LaJOC. Consequently, the activity of the low-angle normal fault systems that affected the Maláguide and Alpujárride complexes in this part of the western Betics ceased prior to the emplacement of the LaJOC (Fig. 8). As rifting proceeded, both the basement and LaJOC should have been passively transported on top of the W to SW-ward Serravallian low-angle normal fault system, the basal detachment of which is represented by the Nevado-Filábride/Alpujárride boundary, 80km E of the study area (Fig. 1; see also García-Dueñas *et al.*, 1992; Martínez-Martínez and Azañón, 1997; Alonso-Chaves and Orozco, 1998).

North of the LaJOC northern sector, a dextral transpression zone affecting the southern outcrop of the Subbetic Domain was active at least from late Miocene to Recent (Torcal transpression zone in Fig. 1; Barcos *et al.*, 2011 and Balanyá *et al.*, 2012). The associated uplift and development of relatively high topography with respect to the LaJOC Basin probably promoted gravitational dismantling processes. As a matter of fact, a higher concentration of the mapped olistoliths can be observed south of El Torcal area, in the northern sector of LaJOC (Fig. 2). The deformation associated with the southern boundary of the transpressive zone could also be responsible for the overturning of both the LaJOC NNE of Riogordo village, and the Viñuela Group 8km north of La Viñuela village (Fig. 2).

The few available measurements of bedding show that the LaJOC is folded (scarce, very open folds). The E-W-trending syncline of the northern sector of the LaJOC is subparallel to the very open folds drawn by the Alborán Domain units near the village of Cartama and in the southwestern part of the LaJOC (see also Chamón Cobos *et al.*, 1976; Sánchez Gómez *et al.*, 1996). The NNE-SSW direction of the syncline of the western LaJOC sector corresponds to that of the folds developed between the late Tortonian and the late Messinian in the Ronda Basin, 30km WNW of the study area (Fig. 1; see references in Crespo-Blanc and Campos, 2001). Both groups of folds can be related to the latest Miocene to recent contractive reorganization defined onshore, in the western (Crespo-Blanc and Campos, 2001; Booth-Rea *et al.*, 2003; Balanyá *et al.*, 2012) and central Betics (Azañón and Crespo-Blanc, 2000; Martínez-Martínez *et al.*, 2002; Marín-Lechado *et al.*, 2007), as well as offshore (Comas *et al.*, 1999).

Open Questions

We focused on the study of the LaJOC in the area mapped in Figure 2, but previous works pointed out that mélanges similar to that described in this paper are also present in the western Gibraltar Arc. West of the study area, on the Ronda Basin (Fig. 1), Bourgois (1978) and Cruz-Sanjulián and Ruiz Reig (1980) described argillaceous sediments with a chaotic appearance and embedded blocks and olistoliths similar to the LaJOC. These authors called them "argiles à blocs" and the existence of blocks of flysch type rocks led them to attribute these sediments to the Flysch Trough Complex. Nevertheless, the mélanges described by these authors are lower Burdigalian or younger, that is younger than the Flysch Trough Complex. Moreover, the aforementioned mélanges do not display a coherent structure of thrust stacking, which is characteristic of the Flysch Trough Complex units (*e.g.* Luján *et al.*, 2006; Crespo-Blanc *et al.*, 2010). Another mélange crops out east of Antequera (Figs. 1; 2) and includes essentially carbonate blocks (although some quartzite sandstones of the Aljibe unit are also present; Pineda Velasco and Ruiz Reig, 1983). All these mélanges could represent the external counterpart of the LaJOC, in the sense that they could represent the gravitational dismantling of the mountain front in basins situated over the external zones. Finally, in the southern branch of the Gibraltar Strait, a transgressive formation of marls and pelites dated as Burdigalian lies over the internal zones of the Rif (El Kadiri *et al.*, 2001; Serrano *et al.*, 2007; Hlila *et al.*, 2008). Over this unit, Chalouan *et al.* (1995) and Hlila *et al.* (2008) describe a large-scale, 7km-long block made of Aljibe type quartzite sandstones, structured in a thrust stack and cut along its base. The similarities between the large-scale olistoliths described in the present paper and this Aljibe type body lead us to consider that it could represent an olistolith included within a sedimentary unit similar to the LaJOC.

All these mélanges require additional work in terms of time-space correlations. They are key sequences to understand the relationships between topographic evolution, erosion and basins in the western part of the Gibraltar Arc orogenic system.

CONCLUSIONS

i) The La Joya Olistostromic Complex (LaJOC) crops out in the western Betics. It is characterized by turbiditic deposits alternating with mélange units that contain blocks and olistoliths of several origins. It is interpreted as a sedimentary complex, lying unconformably over the internal-external zone boundary.

ii) In terms of lithology, the blocks and olistoliths included in the LaJOC can be classified into three main groups: Jurassic to Paleocene carbonate rocks from the Subbetic, Flysch Trough Complex or Alborán Domain, Paleozoic shales and Permo-Triassic red clays of the Alborán Domain, and clastic rocks of the Flysch Trough Complex. They are mainly extrabasinal in origin. No tectonic contact has been observed at the bottom of the olistoliths.

iii) The deposition of the LaJOC is interpreted as due to the gravitational dismantling of the units situated in the neighbouring of the Miocene mountain front of the western Gibraltar Arc. The blocks and olistoliths which make up the LaJOC were transported mainly towards the hinterland.

iv) Two kilometre-scale olistoliths have been described. They preserve the internal structure prior to their emplacement and show an imbricate thrust stack, similar to some units of the Flysch Trough Complex.

v) The sedimentation of the LaJOC should be post-late Burdigalian and pre-Tortonian in age, and it seems to have a wider area than that described in the study area.

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