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Arc-parallel vs back-arc extension in the Western Gibraltar arc: Is the Gibraltar forearc still active?

J.C. BALANYÁ [1] **A. CRESPO-BLANC** [2, 3] **M. DÍAZ-AZPIROZ** [1] **I. EXPÓSITO** [1] **F. TORCAL** [1, 4] **V. PÉREZ-PEÑA** [2] **G. BOOTH-REA** [2]

[1] **Departamento de Sistemas Físicos, Químicos y Naturales, Universidad Pablo de Olavide**
Cra. de Utrera km 1, 41013-Sevilla, Spain. Balanyá E-mail: jcbalrou@upo.es Díaz-Azpiroz E-mail: diaazp@upo.es
Expósito E-mail: iexpram@upo.es Torcal E-mail: ftormed@upo.es

[2] **Departamento de Geodinámica, Universidad de Granada**
Avda. Fuentenueva s/n, 18071-Granada, Spain. Crespo-Blanc E-mail: acrespo@ugr.es Pérez-Peña E-mail: vperez@ugr.es
Booth-Rea E-mail: gbooth@ugr.es

[3] **Instituto Andaluz de Ciencias de La Tierra**
Avda. Fuentenueva s/n, 18071-Granada, Spain

[4] **Instituto Andaluz de Geofísica y Prevención de Desastres Sísmicos**
Cuesta del Observatorio 1. Campus Universitario de Cartuja, 18071-Granada, Spain

ABSTRACT

Extremely tight arcs, framed within the Eurasia-Africa convergence region, developed during the Neogene on both sides of the western Mediterranean. A complex interplate deformation zone has been invoked to explain their structural trend-line patterns, the shortening directions and the development of back-arc basins. Updated structural and kinematic maps, combined with earthquake data covering the complete hinge zone of the western Gibraltar arc help us to explore the mode of strain partitioning from 25My ago to present. During the Miocene, the strain partitioning pattern showed arc-perpendicular shortening in the active orogenic wedge –assessed from the radial pattern of tectonic transport directions– accompained by subhorizontal stretching. Structures accommodating stretching fall into two categories on the basis of their space distribution and their relationships with the structural trend-line pattern: i) arc-parallel stretching structures in the external wedge (mainly normal faults and conjugate strike-slip faults); and ii) extensional faults developed in the hinterland zone in which transport directions are centripetal towards the Alborán back-arc basin. Pliocene to Recent deformational structures together with focal solutions from crustal earthquakes (n=167; 1.5<Mw<6.3) support that this strain partitioning pattern still occurs. By contrast, the eastern end zones of the western Gibraltar arc, especially during the last 5My, underwent intense transpression tectonics with a NW to NNW main shortening axis. These results agree with a still active Gibraltar forearc, governed by westward migrating subduction retreat or subcontinental mantle delamination.

KEYWORDS **Forearc tectonics. Strain partitioning. Crustal earthquakes. Gibraltar arc.**

INTRODUCTION

Strain partitioning within collisional and subduction arcs is thought to be strongly controlled by i) the angular relationships between plate convergence vectors and the segments that draw the plate boundary, ii) the amount of strain decoupling of -and within - the forearc terranes and iii) the operating deep-seated lithospheric mechanisms that underlie the complete arc/back-arc system. From the forearc to the arc's inner zones, both structural and seismic data indicate that common cases include: i) strain partitioning into strike-slip faults and into thrusts and folds which accommodate, respectively, arc-parallel and arc-perpendicular components of plate convergence (Barrier *et al.,* 1991; Aurelio, 2000; Dewey and Lamb, 1992; Pinet and Cobbold, 1992); and ii) arc-parallel stretching produced by strike-slip faults that cross the forearc structural trend line pattern and arc-perpendicular extensional faults (McCaffrey, 1991; Avé Lallemant, 1996).

In most cases arc-parallel stretching is expected to achieve its maximum values in lateral zones of the arc where the angle between plate convergence and the boundary approaches zero. In this context, the exhumation of deep-seated rocks (Avé Lallemant and Guth, 1990) or the development of deep depressions on attenuated lithosphere (Maldonado *et al.,* 1998) could be understood as attributed to high values of estimated arc-parallel strain rates (McCaffrey, 1996). From another point of view, the knowledge of the 3D distribution of strain partitioning along the arcuate orogenic belts gives critical information on arc formation kinematics (Hindle and Burkhard, 1999), and allows to inquire about the anatomy of the orogen's deep structure (Scrocca *et al.,* 2007).

Spectacular examples of orogenic arcs are present in the Mediterranean region. Indeed, the western Mediterranean is bounded by the Gibraltar and Calabrian arcs (Fig. 1A), which are extremely tight, as their radius of curvature is one order of magnitude smaller than that of any other arc observed on earth (Faccenna *et al.,* 2004). Both arcs show different strain partitioning modes that include evidence of arc-parallel stretching (*e.g.*, Oldow *et al.,* 1993 for Calabria and Balanyá *et al.,* 2007 for Gibraltar). They started to develop 28My ago, and back-arc extension gave rise to thinned continental crust in the Alborán sea (Comas *et al.,* 1999) and oceanic crust in the Algero-Balear and Tyrrhenian seas (Faccenna *et al.,* 1997; Jolivet *et al.,* 1999; Fig. 1A).

The slow, N-S to NW-SE convergence of Eurasia and Africa in the western Mediterranean area during the Neogene (1 to 2cm/year; Dewey *et al.,* 1989) is not sufficient to explain the large E-W tectonic transports that simultaneously affected the different terranes involved

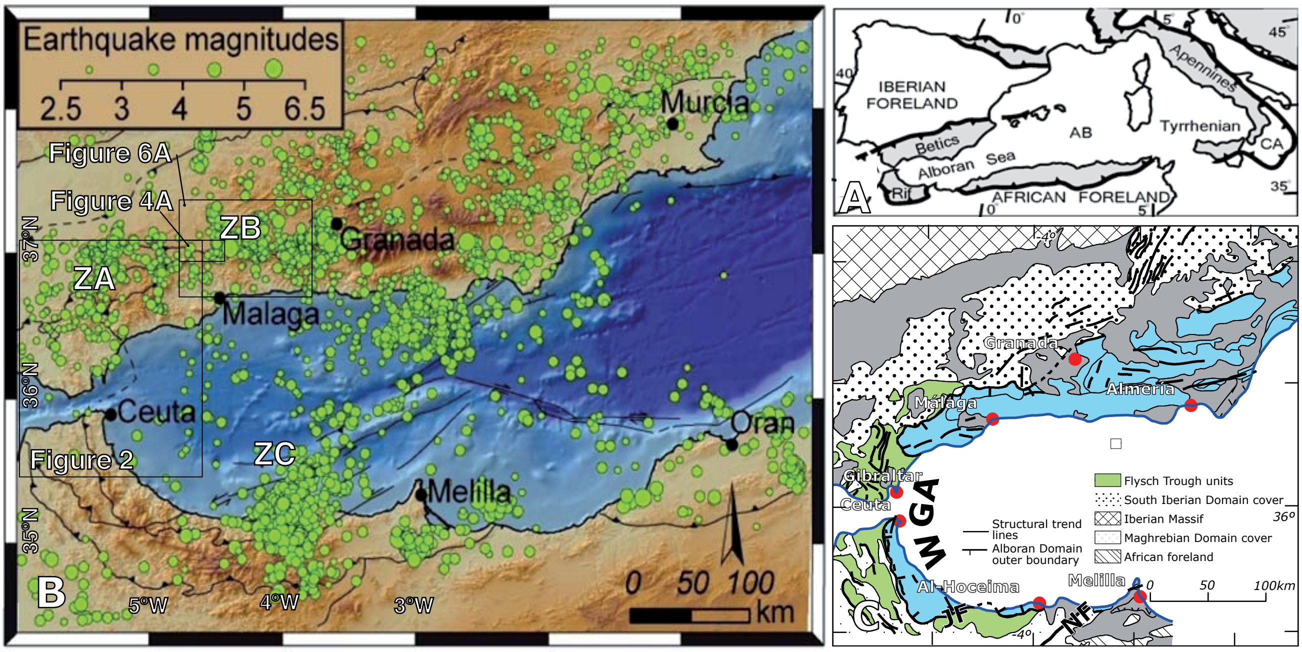

FIGURE 1 | A) Gibraltar and Calabrian arcs (GA and CA, respectively) within the western Mediterranean; AB: Algero-Balear basin. B) Tectonic map of the Gibraltar arc showing the distribution of crustal seismicity. Earthquake location database from Fernández-Ibáñez *et al.*, 2007. ZA, ZB and ZC, main earthquake concentration zones in the western Gibraltar arc. C) Onshore main tectonic elements within the Gibraltar arc (WGA: western Gibraltar arc; JF: Jebha fault; NF: Nekor fault).

along the plate boundaries. Accordingly, subduction retreat coupled with back-arc extension and/or mantle lithosphere delamination are processes often invoked to explain most of the tectonic features observed in both arcs (Malinverno and Ryan, 1986; Channel and Mareschal, 1989; Royden, 1993; Doglioni *et al.,* 1997; Faccenna *et al.,* 2004; Capitanio and Goes, 2006).

In this paper, we focus on the Gibraltar arc (Fig. 1). We present updated kinematic maps by completing the inventory of the structures producing strain partitioning during the last 25My, in particular those related with arc-parallel stretching. This allows us to discriminate between back-arc related and arc-parallel extension, to inquire about the step-by-step evolution of strain partitioning in the westernmost arc of the Mediterranean area (from 25My ago onwards), and to explore the different modes of arc formation (Hindle and Burkhard, 1999). In addition, we have analysed strain partitioning using seismicity data. For this purpose, we have revised the distribution of present-day crustal seismicity (Fig. 1B) and their related focal mechanisms. These data, taken together with current stresses and recently acquired marine data (Thiebot and Gutscher, 2006; Fernández-Ibáñez *et al.,* 2007; Fernández-Ibáñez and Soto, 2008), allow us to test whether or not the Gibraltar outer wedge stayed active as a forearc zone for the last 5My and whether it still is today. Finally we try to use these results to discuss previously proposed lithospheric models.

DISTINCTIVE TECTONIC FEATURES OF THE WESTERN GIBRALTAR ARC

The Gibraltar arc, that includes the Betic and Rif chains, resulted from the Neogene collision between the hinterland zone (the Alborán domain) and two foreland domains (the South Iberian and Maghrebian palaeomargins; Fig. 1C). The foreland domains build most of the external fold-and-thrust belt and are composed by Mesozoic to Tertiary sequences (Crespo-Blanc and Campos, 2001; Vera *et al.,* 2004; Crespo-Blanc and Frizon de Lamotte, 2006). The Flysch Trough complex is incorporated into the inner part of the foreland fold-and-thrust belt (Luján *et al.,* 2006), and corresponds to the detached cover of a deep trough, within which oceanic (?) basement (Durand-Delga *et al.,* 2000) was subducted. The Alborán domain is a metamorphic composite terrane that underwent collisional and intraorogenic extensional episodes mainly during Paleogene times (Feinberg *et al.,* 1990; Tubía and Gil Ibarguchi, 1991; Durand-Delga *et al.,* 1993; Azañón *et al.,* 1997; Balanyá *et al.,* 1997). On the inner side of the arc and simultaneously to the hinterland-foreland collision, the Alborán back-arc–basin developed from the Lower Miocene onwards (Comas *et al.,* 1992, 1999). Parts of the Miocene Alborán basin basement are now exposed onshore and are closely coincident with the outcropping Alborán domain units (García-Dueñas *et al.,* 1992; Crespo-Blanc *et al.,* 1994; Martínez-Martínez and Azañón, 1997; Martínez-Martínez *et al.,* 2002). Lower Miocene deposits, including olistostromes (Alozaina complex), unconformably overlie the Alborán basin basement and show evidences of progressive floor subsidence linked to the opening of the Alborán basin (Serrano *et al.,* 2006).

Within the Gibraltar arc system that comprises the total of Betic and Rif chains and the Alborán basin, the western Gibraltar arc is defined as the hinge zone of the arc (Fig. 1C). The western Gibraltar arc delineates, west of 4ºW, a 400km long orogenic segment –considering the internal-external zone boundary– that shows important specific structural features when compared with the zones of the Gibraltar arc system located east of 4º30'W (Balanyá *et al.,* 2007; Crespo-Blanc *et al.,* 2007; this paper): i) the structural trend line pattern defines a protruded salient (Macedo and Marshak, 1999), bounded by two end (recess) zones near 4ºW; ii) the thrust-related transport direction in the external zones shows an outward divergent pattern around the arc; iii) the main deformation phase in the external zones is not synchronous respect to the eastern part of the arc; iv) structures accommodating suborthogonal shortening are coetaneous with structures accommodating arc-parallel stretching; v) the structure of the hinterland mountain front is governed by the constant hanging-wall position of the Alborán metamorphic domain with respect to the external zone; vi) in the Betics, the Flysch Trough units mostly crop out in the western Gibraltar arc, while they are almost absent in the central and eastern Betics; vii) the submerged forearc zone in the gulf of Cadiz shows an internal structure similar to an accretionary wedge (Gutscher *et al.,* 2002; Thiebot and Gutscher, 2006), although partially chaotic and gravitationally driven (Medialdea *et al.,* 2004) and viii) offshore, the inner side of the western Gibraltar arc (the western Alborán basin) is characterized by a huge thickness of Neogene to Quaternary deposits floored by Alborán domain metamorphic rocks, and the absence of an outcropping or suboutcropping volcanic basement (Comas *et al.,* 1999).

Geophysical data also point to the specific features of the western Gibraltar arc which crops out onshore when compared with the lateral zones of the Betic-Rif orogen east of 4ºW. They mainly correspond to: i) greater crustal and lithospheric thicknesses (Torné *et al.,* 2000); ii) higher Pn velocities in the lower lithospheric mantle (Serrano *et al.,* 2007); iii) lower heat flow (Polyak *et al.,* 1996); iv) lower seismic flux within the crust (seismic moment released per year and per unit area; Serpelloni *et al.,* 2007); and v) lower Moho temperature and higher total strength of the crust (Fernández Ibáñez and Soto, 2008).

STRAIN PARTITIONING MODES IN THE WESTERN GIBRALTAR ARC FROM 25My TO PRESENT

The Neogene and Quaternary structural record

A first study on the strain partitioning and its relations with the structural trend-line pattern in the external western Gibraltar arc was carried out by Balanyá *et al.* (2007), essentially based on the Miocene structural record. Based on this, in the present paper we have improved this catalogue of Neogene structures in three different ways: i) with detailed mapping of selected areas, with special attention to kinematic data; these are the westernmost outcrops of the external wedge in the Betics (Flysch Through complex and Subbetic units of South Iberian domain; Figs. 2; 3), the region close to the Gibraltar straits (Fig. 2), and the South Iberian domain segment located at the NE end of the western Gibraltar arc, between the central and western Betics (Fig. 4); ii) by extending the age interval of the observed structures up to the Pliocene and Plio-Quaternary; to do so, we characterized the structures that affected the late Miocene to Pliocene formations; and iii) we revised the previously described extensional fault zones within the Alborán domain outcrops (García-Dueñas and Balanyá, 1991; García-Dueñas *et al.,* 1992) in order to better define their kinematics and age (Figs. 2; 3); we also considered the faults mapped offshore in the western Alborán sea (Comas *et al*., 1992, 1999).

Structural associations within the western Gibraltar arc

Main structures accommodating arc-perpendicular shortening within the western Gibraltar arc are thrusts and W-vergent or upright folds. Along the arc, the shortening structures have a variable vergence that changes according to the structural trend-line variation, being to the NW in western Betics (Balanyá *et al.,* 2007), and to the SSW in the southern branch of the western Gibraltar arc (Chalouan, 2006b). Structures accommodating arc-parallel stretching include arc-perpendicular extensional faults, conjugate strike-slip faults, and widely distributed veins and small-scale shear zones that produce fold axis-parallel extension (Figs. 2; 3). Most of these structures are located in the outer external wedge. When possible, we can group these structural associations within three age intervals: Lower and Middle Miocene, Upper Miocene, and Pliocene or later.

As can be seen in Figure 2, extensional faults generating arc-parallel stretching are widely distributed in the study area, especially in the external wedge (Subbetic units of the South Iberian domain and Flysch units). They develop from Middle Miocene (*i.e.*, the Colmenar fault) to Pliocene (Barbate fault) or even to the Quaternary (Punta Camarinal fault). The Ronda basin is one of the most conspicuous normal fault-related structures. The NW-SE directed faults bounding or within the Ronda basin (Figs. 2; 3C) are either sealed by Upper Miocene deposits or cut across them. This conjugate normal fault system is scarcely developed within the Alborán domain and the few cases are located near its mountain front (*e.g.*, as seen in the NE corner of Fig. 2). On the other hand, the conjugate strike-slip fault system, also accommodating arc-parallel stretching, seems to have been active essentially during the latest Miocene and the Pliocene (*e.g.*, Gaucín, Jebel Mousa, and Embalse de Barbate faults). They are widely developed over the external wedge and the Alborán domain mountain front, both in the Betic and Rifean branches of the western Gibraltar arc (Figs. 2; 3B).

Comparable structures accommodating N-S –*i.e.*, arc-parallel– stretching in the Gibraltar strait are observed (Fig. 2). Indeed, very detailed available swath bathymetry data (Sandoval, 1996) and sea-floor geological maps built up from dredged rocks and sonograph interpretations (Sandoval *et al.,* 1995) show the presence of morphotectonic lineaments crossing the Camarinal Sill, a residual structural high composed of Flysch Trough units (Luján *et al.,* 2009). These lineaments are oriented along two maxima, striking roughly E-W and N-S. Some of the E-W lineaments clearly evidence topographic and structural arguments for normal faulting. The oldest possible age for this faulting would be Pliocene, the age of the Gibraltar strait's opening.

It must be stressed that relevant tectonic features found in the external wedge have conspicuous similarities for the three considered age intervals: i) the tectonic transport pattern related to folds and thrusts is radial (main azimuth range of about 90º, Fig. 2); ii) transpressive structures are scarcely represented; and iii) among the identified strain partitioning modes, arc-perpendicular shortening coeval with arc-parallel stretching prevails. Indeed, from the structural data of this region, based on 56 representative groups of outcrops, it is deduced that shortening and extension directions coexist at nearly 90º independently of the structural trend variation (graph in Fig. 2).

By contrast, within the outcropping Alborán domain of the western Gibraltar arc –north and south of the Gibraltar strai– the main structures expressing post-metamorphic extension are low-angle normal faults, lower to middle Miocene in age, which shows a centripetal tectonic transport towards the inner part of the arc (Fig. 2). These fault systems that generated arc-perpendicular extension are similar to the extensional faults mapped offshore in the Alborán basin, where three main extensional episodes from the Early Miocene to Late Miocene were recognized (Comas *et al.*, 1999). They produced the negative tectonic inversion of the Alborán domain thrust front during the Middle Miocene (Figs. 2; 3E, F) and are probably related

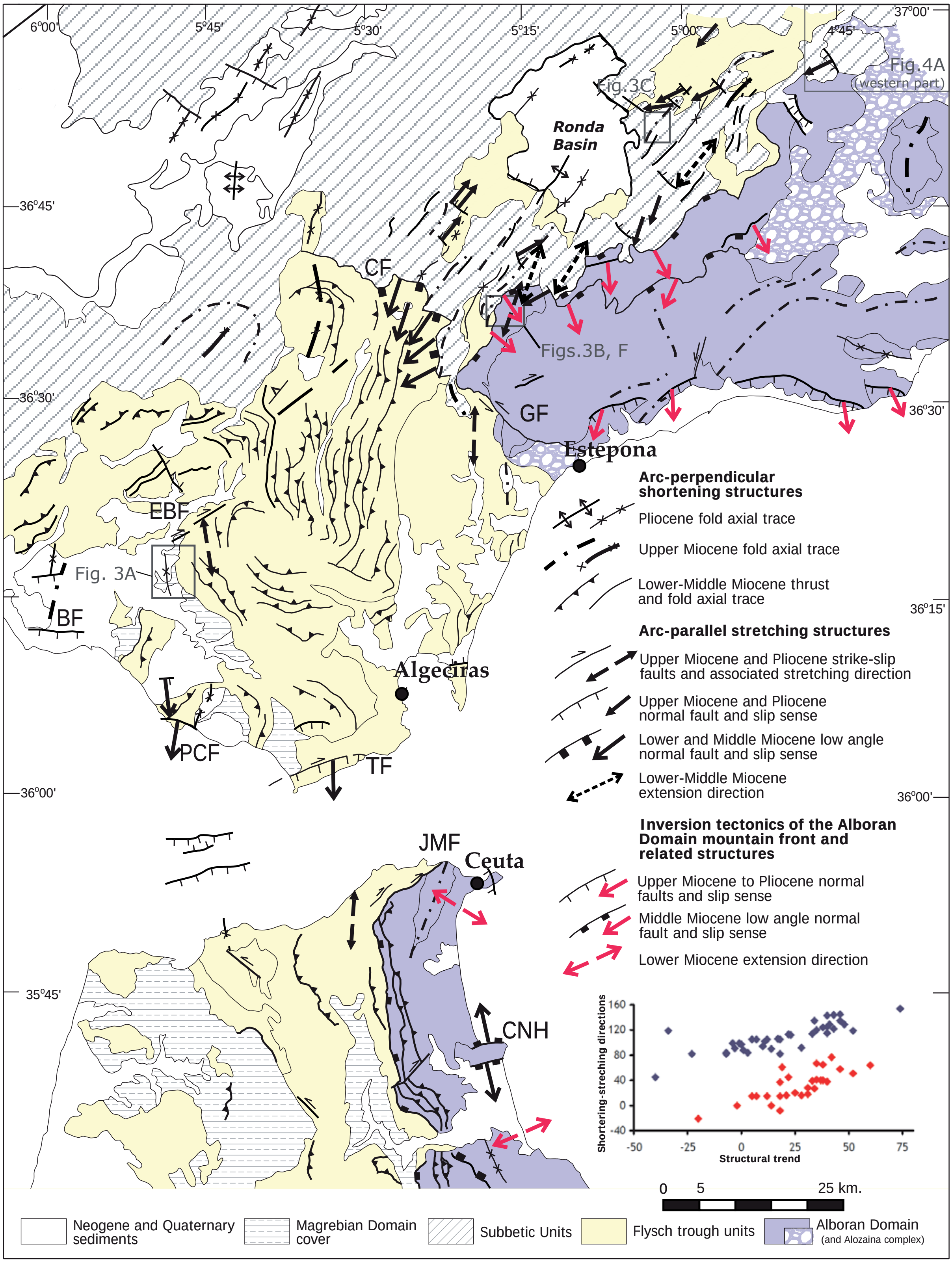

FIGURE 2 | Structural map of the central and northern western Gibraltar arc, with emphasis on strain partitioning modes. See location in Figure 1B. Lower right corner: graph of Neogene shortening (blue dots) and stretching (red dots) directions versus structural trend within the external wedge of the western Gibraltar arc (Subbetic units and Flyschs Trough units). BF: Barbate fault; CF: Colmenar fault; CNH: Cabo Negro Horst; EBF: Embalse de Barbate fault; GF: Gaucín fault; Embalse de Barbate fault; JMF: Jebel Mousa fault; PCF: Punta Camarinal fault; TF: Tarifa fault. Locations of Figures 3A, B, C, F; 4A are shown.

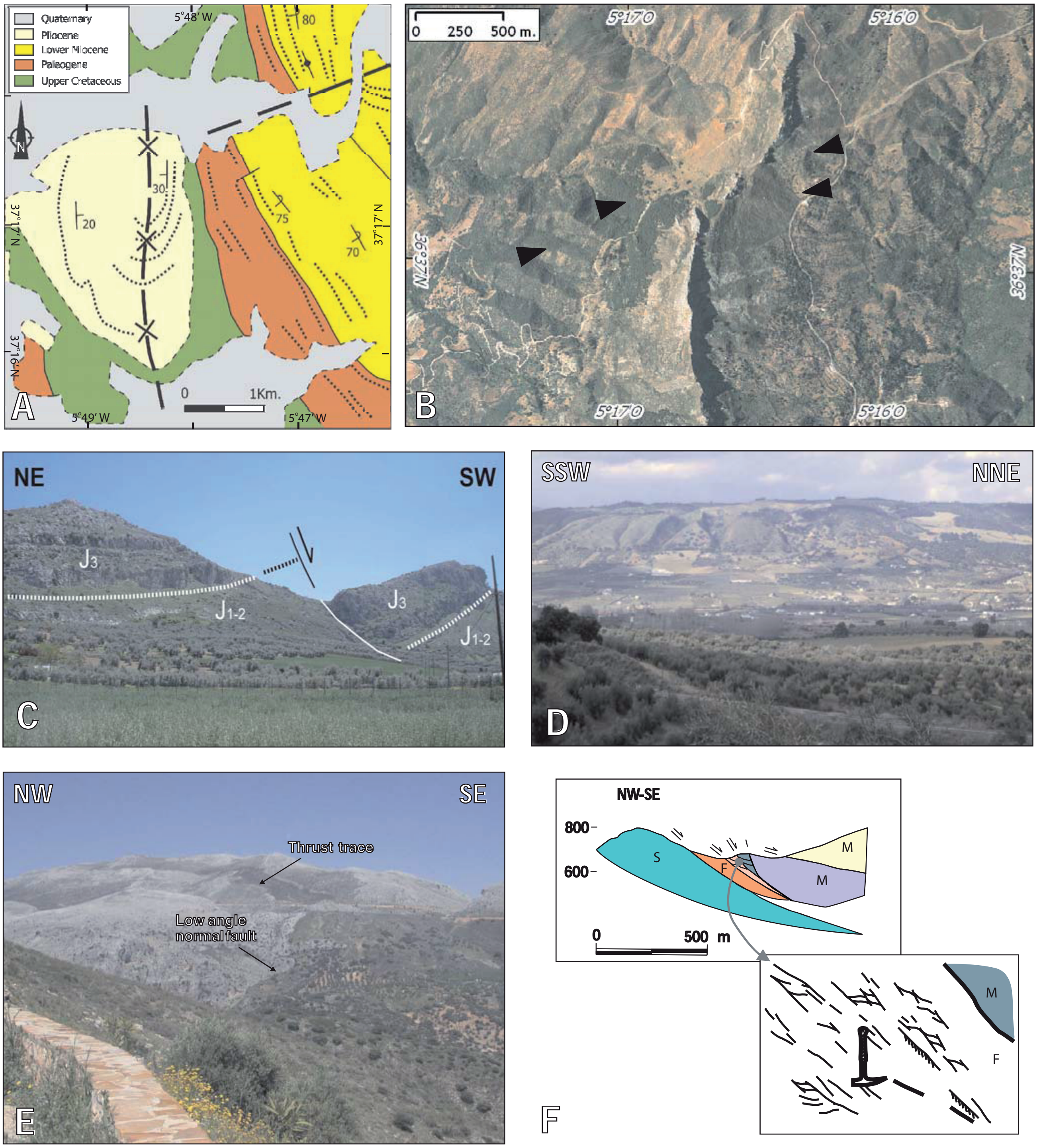

FIGURE 3 | Representative examples of main strain partitioning modes within the western Gibraltar arc. (see locations in Fig. 2). A) Arc-paralell, N-S trending folds affecting Pliocene formations 20km to the North of Gibraltar straits. B) Upper Miocene to Pliocene right handed strike-slip faults (arrows) cutting the western Alborán domain mountain front (crest of Benadalid range) with stretching axis parallel to the dominant structural trend (see it in the left part of photography). C) Normal faults stretching the hinge zone of an Upper Miocene to Pliocene open fold (eastern boundary of Ronda basin; J1-2: Lower and Middle Jurassic; J3: Upper Jurassic). D) Panoramic view of folded Upper Tortonian to Messinian Ronda basin deposits in which the elongate hill (Sierra de Las Salinas) coincides with the anticline axial trace. E-F) Back-arc extension related structures. E) Panoramic view of low angle normal faults affecting the innermost part of the Southiberian units, near the Alborán domain mountain front. F) Cross section of the Middle Miocene Atajate extensional fault zone, 25km to the NNW of Estepona (see location in Fig. 2), showing the extreme thinning of the Flysch complex and a detail drawn from a photograph showing shear sense indicators. S: Southiberian units; F: Flysch complex; M: Alborán domain (Maláguide complex).

to back-arc extension as previously proposed by García-Dueñas *et al.* (1992).

Additionally, in the western Alborán basin, subsidence took place since the Late Pliocene, accompained by extensional tectonics (Comas *et al.,* 1999; De Larouzière, 1999). These results fit well with the fact that a significant part of the Gibraltar arc shoreline runs parallel or even coincides with the trace of younger developed normal faults (Fig. 2).

The recession zones at the eastern ends of the Western Gibraltar arc

In the NE end zone of the western Gibraltar arc, where the structural trend-lines draws a recess pattern, the resulting kinematic map identifies structural associations that differ from those referred in the westernmost parts. A conspicuous 70km long, E-W deformation zone (hereafter the Torcal shear zone) is defined in the South Iberian domain close to the Alborán domain tectonic boundary. This zone corresponds to a general E-W high topographic lineament built up by a set of en echelon small ranges that trend NE to ENE in which the internal Subbetic units of the South Iberian domain (the deeper tectonic units of the orogenic building in this sector) crop out. Deformation is taken up by two main structures (Fig. 4): dextral strike-slip faults, striking E-W or NW-SE, and NE-SW-directed folds and thrusts. Additionally, subordinate NW-SE-striking conjugate extensional faults also develop. Taken together the structural associations of this zone define a roughly E-W, dextral transpressive shear zone, in which strain was highly partitioned.

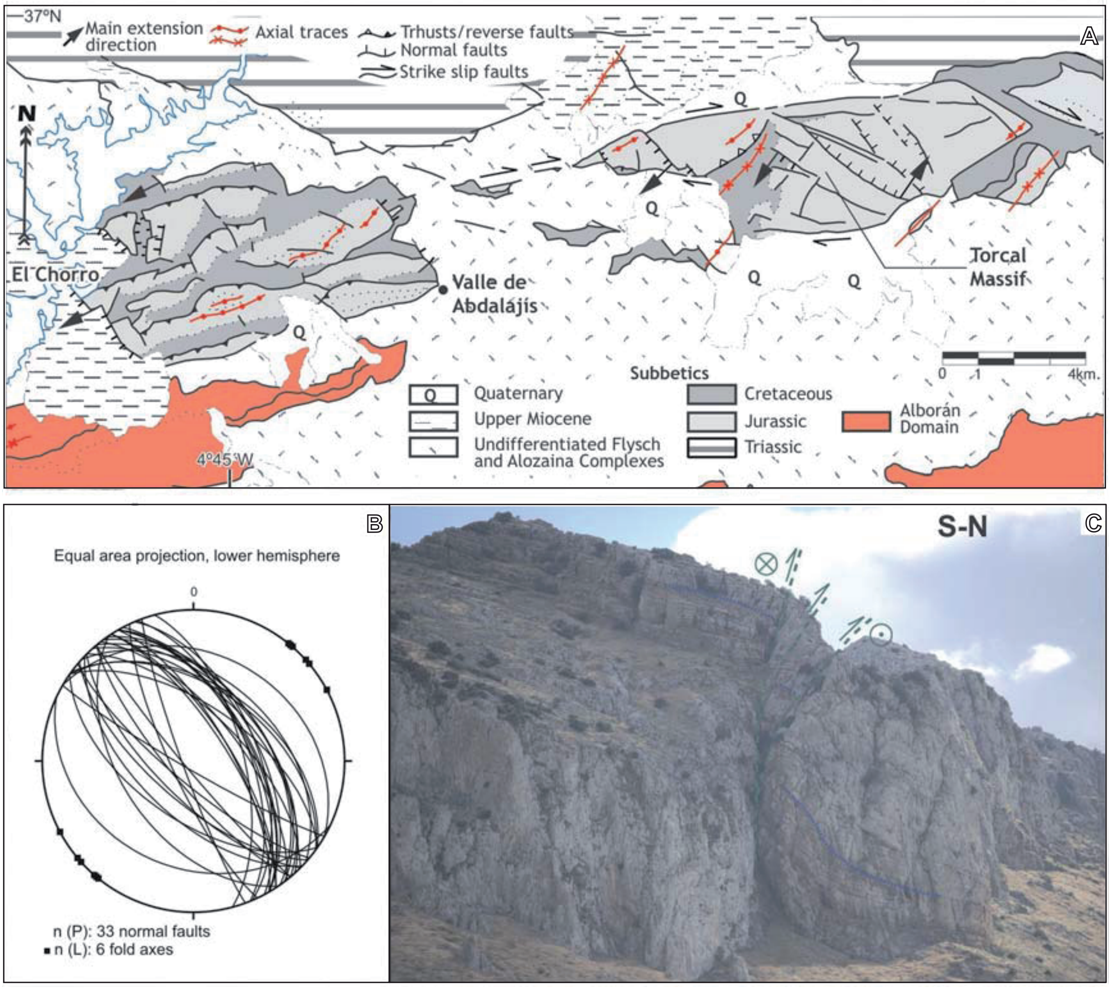

FIGURE 4 | Structural associations characterizing the NE end of the western Gibraltar arc. A) Structural map of the central part of the Torcal shear zone (location in Fig. 2). See relationships among folds and reverse faults, normal faults and strike-slip faults. B) Stereoplot of normal faults within the Torcal massif. C) Flower structure related to right lateral strike-slip fault in the northern boundary of the Torcal massif.

Although these folds and faults of the Torcal shear zone are locally sealed by Upper Miocene formations, we have also mapped other cases in which similar structures (both in geometry and kinematics) clearly affect Upper Miocene rocks (Fig. 4A; see El Chorro normal faults and the Upper Miocene folded rocks 6km to the NE of Valle de Abdalajis). Furthermore, recent activity of both normal and strike-slip faults is suggested by well preserved scarps and, at places, fault planes. In addition, karst evolution within the outcropping South Iberian units in the Torcal massif indicates recent vertical movements among faulted blocks (Moral, 2010).

Like in the northern branch of the western Gibraltar arc, the recess zone at the SE end of the western Gibraltar arc, also located near 4º30'W (Figs. 1; 7), can be related to another strike-slip fault zone, the ENE-WSW Jebha fault zone. This fault zone has a main left-lateral movement (Leblanc and Olivier, 1984; Leblanc, 1990) and was active up to the latest Miocene (Chalouan *et al.,* 1997). To the east, between Al Hoceima and Melilla (Fig. 1C), the NE-SW sinistral Nekor fault and associated deformation zone generates a similar deflection pattern of the structural trend lines (Frizon de Lamotte, 1985). A first stage of the Nekor fault (probably sinistral and extensional) seems to be related to the exhumation of the adjacent external zone (Temsamane) units which record a main metamorphic event of Middle Miocene age (Negro *et al.,* 2007). In a later deformation stage (Upper Miocene), the Nekor fault continued to move with a left-lateral slip.

Present-day strain partitioning as viewed from seismicity data

Strain partitioning is still occurring presently in a complex way. This is evidenced by crustal seismicity (<30km; most of them between 3 and 15km), as the 3D distribution and focal mechanisms of seismic events denote thrust, strike-slip and normal fault events. Earthquakes from 1984-2004 were compiled from the IAG catalogue (n=3600). Time domain moment tensors of local and regional waveforms were applied to shallow earthquakes, of small to moderate magnitude (<30km deep, 1.5<Mw<6.3, respectively). We used the program Focmec (Snoke *et al.,* 1984) included in SEISAN (Havskov and Ottemöller, 2003) to determine fault-plane solutions for P-wave first motion polarities for 167 events, thus greatly improving the available solutions of the western Gibraltar arc area (Stich *et al.,* 2006; Fernández-Ibáñez, 2007). The source parameters of earthquakes analyzed in this paper are listed in Table I, Electronic appendix available at www.geologica-acta.com.

The epicenter map of Figure 1 shows several earthquake concentration zones, three of them located within the western Gibraltar arc (zone A, west of 5ºW) or around the western Gibraltar arc end zones (zones B and C). Outside the concentration zones, seismic foci are scarce and generally of low magnitude.

Focal mechanism solutions belonging to zone A in the external zones (Fig. 5) indicate the coexistence of thrust and normal fault earthquakes. The first type of events shows a shortening axis varying from NW-SE to E-W, whereas the second type indicates nearly N-S extension. These results compare well to thrust earthquakes with nodal planes oriented NE-SW obtained within this zone by Ruiz-Constán *et al.* (2009) and Stich *et al.* (2010), most of them based on earthquakes occurred after 2005. Near the outer boundary of the Alborán domain and close to the shoreline, normal-fault earthquakes with NW-SE direction of extension take place (Fig. 5).

Strike-slip earthquakes are dominant among the solutions belonging to zone B (Fig. 6A, B), although thrust and normal fault earthquakes are also present. Strike-slip events can be divided into two main types, coherent with dextral faults striking E-W and NW-SE. Most of the seismic foci with focal solutions compatible with NW-SE dextral faults depict a conspicuous NW-SE seismogenic lineament located in the Subbetic ranges of the central Betics. Most of shortening axes of thrust earthquakes

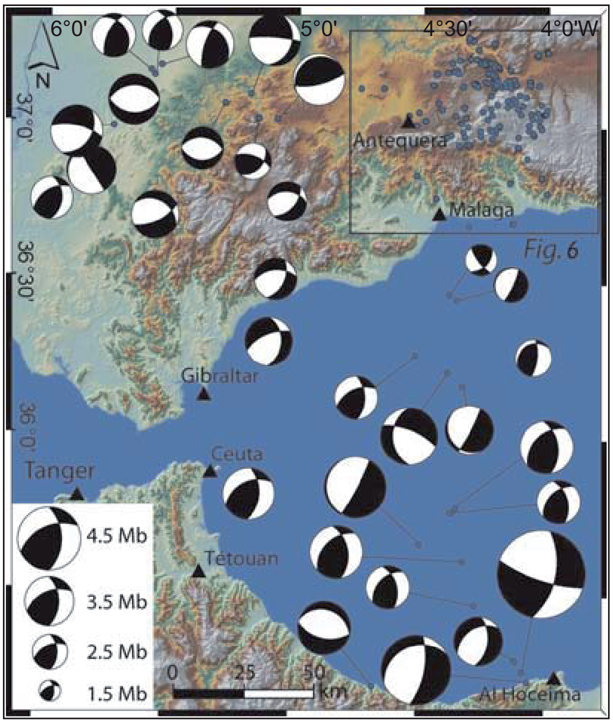

FIGURE 5 | General picture of the calculated focal mechanism solutions in the western Gibraltar arc. Location of Figure 6 is shown.

vary from N-S to NW-SE, being comparable to the main shortening direction reported within the NE end zone of the western Gibraltar arc (Fig. 4). Normal fault solutions indicate variable directions of extension, with a third of the cases indicating a NE-SW-directed extension, as identified in surface geology (Fig. 4).

Zone C, which includes the February 24 Al Hoceima 2004 earthquake (Mw=6.3), shows strike-slip solutions with main shortening axes oriented NNW-SSE, thrust earthquakes with a nearly ESE-WNW shortening axis, and subordinate normal fault earthquakes indicating NW-SE and NE-SW extension (Fig. 5). Tahayt *et al.* (2008) made a combined analysis of the Al Hoceima 2004 earthquake, including remote sensing satellite data and ground rupture mapping, and proposed this earthquake to be part of a major NNE-SSW complex seismogenic fault zone that bounds two main Rif blocks.

Furthermore, zones A, B and C include solutions (10% of the total) with a flat (<15º in deep) nodal plane (see Table I). This probably indicates subhorizontal shear surfaces, but variability in depth among the analyzed cases (1.3 to 29km) suggests that they do not represent regional decoupling levels (Huang *et al.,* 1996).

DISCUSSION

We have presented strong evidence –on the basis of our results and compiled data from the literature– about the distinctive tectonic features of the western Gibraltar arc. They appear both in structure development and geophysic features when the western Gibraltar arc is compared with its north and south ending zones and the easternmost parts of the arc. Differences include, as one of their principal aspects, characteristic extensional strain partitioning modes linked to radial outward shortening. In the external wedge, widely represented arc-parallel extension appears to be the most important case.

Age and tectonic significance of strain partitioning modes: Is the Gibraltar forearc still active?

The prevailing strain partitioning modes within the western Gibraltar arc seem to have followed similar patterns from 25My onwards, and are characterized mainly by the coexistence of both arc-parallel and back-arc extension. Back-arc extension in the inner side of the orogen developed with centripetal tectonic transport (García-Dueñas and Balanyá, 1991; García-Dueñas *et al.,* 1992; Comas *et al.,* 1999; this paper). Arc-parallel stretching developed together with arc-perpendicular shortening and associated centrifugal tectonic transport in the outer wedge. We have shown that this regime, pointed out for the Miocene by Balanyá *et al.* (2007), can be identified in a broader area than previously recognized (including the seafloor of the Gibraltar strait and the vicinity of the Guadalquivir foreland basin) and their age reconsidered. Indeed, the results obtained over the external wedge and the Alborán domain mountain front suggest it is still active, as the Pliocene deposits are deformed following a comparable pattern and most focal mechanism solutions of the crustal seismic events are compatible with the kinematics of previously developed structures. It is interesting to note that in the external neogene basins of the central Rif, polyphase deformation (leading up to positive inversion tectonics) was active up to Plioquaternary times (Michard *et al.,* 1996; Samaka *et al.,* 1997). Additionally, recent works carried out in the Rif deformation front (in the so-called Prerif Ridges, located at the SW corner of

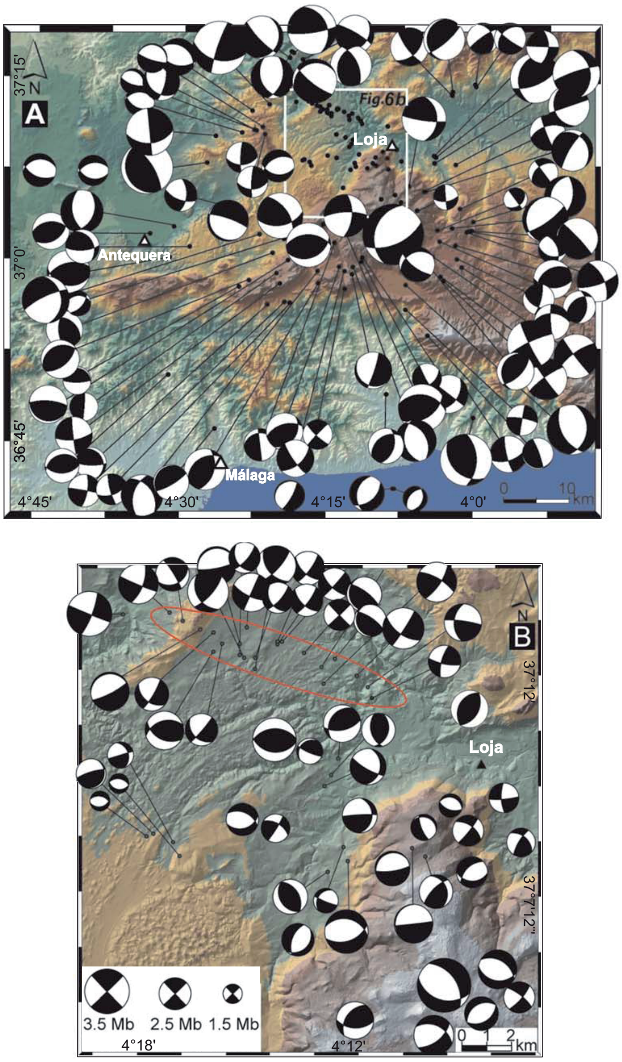

FIGURE 6 | A) Detailed map of earthquake concentration zone B (see location in Figs. 1B; 5). B) Close-up of the northern part of zone B; note that strike-slip earthquakes are dominant. The seismogenic lineament mentioned in the text is shown as an elongate ellipse.

Fig. 1A), have evidenced Pliocene and Quaternary outward thrusting: to the S or SSE in the segments oriented E-W (Bargach *et al.,* 2004) and towards the W in the segments oriented N-S (Roldán-García *et al.,* 2009). Such variation has been explained as a general movement toward the SW of large tectonic wedges (Chalouan *et al.,* 2006a).

In addition, seismic foci located inside the Alborán domain area (including its outer boundary) show extension perpendicular to the shoreline, probably related to present day centripetal back-arc extension towards the Alborán sea (Fig. 7). All seismic data indicate a heterogeneous stress field in which thrust, strike-slip and normal fault earthquakes coexist. Within this context, the end zones of the western Gibraltar arc are the regions where active deformation is more intense and wrench tectonics control strain partitioning modes. In the northeastern ending zone of the western Gibraltar arc we have characterized a well defined dextral transpressive shear zone (the Torcal shear zone), in which strain is highly partitioned.

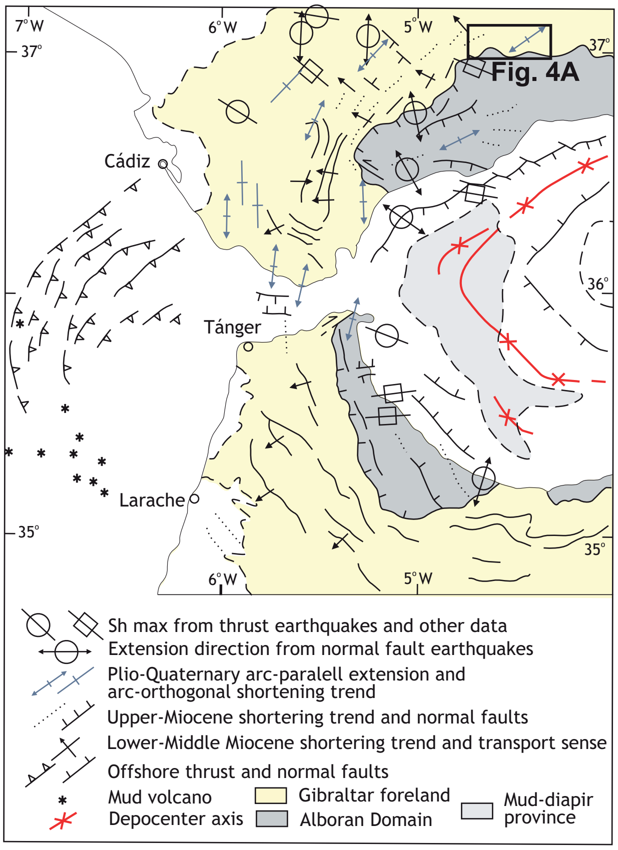

FIGURE 7 | Summary of structural trend-line pattern and main tectonic transport directions (arrows) along the western Gibraltar arc during the last 25My. Offshore data in the gulf of Cadiz from Medialdea et al. (2004); mapped back-arc extensional faults within the western Alborán basin from Comas *et al.* (1999); representative shortening and extensional directions deduced from focal mechanisms solutions are plotted to compare results (see discussion); square symbols correspond to Fernandez-Ibáñez and Soto (2008) data obtained from borehole, hydraulic fractures and focal mechanisms.

Around the hinge zone of the western Gibraltar arc, the permanence up to the Pliocene, and even to present, of a shortening axes radial pattern (and arc-parallel associated extension) suggests that deformation does not result from the simple overprinting of the Eurasia-Africa convergence over a previously locked Gibraltar arc (calc-alkaline volcanism ceased around 7Ma; Duggen *et al.,* 2005), but represents the late stage of a westward migrating collisional arc which started to form at 25Ma. Indeed, the maximum stress axes of the seismic events strongly differ from those expected in relation to present-day Eurasia-Africa NW-SE convergence (model NUVEL 1A; DeMets *et al.,* 1994) in a large number of analyzed cases.

All these data are coherent with strain partitioning associated with an arc formation mode close to the piedmont glacier type (Hindle and Burkhard, 1999; Balanyá *et al.,* 2007), and the westward migration of the Gibraltar arc mountain front (García-Dueñas *et al.,* 1992), from the Lower Miocene to Present. This also fits with two main features of the offshore geology: i) the position and shape of the ongoing westward accretionary wedge identified in the gulf of Cádiz, in which E-W striking seismic profiles show emergent thrusts, developed above an eastward very gently dipping main detachment level, that offset the sea floor topography, (Gutscher *et al.,* 2002; Thiebot and Gutscher, 2006); and ii) the extensionally-controlled Pliocene depocenters developed in the western Alborán basin (Comas et al, 1999; Fig. 7).

Checking previously proposed lithospheric models

The genesis of the Gibraltar arc has for a long time been controversial. Tectonic evolution, depth distribution of shallow and intermediate earthquakes, seismic tomography, and geodetic data have been used to suggest either mantle lithosphere delamination following different directions (García-Dueñas *et al.,* 1992; Docherty and Banda, 1995; Seber *et al.,* 1996; Fadil *et al.,* 2006) or subduction retreat beneath the Gibraltar region (Royden, 1993; Thiebot and Gutscher, 2006; Faccenna *et al.,* 2004), whereas volcanic geochemical zonation and the crustal structure in the back-arc domain suggest a combination of both mechanisms (Duggen *et al.,* 2005; Booth-Rea *et al.,* 2007).

The prevailing strain partitioning modes in the western Gibraltar arc region presented in this paper show a continuous Lower Miocene to Present, back-arc extension coexisting with arc-parallel stretching and arc-perpendicular shortening in the outer wedge. These results are not explained by the models that assume a N-S dipping continental subduction zone (Serrano *et al.,*

FIGURE 6 |

1998; Morales *et al.,* 1999) or N-S delaminated lithosphere (Fadil *et al.,* 2006). The results also argue against the Neotectonic transpressive models evoked for the Europe-Africa deformation zone (Morel and Meghraoui, 1996). In fact, our results indicate that within the western Gibraltar arc, strain partitioning modes do not express a general transpressive regime, which is only identified in the two eastern recess zones of the western Gibraltar arc. On the other hand, our results are partially coincident with those of Pedrera *et al.* (2011) who consider that only part of the subduction beneath the Gibraltar arc is still active (the part of the subduction slab oriented N30º-40ºE). In addition to the different type and/or location of geological data used, the data base of moment tensor solutions taken into account in Pedrera *et al.* (2011) also differs from ours, since seismic events used by the authors are of Mw>3.5 and both crustal and subcrustal earthquakes are considered (down to 60km in depth). In both cases, most of them are located east of 4º30'W.

Although the westward movement of the Gibraltar area relative to stable Iberia and Africa (Nubia) probably slowed down (5mm/y) in recent times (GPS data from Serpelloni *et al.,* 2007; Stich *et al.,* 2006; Fernandes *et al.,* 2007), our results suggest that a lithospheric mechanism, still active, is driven by an east-dipping subduction-rollback zone and/or delaminated continental lithospheric mantle in the western end of the proposed slab-segmented western Mediterranean subduction zone of Faccenna *et al.* (2004). The geometry and origin of the deep slab identified by tomographic images beneath the Alborán sea (Blanco and Spakman, 1993; Spakman and Wortel, 2004) is controversial, but recent work based on wave form analysis suggests it is nearly N-S trending in the Gibraltar area and more likely oceanic in nature (Bokelmann and Maufroy, 2007; Bokelmann *et al.,* 2010). The western Gibraltar arc retreating was coupled with back-arc extension. The concomitant westward migration of the extending back-arc area finally reached the forearc region (inner parts of the western Gibraltar arc) surrounded by the outer part of the forearc belt that continues to undergo arc-parallel extension.

CONCLUSIONS

Within the western Gibraltar arc, strain partitioning followed a characteristic pattern during the Miocene to Plio-Quaternary in which two extensional-type modes can be spatially and kinematically differentiated. The structural record evidences that coevally to outward radial thrusting, the external wedge underwent arc-parallel stretching while the inner zones (Alborán domain) underwent centripetal extension related to the development of the Alborán back-arc basin. Decoupling between the two extensional modes roughly coincides with the Alborán domain outer tectonic boundary.

Kinematics of the ending (recession) zones of the western Gibraltar arc and the resulting strain partitioning modes differ from the rest of the western Gibraltar arc. In these zones, located near the 4º30'W, transpressive tectonics dominated from the Upper Miocene to the Quaternary. The northeastern ending zone (the here defined Torcal shear zone) corresponds to a highly partitioned E-W brittle-ductile dextral shear zone located at the Internal-External zones tectonic boundary. The Torcal shear zone is responsible for the uplifting of the innermost Subbetic units in the core of NE-SW antiforms. This structure has built a characteristic relief of en echelon ranges that trend oblique to the major strike-slip faults. Moderate NE-SW stretching favoured by conjugate normal fault systems also occurs.

Focal mechanism solutions from crustal earthquakes (1,5<Mw>6,3; D<30km) over the western Gibraltar arc point to a highly partitioned strain at present. Solutions of 167 events include examples of all the cases evidenced by the Miocene and Pliocene structural record: i) thrust fault earthquakes with intermediate stress axis approximately following up the regional structural trend; ii) normal fault earthquakes indicating arc-parallel stretching in the external wedge and, within the Alborán domain area and western Alborán basin, arc-perpendicular extension; and iii) strike-slip fault earthquakes mostly occurring at the ending zones of the western Gibraltar arc. Other cases not directly comparable with identified surface structures include solutions characterized by a very flat nodal plane, which can be interpreted as subhorizontal shear surfaces but not as regional decoupling levels.

The new structural data and focal solutions reported in this paper taken together with available offshore data of the western Alborán basin and the gulf of Cadiz, allow us to conclude that the external wedge of the western Gibraltar arc has continued acting as a westward migrating forearc tectonic zone from the Miocene to Present. Neither the Miocene nor the Plio-Quaternary arcuate trend line pattern associated with radial shortening, coevally developed with arc-parallel extension in the outer wedge and coupled by back-arc extension in the inner part of the western Gibraltar arc, can be explained by the solely N-S to NW-SE Europe-Africa convergence.

Evidence about the distinctive tectonic features of the western Gibraltar arc respective to the easternmost parts of the Betic-Rifean orogen is grounded both in structure development (strain partitioning in particular) and geophysical characteristics. This E-W asymmetry of the Betic-Rifean orogen has been built during the Miocene to Plio-Quaternary. In this context, our results suggest the existence of a lithospheric mechanism, still active, responsible for the arc-parallel/back-arc extension couple that finally results in a convex-to-the-west very tight arc. This tectonic scenario is probably driven by an east-dipping subduction-rollback zone and/or delaminated continental lithospheric mantle, developed at the western end of the slab-segmented western Mediterranean subduction zone. Our results fit well with the strong evidence presented by Bokelmann *et al.* (2010), based on body waves dispersion analysis, of a nearly N-S trending oceanic slab beneath the Gibraltar strait area.

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ELECTRONIC APPENDIX

TABLE I | Source parameters of earthquakes analysed in this study

Event number	Event date	Origin time	Lat, deg	Long, deg	Number of stations	Z, km	Best fitting double couple (strike/dip/rake)		Magnitude mb
1	19840831	7 : 16 : 34.6	-4.00	36.79	8	5	225 / 42 / 0	91 / 58 / 0	3.5
2	19841017	13 : 45 : 26.4	-4.26	37.05	8	11	159 / 41 / 75	359 / 51 / 103	3
3	19851209	0 : 54 : 25.0	-4.01	37.04	6	13	161 / 76 / 27	64 / 64 / 164	2.8
4	19850214	1 : 1 : 41.8	-4.24	37.18	9	5	358 / 48 / 85	186 / 42 / 96	3.5
5	19850215	2 : 28 : 25.0	-4.15	37.14	5	11	35 / 61 / -7	129 / 84 / -151	2.5
6	19850216	2 : 36 : 40.9	-4.19	37.13	9	5	172 / 78 / -85	328 / 13 / -113	2.8
7	19850221	14 : 13 : 12.2	-4.21	37.13	8	4	238 / 40 / 90	58 / 50 / 90	2.8
8	19851231	4 : 20 : 46.0	-4.39	36.22	10	20	270 / 41 / -27	22 / 72 / -128	4.1
9	19850214	5 : 9 : 25.9	-4.15	37.13	8	1	182 / 42 / -53	316 / 58 / -119	2.5
10	19850215	7 : 34 : 53.6	-4.18	37.14	7	13	174 / 89 / -84	273 / 6 / -171	3.1
11	19851002	8 : 3 : 35.6	-4.22	37.04	11	15	149 / 53 / 65	7 / 44 / 120	3.2
12	19850217	10 : 9 : 13.3	-4.22	37.16	7	7	100 / 33 / -23	210 / 78 / -121	2.9
13	19850215	17 : 55 : 28.5	-4.25	37.15	6	10	23 / 53 / -65	164 / 44 / -120	2.6
14	19850223	18 : 1 : 55.3	-4.21	37.13	10	10	13 / 41 / -65	161 / 54 / -110	3.5
15	19850710	19 : 31 : 59.3	-4.02	36.84	7	5	161 / 62 / -12	257 / 80 / -152	2.5
16	19850212	20 : 50 : 59.9	-4.21	37.16	5	8	256 / 53 / 71	105 / 41 / 113	2.7
17	19851114	22 : 21 : 23.4	-5.08	37.02	11	20	331 / 16 / 76	166 / 74 / 94	3.7
18	19850213	22 : 39 : 58.4	-4.20	37.15	9	5	93 / 30 / 7	357 / 87 / 120	2.8
19	19850213	23 : 38 : 2.5	-4.21	37.17	10	5	306 / 36 / 54	168 / 62 / 113	3
20	19860813	2 : 54 : 3.6	-4.20	37.08	7	10	306 / 49 / 46	182 / 57 / 129	3
21	19861020	3 : 3 : 23.0	-4.16	37.09	14	9	55 / 53 / -65	197 / 44 / -120	4.3
22	19861104	3 : 21 : 28.9	-4.23	37.06	5	10	357 / 76 / -27	95 / 64 / -164	2.9
23	19860719	11 : 22 : 35.2	-4.14	37.09	6	9	30 / 51 / -77	190 / 41 / -105	3.1
24	19860720	12 : 55 : 6.2	-4.14	37.08	6	9	329 / 42 / -90	149 / 48 / -90	2.7
25	19860829	15 : 48 : 9.8	-4.07	37.15	6	15	284 / 33 / 42	156 / 68 / 116	3.4
26	19860717	15 : 57 : 5.8	-4.12	37.06	9	8	156 / 63 / -62	286 / 38 / -133	4.1
27	19860829	16 : 0 : 2.4	-4.07	37.15	5	11	183 / 90 / 30	93 / 60 / 180	2.2
28	19860718	17 : 19 : 32.5	-4.16	37.07	9	8	25 / 48 / -38	142 / 63 / -131	3.2
29	19860508	21 : 4 : 33.9	-4.27	36.97	5	7	106 / 53 / 65	324 / 44 / 120	2.8
30	19860804	23 : 18 : 41.2	-5.66	37.07	6	10	184 / 45 / -86	358 / 45 / -94	3.6
31	19870605	1 : 13 : 43.7	-4.12	36.97	17	5	98 / 40 / -61	242 / 56 / -112	3.4
32	19870809	1 : 14 : 22.3	-5.10	36.31	15	1	337 / 68 / -51	91 / 44 / -147	3.4
33	19870925	19 : 17 : 47.9	-4.69	37.10	15	31	1 / 59 / 84	192 / 31 / 100	3.1
34	19870701	21 : 48 : 5.2	-5.19	37.10	25	8	4 / 82 / -57	106 / 34 / -166	3.7
35	19870822	21 : 58 : 53.8	-4.07	37.01	10	10	324 / 76 / 4	233 / 86 / 165	3
36	19881203	2 : 40 : 58.8	-4.17	37.13	8	5	70 / 36 / 31	315 / 73 / 122	2.7
37	19881121	7 : 9 : 31.0	-4.22	37.17	10	12	317 / 22 / 26	203 / 81 / 110	2.1
38	19881004	13 : 20 : 57.3	-4.44	36.77	6	3	307 / 11 / 68	149 / 80 / 94	2.4
39	19881010	13 : 37 : 50.9	-4.52	36.84	8	2	341 / 37 / 77	178 / 54 / 100	2.3
40	19880804	20 : 40 : 10.3	-4.06	37.03	5	17	96 / 52 / 59	321 / 47 / 124	2.2
41	19890608	4 : 19 : 54.0	-4.66	37.12	10	2	192 / 43 / -72	349 / 49 / -106	3.1
42	19890608	4 : 48 : 55.6	-4.75	37.12	15	16	202 / 57 / -73	353 / 36 / -114	3.4
43	19890113	4 : 48 : 6.0	-4.33	37.03	9	9	354 / 36 / -54	133 / 62 / -113	1.7
44	19890215	7 : 43 : 13.8	-4.03	37.01	9	13	206 / 51 / 17	105 / 77 / 140	2.1
45	19890817	8 : 52 : 41.7	-4.11	37.05	6	13	217 / 73 / -58	333 / 36 / -149	2.4
46	19890808	10 : 23 : 22.2	-4.14	36.69	6	1	141 / 53 / -65	283 / 44 / -120	2.4
47	19890107	14 : 43 : 10.6	-4.27	35.47	8	5	75 / 56 / 48	314 / 52 / 135	3.1
48	19890725	22 : 35 : 49.1	-4.04	37.05	13	11	145 / 78 / -78	278 / 17 / -136	3.1
49	19900719	0 : 2 : 38.6	-4.28	37.14	9	10	73 / 40 / 0	343 / 90 / 130	2.1
50	19900719	0 : 16 : 5.0	-4.29	37.14	9	10	116 / 14 / 45	343 / 80 / 100	2.4
51	19900719	0 : 17 : 39.8	-4.31	37.14	9	9	88 / 31 / 17	343 / 81 / 120	1.5
52	19900719	0 : 30 : 15.6	-4.30	37.14	5	9	10 / 51 / -77	170 / 41 / -105	1.6
53	19900417	1 : 2 : 39.9	-4.22	36.97	13	8	223 / 81 / -3	314 / 87 / -171	2
54	19900928	3 : 51 : 37.3	-4.46	37.14	10	7	57 / 72 / 87	247 / 18 / 100	3.5
55	19901223	4 : 51 : 5.0	-4.42	37.06	10	4	239 / 13 / -51	19 / 80 / -98	2.8
56	19901001	7 : 32 : 1.1	-4.23	37.00	9	8	127 / 37 / 59	343 / 59 / 111	2.5
57	19900927	7 : 58 : 30.0	-4.03	37.08	9	15	53 / 90 / 42	323 / 48 / 180	2
58	19900911	8 : 6 : 22.8	-4.00	37.25	8	6	66 / 36 / 14	325 / 82 / 125	1.6
59	19900904	8 : 59 : 12.8	-4.24	37.14	9	8	122 / 85 / 30	29 / 61 / 174	2.3
60	19901217	9 : 58 : 1.6	-4.44	37.08	8	16	95 / 61 / -28	200 / 66 / -147	2.2
61	19900711	15 : 35 : 47.0	-4.10	37.07	8	10	173 / 63 / -3	265 / 88 / -153	1.7
62	19901114	15 : 43 : 34.2	-4.09	37.10	8	17	301 / 79 / -66	54 / 27 / -155	2.8
63	19901224	18 : 19 : 28.9	-4.02	37.00	8	9	267 / 84 / -40	2 / 51 / -172	2.4
64	19900718	18 : 46 : 48.5	-4.16	37.15	5	15	19 / 30 / -90	199 / 60 / -90	1.9
65	19900909	19 : 2 : 29.3	-4.00	37.24	9	9	216 / 82 / -50	315 / 41 / -168	1.6
66	19900910	19 : 24 : 6.6	-4.10	36.64	5	8	12 / 74 / 82	220 / 18 / 117	1.5
67	19901225	19 : 59 : 42.4	-4.51	37.05	12	4	115 / 44 / -60	256 / 53 / -115	2.9

TABLE I | (continued)

Event number	Event date	Origin time	Lat, deg	Long, deg	Number of stations	Z, km	Best fitting double couple (strike/dip/rake)		Magnitude mb
68	19901114	20 : 34 : 45.7	-4.09	37.10	8	19	249 / 85 / -30	342 / 61 / -174	2.4
69	19900718	23 : 47 : 32.7	-4.28	37.15	7	9	147 / 72 / -84	307 / 19 / -109	1.5
70	19911007	0 : 6 : 58.8	-5.58	37.16	18	5	74 / 55 / 47	312 / 53 / 134	2.9
71	19910128	1 : 4 : 49.1	-4.05	36.98	7	12	234 / 87 / -9	324 / 81 / -177	2.8
72	19910209	3 : 51 : 40.1	-4.03	37.14	9	19	251 / 30 / 0	161 / 90 / 120	2.8
73	19911211	11 : 45 : 22.1	-4.52	36.27	3	6	90 / 57 / 40	335 / 57 / 140	3.1
74	19911007	15 : 16 : 28.4	-5.55	37.19	13	9	43 / 36 / 28	289 / 74 / 122	3.4
75	19911007	15 : 23 : 35.3	-5.59	37.17	14	7	56 / 39 / 37	295 / 68 / 123	3.1
76	19910503	17 : 16 : 1.7	-4.06	37.05	8	15	233 / 90 / 50	143 / 40 / 180	1.6
77	19910425	19 : 16 : 32.2	-4.21	37.14	9	16	202 / 83 / -58	303 / 33 / -167	2
78	19910425	19 : 23 : 25.6	-4.07	37.14	19	5	81 / 41 / 12	342 / 82 / 130	3.2
79	19910425	19 : 24 : 13.2	-4.14	37.16	7	16	176 / 83 / -14	267 / 76 / -173	2.4
80	19910425	19 : 30 : 49.2	-4.17	37.15	9	17	248 / 75 / -73	20 / 22 / -136	2.1
81	19910425	19 : 39 : 21.0	-4.13	37.14	5	15	41 / 53 / 16	301 / 77 / 142	2.3
82	19910531	20 : 54 : 57.9	-4.03	37.00	4	14	79 / 61 / 78	282 / 31 / 109	1.5
83	19911024	23 : 1 : 8.9	-4.15	37.19	10	3	120 / 50 / 90	300 / 40 / 90	3
84	19910102	23 : 23 : 54.6	-4.06	36.98	13	12	244 / 85 / -9	335 / 81 / -175	3.2
85	19931211	1 : 40 : 56.7	-4.32	37.00	7	8	4 / 75 / 85	203 / 16 / 109	2.6
86	19930116	3 : 55 : 1.7	-4.52	37.01	8	2	347 / 57 / 76	192 / 36 / 111	2.9
87	19930304	8 : 11 : 13.5	-4.01	37.05	6	7	69 / 59 / -54	194 / 46 / -134	1.9
88	19931210	12 : 4 : 30.7	-4.39	36.98	6	6	141 / 60 / 83	334 / 31 / 102	2.6
89	19931212	18 : 43 : 27.0	-5.08	36.51	7	7	356 / 55 / -44	115 / 55 / -136	3
90	19930829	23 : 57 : 2.3	-5.29	37.07	7	10	6 / 48 / -86	180 / 42 / -94	3
91	19940125	3 : 40 : 40.6	-4.32	37.28	9	8	112 / 22 / -26	226 / 81 / -110	2.9
92	19940227	5 : 51 : 36.8	-4.30	37.28	12	7	133 / 32 / 15	30 / 82 / 121	2.6
93	19940120	6 : 32 : 37.5	-4.31	37.29	16	8	172 / 80 / 53	69 / 38 / 164	3.3
94	19940104	11 : 34 : 55.5	-5.15	37.02	8	3	134 / 48 / 34	20 / 65 / 133	2.6
95	19941114	14 : 31 : 6.1	-4.04	37.23	8	13	233 / 77 / 38	133 / 53 / 164	2.6
96	19940129	17 : 5 : 2.8	-4.22	37.27	11	9	65 / 63 / 63	293 / 38 / 132	2.8
97	19940620	19 : 26 : 26.4	-4.01	37.05	9	12	47 / 85 / 88	249 / 5 / 112	2.8
98	19940810	20 : 5 : 13.7	-4.45	37.17	8	7	265 / 90 / 40	175 / 50 / 180	3.2
99	19940127	21 : 21 : 50.1	-4.32	37.29	11	7	106 / 53 / -65	247 / 44 / -120	2.9
100	19950207	1 : 58 : 2.4	-5.98	36.75	20	15	93 / 48 / 48	327 / 56 / 127	3
101	19951123	2 : 33 : 20.0	-4.49	37.02	6	8	176 / 72 / 58	60 / 36 / 148	2.3
102	19951009	8 : 30 : 7.2	-4.35	37.01	8	5	31 / 41 / 41	268 / 64 / 124	2.5
103	19950917	14 : 42 : 21.9	-4.12	36.94	8	12	280 / 88 / -10	10 / 80 / -178	2.1
104	19950107	14 : 46 : 59.2	-5.56	36.70	17	3	31 / 37 / -40	154 / 67 / -121	3.4
105	19950206	14 : 52 : 0.7	-5.82	36.84	16	1	328 / 8 / 0	238 / 90 / 98	3.5
106	19950825	19 : 58 : 6.8	-4.37	37.04	10	9	335 / 78 / -58	83 / 34 / -158	3.2
107	19950210	20 : 26 : 34.1	-4.11	35.29	12	6	328 / 46 / -49	97 / 57 / -124	3.5
108	19951127	21 : 54 : 18.5	-4.38	37.18	7	8	47 / 22 / -63	198 / 70 / -101	1.7
109	19951004	23 : 16 : 50.4	-4.05	36.27	7	0	96 / 73 / 69	329 / 27 / 140	2.6
110	19951127	23 : 18 : 19.8	-4.37	37.19	5	9	19 / 10 / -90	199 / 80 / -90	2
111	19950223	23 : 42 : 26.7	-4.21	36.99	12	7	108 / 84 / -72	215 / 19 / -162	2.5
112	19951127	23 : 55 : 41.6	-4.40	37.18	7	7	202 / 51 / -77	2 / 41 / -105	2
113	19961010	1 : 37 : 12.2	-4.38	37.18	7	14	103 / 73 / -58	219 / 36 / -149	2.5
114	19960622	2 : 43 : 40.7	-4.19	37.00	8	8	146 / 51 / -8	241 / 84 / -140	2
115	19960620	9 : 26 : 54.2	-4.19	37.01	7	10	127 / 50 / 0	37 / 90 / 140	2.6
116	19960802	10 : 30 : 21.4	-4.40	36.97	6	7	179 / 78 / 84	26 / 13 / 117	1.9
117	19961010	12 : 15 : 21.2	-4.36	37.18	7	8	273 / 84 / 40	177 / 51 / 172	2.1
118	19960309	13 : 1 : 3.1	-4.35	36.94	5	9	181 / 79 / 72	60 / 22 / 147	2.1
119	19960618	13 : 58 : 53.0	-4.67	35.21	6	9	17 / 32 / -86	193 / 58 / -92	3.8
120	19960208	14 : 12 : 46.0	-4.32	36.95	6	7	100 / 75 / 1	10 / 89 / 165	2.2
121	19960224	15 : 23 : 46.2	-4.24	37.03	6	8	84 / 90 / 60	354 / 30 / 180	2.2
122	19960322	17 : 55 : 1.8	-4.32	36.95	5	8	255 / 80 / 28	160 / 62 / 169	2.1
123	19960620	18 : 33 : 21.7	-4.21	37.00	8	9	259 / 45 / -76	59 / 47 / -104	2.8
124	19970815	2 : 38 : 42.3	-4.27	36.99	8	9	286 / 56 / -53	53 / 48 / -132	2.8
125	19971209	3 : 24 : 38.2	-4.33	36.97	8	8	172 / 70 / -4	263 / 87 / -160	2.5
126	19970616	13 : 2 : 34.6	-4.33	37.06	8	9	170 / 54 / 37	56 / 61 / 138	3.1
127	19970318	14 : 30 : 55.3	-4.38	37.21	6	13	33 / 41 / -75	193 / 51 / -103	2.5
128	19970322	23 : 59 : 59.7	-4.04	37.24	9	15	272 / 17 / 44	139 / 78 / 102	2.8
129	19980413	3 : 55 : 31.7	-4.25	37.20	6	12	232 / 53 / 16	132 / 77 / 142	3.2
130	19980414	4 : 8 : 4.4	-4.24	37.21	6	10	132 / 87 / -20	224 / 70 / -176	2.6
131	19980418	4 : 15 : 59.4	-4.20	37.19	8	9	285 / 75 / 13	192 / 77 / 164	2.6
132	19980413	4 : 44 : 57.5	-4.22	37.20	6	11	37 / 76 / 82	248 / 16 / 120	2.8
133	19980325	5 : 4 : 12.2	-4.33	36.17	12	29	118 / 84 / -76	230 / 15 / -157	3.5
134	19980420	5 : 6 : 10.7	-4.20	37.20	7	12	8 / 84 / 40	273 / 51 / 172	3
135	19980413	5 : 33 : 33.8	-4.27	37.21	6	10	131 / 86 / -48	226 / 42 / -173	2.6

TABLE I | (continued)

Event number	Event date	Origin time	Lat, deg	Long, deg	Number of stations	Z, km	Best fitting double couple (strike/dip/rake)		Magnitude mb
136	19980413	5 : 49 : 25.5	-4.24	37.21	6	12	127 / 78 / -28	223 / 63 / -167	2.7
137	19980717	6 : 8 : 51.2	-4.13	37.08	8	10	38 / 77 / -12	131 / 78 / -166	2.5
138	19980518	6 : 19 : 2.4	-4.28	37.25	7	13	218 / 79 / -72	339 / 22 / -147	3
139	19980414	8 : 26 : 57.9	-4.24	37.21	6	12	127 / 78 / -28	223 / 63 / -167	2.6
140	19980415	9 : 19 : 30.8	-4.26	37.21	7	12	132 / 75 / -48	238 / 44 / -158	2.5
141	19980422	9 : 43 : 38.9	-4.23	37.10	8	4	138 / 32 / -67	291 / 61 / -104	2.6
142	19980412	9 : 51 : 56.4	-4.28	37.22	6	14	121 / 82 / -41	218 / 49 / -169	2.7
143	19980412	11 : 9 : 0.8	-4.25	37.21	6	9	58 / 83 / -51	157 / 40 / -169	2.7
144	19980412	12 : 36 : 0.6	-4.27	37.22	6	15	351 / 9 / -71	153 / 81 / -93	3.1
145	19980412	12 : 52 : 39.2	-4.29	37.22	7	15	111 / 70 / -4	202 / 87 / -160	3.2
146	19980412	12 : 58 : 34.0	-4.26	37.21	6	12	132 / 75 / -48	238 / 44 / -158	2.5
147	19980412	13 : 10 : 36.0	-4.35	37.22	8	10	289 / 84 / 40	193 / 51 / 172	3.6
148	19980412	15 : 15 : 17.1	-4.31	37.22	8	14	112 / 80 / -2	202 / 88 / -170	3.6
149	19980413	15 : 25 : 5.3	-4.25	37.22	7	11	294 / 90 / 18	204 / 72 / -180	3.1
150	19980815	16 : 3 : 42.5	-4.27	37.21	7	13	343 / 49 / 57	207 / 51 / 122	3.1
151	19980413	17 : 59 : 38.0	-4.26	37.21	6	12	349 / 10 / -90	169 / 80 / -90	3.1
152	19980423	18 : 26 : 4.4	-4.23	37.21	8	12	226 / 89 / 1	136 / 89 / 179	2.5
153	19980417	19 : 56 : 18.9	-4.20	37.20	8	13	123 / 86 / -25	215 / 65 / -175	3.3
154	19980412	22 : 14 : 7.5	-4.25	37.21	6	12	238 / 44 / 22	132 / 75 / 132	3.3
155	19980412	22 : 35 : 37.5	-4.21	37.21	6	11	34 / 75 / 81	247 / 17 / 121	2.6
156	19981230	22 : 35 : 17.6	-4.37	35.76	7	23	228 / 7 / -56	14 / 84 / -94	2.9
157	19980420	23 : 3 : 53.9	-4.22	37.20	8	13	124 / 75 / 17	30 / 74 / 165	3.2
158	19990713	10 : 38 : 52.3	-4.07	36.99	8	9	285 / 27 / 62	135 / 67 / 103	2.5
159	19991110	13 : 10 : 13.6	-4.49	35.66	10	19	118 / 85 / -85	253 / 7 / -135	4.4
160	19991222	19 : 12 : 25.4	-5.04	36.76	6	5	5 / 48 / -48	132 / 56 / -127	2.8
161	19990604	23 : 34 : 23.5	-4.22	36.99	8	9	139 / 62 / -11	235 / 80 / -152	2.5
162	20000719	2 : 28 : 33.4	-4.00	37.06	8	13	280 / 30 / -90	100 / 60 / -90	2.8
163	20001213	8 : 9 : 3.3	-5.17	35.82	9	5	95 / 56 / 48	333 / 52 / 135	3.7
164	20000614	12 : 19 : 57.9	-5.74	36.99	12	11	13 / 71 / -52	126 / 42 / -151	3.7
165	20010721	0 : 2 : 1.6	-4.11	37.11	11	19	188 / 82 / 50	89 / 41 / 168	3
166	20040224	2 : 27 : 46.6	-4.08	35.26	12	12	102 / 63 / -14	198 / 78 / -152	6.3
167	20040307	6 : 37 : 53.1	-4.06	35.22	15	11	336 / 31 / -39	101 / 71 / -116	5