1 **Constraining the crustal root geometry beneath Northern Morocco**

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12 **Abstract**

13 Consistent constraints of an over-thickened crust beneath the Rif Cordillera (N. Morocco) are
14 inferred from analyses of recently acquired seismic datasets including controlled source wide-
15 angle reflections and receiver functions from teleseismic events. Offline arrivals of Moho-
16 reflected phases recorded in RIFSIS project provide estimations of the crustal thicknesses in 3D.
17 Additional constraints on the onshore-offshore transition are inferred from shots in a coeval
18 experiment in the Alboran Sea recorded at land stations in northern Morocco. A regional crustal
19 thickness map is computed from all these results. In parallel, we use natural seismicity data
20 collected throughout TopoIberia and PICASSO experiments, and from a new RIFSIS
21 deployment, to obtain receiver functions and explore the crustal thickness variations with a H- κ
22 grid-search approach. This larger dataset provides better resolution constraints and reveals a
23 number of abrupt crustal changes. A gridded surface is built up by interpolating the Moho depths
24 inferred for each seismic station, then compared with the map from controlled source

experiments. A remarkably consistent image is observed in both maps, derived from completely independent data and methods. Both approaches document a large crustal root, exceeding 50 km depth in the central part of the Rif, in contrast with the rather small topographic elevations. This large crustal thickness, consistent with the available Bouguer anomaly data, favor models proposing that the high velocity slab imaged by seismic tomography beneath the Alboran Sea is still attached to the lithosphere beneath the Rif, hence pulling down the lithosphere and thickening the crust. The thickened area corresponds to a quiet seismic zone located between the western Morocco arcuate seismic zone, the deep seismicity area beneath western Alboran Sea and the superficial seismicity in Alhoceima area. Therefore, the presence of a crustal root seems to play also a major role in the seismicity distribution in northern Morocco.

1 Introduction

The Rif Cordillera forms, together with the Betic Range and the Alboran Basin, the so-called Gibraltar Arc System, one of the tightest orogenic arcs on Earth (Platt et al., 2013). This asymmetric curved mountain belt originated during a Miocene continent-continent collision as a result of the westward motion of the Alboran domain between northwest Africa and Iberia. This continental boundary zone is dominated now by the slow convergence between Nubia and Eurasia. However, clear evidences of extensional tectonics can be observed which require a complex geodynamic scenario to be explained. Diverse and often excluding models have been proposed for the area, involving lithospheric delamination (Seber et al., 1996, Calvert et al., 2000a), slab break-off (Blanco and Spakman, 1993, Zeck, 1996), convective removal (Platt and Vissers, 1989) or active eastward subduction of oceanic crust (Gutscher et al., 2002). Currently, there is a certain agreement on models explaining the area as the result of roll-back of a narrow slab of oceanic lithosphere, resulting from the segmentation of the Western Mediterranean Subduction Zone which was active during Oligocene-Miocene times (Royden, 1993, Lonergan

50 and White, 1997, Rosenbaum and Lister, 2004, Faccenna et al., 2004, Jolivet et al., 2009, Vergés
51 and Fernández, 2012). Nevertheless, large uncertainties remain on major points of such
52 hypothesis. One of the missing knowledge that needs to be fulfilled is on the seismic crustal
53 structure of Morocco, including the topography of the crust-mantle boundary, as very few data are
54 available so far. In the last decade a major effort has been done in this sense, with a significant
55 number of initiatives focused on constraining the regional crustal structure using controlled
56 source experiments, as the RIFSIS (Seismic Investigations across the Rif, Gallart et al, 2012) and
57 SIMA (Active Seismic Investigation across the Atlas; Ayarza et al., 2014) projects. Coeval, large
58 scale projects based on the analysis of natural seismicity, as the TopoIberia (Díaz et al., 2009) and
59 PICASSO (Program to Investigate Convective Alboran Sea System Overturn; Platt et al., 2008)
60 initiatives, have also provided relevant information on the crust, even if their main objective has
61 been at lithospheric and upper mantle scale.

62 This contribution is focused in providing new constraints on the geometrical variations of the
63 crust-mantle boundary beneath North Morocco, using data from active and passive seismic
64 experiments, mostly from the RIFSIS and TopoIberia projects. The RIFSIS project involved the
65 acquisition across the Rif domains of two profiles of ~330 km-length oriented N-S and E-W
66 respectively. The interpretation of both profiles in terms of ray-tracing modeling has been
67 presented by Gil et al., (2014). Here, we will focus on the analysis of complementary data mostly
68 coming from offline recordings, that is, the analysis of shot gathers from stations located outside
69 the corresponding profile. Additionally, taking advantage of a coeval, independent experiment in
70 the Alboran Sea (GASSIS-Westmed project, Gracia et al., 2012) focused in the acquisition of
71 multichannel reflection seismic profiles, we have used inland recordings of air-gun shots fired
72 along the marine transects by the Spanish research vessel, Sarmiento de Gamboa.

73 Concerning natural seismicity, we built up a large database from broad-band stations deployed
74 over the area in different experiments, and we used teleseismic receiver functions (RF) to

estimate crustal depths. The contributing data came not only from the whole periods where the TopoIberia and PICASSO deployments were active, but also from a more recent deployment of 13 stations in the Rif domains within the RIFSIS project. Previous work on the area dealing with RFs (Mancilla et al. 2012, Thurner et al. 2014, Mancilla and Diaz, 2015) came only from first datasets gathered within the former projects.

2 Geological and Geophysical setting

The Rif Cordillera, similarly to the Betic Ranges and other Alpine Mediterranean cordilleras, includes the Internal and the External Zones, separated by Flysch units (Chalouan et al., 2001, 2008). The Internal zones are formed by Paleozoic, Mesozoic and Cenozoic sequences affected by Alpine deformation. The External Zones are formed by units with generally carbonate and pelitic Mesozoic and Cenozoic series, and form a fold-and-thrust belt detached along the Late Triassic evaporitic beds from the thinned continental crust of the North Africa margin. The Flysch units are mainly composed of Cretaceous-Lower Miocene detritic rocks. The main reliefs of the Rif Cordillera are the result of recent compressional structures related to Eurasian-African convergence developing since the Late Miocene.

The main geodynamical feature in the upper mantle is the presence of a step fast velocity slab beneath Alboran, reaching depths close to 600 km. This body, already imaged by Blanco and Spakman (1993) and Spakman and Wortel (2004), has been clearly mapped in the new teleseismic tomographic images obtained from the exploitation of the TopoIberia and PICASSO datasets (Bezada et al., 2013, 2014, Bonnín et al., 2014). Those images suggest that the almost vertical slab tears beneath the Eastern Betics, hence providing an explanation of the uplift rates observed in this zone (García-Castellanos and Villaseñor, 2011). Data from SKS splitting (Buontempo et al., 2008, Diaz et al., 2010, Miller et al., 2013) have evidenced a spectacular

rotation of the inferred fast polarization directions along the Gibraltar arc, interpreted as an evidence of asthenospheric mantle flow deflected around the Alboran Sea fast velocity slab (Alpert et al., 2013, Diaz and Gallart, 2014). Studies based on GPS observations from both permanent and non-permanent sites (Fadil et al., 2006, Vernant et al., 2010, Koulali et al., 2011, Palano et al., 2013) have shown a previously unexpected south to southwest escape of the Rif region, which is interpreted as a wide transpressive zone. To account for those observations, Pérouse et al. (2010) presented a geodynamical model involving dragging from the slab beneath eastern Rif, resulting in a crustal thickening beneath this area. A similar hypothesis, involving an attached slab pulling down the crust beneath the eastern Rif, has been retaken by Palomeras et al. (2014) to explain the recent surface wave tomography models for the western Mediterranean region.

Very scarce seismic profiles beneath the Rif Cordillera and surrounding regions are available, resulting in a poor knowledge of the crustal structure. First explorations carried out in the 1970s using low-dense refraction seismics (Hatzfeld and Bensari, 1977), suggested 30 km crustal depths towards the Gharb Basin. Beneath the Alboran Sea, early wide-angle profiles inferred Moho depths of 18-20 km beneath the central part of the basin (Working Group for Deep Seismic Sounding., 1978). In the late 1980s, new explosion seismic investigations were carried out across the High and Middle Atlas (Wigger et al., 1992), leading to Moho depths close to 35 km beneath the southern limit of the Rif domain.

Crustal models based on the interpretation of elevation and gravity data, in some cases combined with heat flow, geoid and petrological have shown a moderately thick crust underneath the Rif and Betics (~32-34 km), whereas a thin continental crust (~18-22 km) characterizes the Alboran Basin (Torne et al, 2000, Zeyen et al., 2005, Fullea et al. 2014). Normal incidence MCS reflection data has shown that the Alboran basin shows a progressively thinning towards the East, reaching 15 km in the East Alboran basin and 6 km further East, in the Algero-Balearic oceanic basin

(Booth-Rea et al., 2007). The geometry of the Moho beneath Northern Morocco has been investigated using the receiver function methods, mostly from the TopoIberia and PICASSO datasets. Beneath the Rif Cordillera, crustal thickness range from 35 to 53 km, while the northeastern part of Morocco the Moho clearly thins to reach values of 22-30 km (Mancilla et al., 2012, Thurner et al., 2014). The eastern limit of the Rif cordillera, in the transition between both areas, show complex signals admitting different interpretations, but clearly stating the presence of a large crustal root. At subcrustal levels, Thurner et al. (2014) observed a negative polarity RF event beneath the eastern Rif, which has been interpreted as a shallow, recently formed, lithosphere-asthenosphere boundary (LAB).

Concerning the velocity structure, most of the available constrains come from regional tomographic studies. Travel time tomographies based on local seismicity recently obtained beneath the Gibraltar Arc system (El Moudnib et al., 2015) have shown low velocity anomalies at depths around 30 km beneath the Betics and the Alhoceima region. This low velocity is interpreted as a crustal root extending along the entire Gibraltar Arc, from the easternmost Betics to the SE edge of the Rif Cordillera. Calvert et al. (2000b) and Serrano et al. (2005) have imaged a robust low-Pn velocity anomaly beneath the Betics and a smaller one beneath the Rif and Middle Atlas, while the Alboran Sea shows normal velocity values. Recent Pn and Sn tomographies of the Euro-Mediterranean region (Diaz et al., 2013) confirm this pattern and show a local region of high Pn and Sn velocity beneath the Alhoceima region (approx. 35°N, 3°W).

3 Data acquisition and processing

The RIFSIS project targeted the seismic structure along different domains of the Rif Cordillera from the acquisition, in October 2011, of two 330 km-long wide-angle profiles oriented respectively N-S and E-W. The geometry and dimensions of the Rif Cordillera are not

favorable to perform a WA seismic profile perpendicular to strike of structures and hence, the Bouguer anomaly pattern was primarily taken as main reference for implementation of the profiles (Figure 1). Southwards, the N-S profile connects and overlaps with the SIMA transect across the Atlas, recorded in 2010 (Ayarza et al., 2014). Jointly, the SIMA and the NS-RIFSIS line delineate a 700 km-long wide-angle seismic profile across the Betic-Rif-Atlas system. The use of a total of 810 Reftek 125a (Texans) instruments from the IRIS-PASSCAL instrument center allowed to achieve a relatively high lateral resolution, with an average station spacing of 750 m. These autonomous seismic stations recorded the energy released by 5 shots roughly spaced 100km. Each shot consisted in 1 Tn of explosive distributed in two 50 m boreholes. Gil et al., (2014) have interpreted the two profiles using ray-tracing modeling (Zelt and Smith, 1992). This analysis resulted in two detailed velocity-depth 2D models that represent a significant upgrade on the crustal structure knowledge beneath this area. The most relevant result is the identification of a large, clearly defined Moho step both in East-West and North-South directions, delimiting an area of crustal thickening, roughly coincident with the Bouguer anomaly. This crustal root, well constrained from both profiles, reaches values of 47-50 km below the external Rif domain. To the east of the Nekkorr fault, the crust thins abruptly down to 20 km and to the south towards the Middle Atlas, the crust thins smoothly.

The deployment logistics of the RIFSIS experiment was designed so that all the stations deployed along the N-S and E-W profiles were able to record all the shots fired within each profile, thus resulting in both online and offline shot records (Figure 1a). As previously stated, this contribution focuses in the investigation of these offline data, with the aim to produce a detailed, comprehensive map of the crustal thickness in northern Morocco. In a first step, the data have been processed following an ad hoc conventional normal incidence approach. Low fold wide-angle stacks can be obtained also with shot records featuring very long offsets (Gallart et al., 1995, Carbonell et al., 1998). A relatively simple processing sequence has been applied to

increase the signal-to-noise ratio of the data. This consists of band pass frequency filtering, spherical divergence amplitude corrections, spectral whitening and amplitude gain. Following Carbonell et al. (2002), a hyperbolic time reduction has been applied. Common-mid-points (CMP) geometry has been calculated from the acquisition geometry and used to sort for CMP and stack. The average velocity applied in the hyperbolic correction was chosen so that the reflections from the Moho appear as subhorizontal events (Figures 2 and 3). The specific acquisition geometry allows for the determination of several low fold stacks in different directions, hence placing 3D constraints on the crustal structure beneath the Rif orogen.

A second and complementary analysis arises from the identification and reading of the PmP phase arrivals in all the offline fan shot gathers. Although the PmP arrivals in these sections are in cases less prominent than the ones observed in the in-line transects, some relatively high amplitudes can be identified and their time-arrivals can be extracted. Assuming a uniform crust with a mean velocity value of 6.2 km/s, the depth of the reflection point can then be calculated and assigned to the midpoint between the shot and the receiver positions. These assumptions imply that significant errors may arise in case of heterogeneities, but we will show that this method still provides meaningful results.

An independent survey in the Alboran Sea, from the GASSIS-Westmed project, was coincident in time with the RIFSIS in-land profiles described above. This marine survey focused on the investigation of the crustal structure beneath the Alboran basin through the acquisition of a set of vertical incidence seismic profiles. These data was acquired by the Spanish RV Sarmiento de Gamboa equipped with an air-gun source array and a 6 km streamer. Therefore, a coordination and logistical effort was carried out within RIFSIS teams so that onshore wide-angle receiver gathers could be recorded using the offshore shots (Figure 1). The complexity of the area make the detailed interpretation of the records difficult, but preliminary models have been presented by Cembroski et al. (2013). Here, we have only retained the Moho depths

around the onshore-offshore transition from GASSIS profiles 17, 19 and 21 (Figure 1a). The analysis followed the main lines described previously for the offline profiles inland; identification of PmP phases, extracting their time and calculating an approximate crustal thickness at the corresponding midpoint. Near to the eastern end of Morocco, we have also applied this approach to estimate the crustal depths along a N-S oriented wide-angle profile running from Almeria to Nador acquired in the framework of the TopoMed project (Galvé et al., 2007).

Concerning natural earthquake data, we have used the database from the TopoIberia and PICASSO experiments for a classical P-wave receiver function analysis. This method analyzes the seismic phases converted at high impedance seismic discontinuities beneath the station and infers an estimation of the depth of this conversor. We benefit here from a more extended database dealing with receiver functions (RF) with respect to previous works on this area already published. Most of the stations used in TopoIberia have been kept in the area and active until 2013, in the framework of the RIFSIS project, and hence provided additional data to those analyzed by Mancilla et al. (2010). Additionally, a set of 13 stations from the same pool of instruments was redeployed in late 2013 to cover those areas where anomalous features were inferred from the so-far available results. The number of valid measurements for these stations is limited due to the short time duration of the deployment (around 6 months), but their results do contribute to a better-constrained image of the sharp Moho depth variations. Figure 1b shows the location of all the investigated sites.

The teleseismic events have been selected based on standard criteria: (1) events with magnitudes higher than 5.5 (2) epicentral distances between 30° and 90° to avoid wavefield complexities that likely arise from upper mantle discontinuities or diffraction at the core-mantle boundary, and (3) high signal-to-noise ratio (SNR) allowing the identification of clear P arrivals. Most of the sites investigated by Mancilla et al., (2010) have been reanalyzed,

223 considering additional data when available. All the PICASSO and the 13 redeployed
 224 ‘TopoIberia’ stations have been analyzed from scratch. The number of retained RF for each of
 225 the investigated stations ranges between 50-60 RFs for the originally deployed TopoIberia sites
 226 and 7-26 RFs for the redeployed ones. The PICASSO sites typically provide an intermediate
 227 number of retained RFs, ranging between 15 and 41. Whenever possible, the crustal depth (H)
 228 and the κ ratio ($\kappa = v_p/v_s$) beneath each station has been derived from the application of the H -
 229 κ method (Zhu and Kanamori, 2000). This method, nowadays widely used, considers a mean
 230 crustal velocity and estimates the arrival time of the Ps, PpPs and PsPs phases for each given
 231 combination of H and κ . The amplitude of the real RFs at those times is then evaluated in the
 232 (H, κ) parameter space. The presence of a well-defined maximum in the stacking surface
 233 defines the preferred solution for each station. However, this method is known to have
 234 limitations in the presence of a dipping convertor (Julià et al. 2003, Lombardi et al. 2008), a
 235 gradient-type boundary or in presence of sedimentary basins (e.g. Zelt and Ellis, 1999). In a
 236 limited number of sites, this method is not applicable due to weak Moho conversions or to a
 237 lack of clear multiples. In those cases, we estimate the crustal thickness by picking the Ps
 238 arrival in the summation trace after applying a Ps-moveout correction to the reference ray
 239 parameter of 0.065 s/km. Delay times are then converted to depth using an average V_p/V_s
 240 ratio, calculated at stations belonging to the same domain. Some stations provide complex
 241 results including two close convertors. On those cases, the general rule has been to interpret
 242 the deeper convertor as the Moho; nevertheless, each particular case has been analyzed in
 243 detail. Following a classical approach (e.g. Spada et al., 2013), the measurements have been
 244 classified in three categories defined as: (a) clear conversion phase and multiples for most of
 245 the back-azimuth; (b) identifiable conversion phase with plausible result of the H - κ stacking
 246 method; (c) use of the Pms travel time to obtain the crustal thickness. Half of the retained 39

new and reanalyzed crustal thickness estimations are classified as “A”, 28% as “B” and about 20% as “C”.

4 Results and Discussion

4.1 Active seismics

The Moho discontinuity is clearly imaged in the low fold wide-angle stacks along the main EW and the NS profiles. Along the EW stack section (Figure 2a) the Moho is imaged with high energy in most areas of the profile covered by two shots, except beneath shot-points R3 and R5, where the lack of coverage does not allow a proper identification. The western part of the section shows a Moho discontinuity located around 15 s, corresponding to depths close to 47 km assuming a typical mean crustal velocity of 6.2 km/s. In the eastern half, the PmP phases arrive clearly earlier, around 10 s corresponding to crustal thickness around 33 km. Therefore, the differences in arrival times -15s vs 10s- and/or the estimated depths -47 km vs 33 km- constitute solid evidence of a significant heterogeneity in the deeper part of the crust and mantle transition.

In the NS stack section (Figure 2b) the Moho is imaged as a high amplitude event at the southern part of the profile (from CDPs 850 to 1100) reaching depths of 35 to 40 km below the transition from the Moroccan Meseta to the External Rif. To the North, the Moho deepens and reaches estimated depth of approximately 46 km, and then it becomes subhorizontal for over 100 km beneath shots R3 and R2 (see Figure 1 for location). In all this area beneath the External Rif domain the Moho reflection is weaker. The northernmost part of the section images a horizontal Moho as a relatively weak event at approximately 43 km depth. The differences of reflected energy along the NS profile evidence again high crustal heterogeneity. This seismic signature can be understood as the effect of sampling different tectonic domains.

271 Figure 3a shows the low-fold wide-angle stack calculated using the seismic signals of shot R2
272 recorded by the instruments located along the RIFSIS EW profile. The corresponding CMP
273 transect that can be constructed with this records samples the Moho along an approximately
274 EW oriented profile across the Central Rif (labeled EW01 in Figure 1a). In this wide-angle
275 stack, to the East, the Moho is identified around 12s, and it most probably corresponds to
276 depths around 35 km. Further West, the Moho deeps down to at least 50 km beneath CMP
277 30375. The Moho depth then decreases smoothly reaching 43 km in the western termination of
278 the profile. Note that in the western section of this profile, a secondary arrival is consistently
279 observed around 30 km. Taking into account the recording offsets for these stations, which
280 range from 70 to 135 km, and the phases observed in the record sections along the E-W profile,
281 these early arrivals are interpreted as an intra-crustal phase associated with the top of the lower
282 crust.

283 Figure 3b show a NS section constructed from the signals of shot R4 recorded along RIFSIS
284 profile NS. The sample area is depicted as NS01 in Figure 1a. As in the previous case,
285 significant differences in the time arrivals of the interpreted PmP phases can be observed. The
286 Moho reflectivity imaged by the NS01 pseudo-profile is more laterally continuous and features
287 higher amplitudes than in the main NS section (Figure 2b), although the observed Moho
288 geometry is similar in both cases. In the southern part of the NS01 section, the Moho is clearly
289 imaged at 13s corresponding to depths around 40 km. Northward, the Moho deepens and
290 reaches values exceeding 45 km near the junction with the previously discussed EW01 pseudo-
291 profile. Further to the north, the PmP arrivals are not so prominent, but still reveal a crust that
292 thins quickly to reach values close to 40 km. A marked difference in Moho reflectivity is
293 evidenced when comparing the main NS profile and the NS01 pseudo-profile. The main profile
294 only shows strong reflectivity at its southernmost termination, while NS01 shows a strong
295 reflector between the 40200 to 40450 CDPs, located at similar latitudes. Taking into account

that both sections are sampling similar geological domains, the reflectivity differences evidenced should be attributed either to differences in the efficiency of energy propagation at the vicinity of the shot-points, or to crustal differences in seismic attenuation along travel paths.

The large variations in crustal thickness observed in the low fold stacks are consistent with the ray-tracing models obtained by Gil et al. (2014) along the N-S and E-W RIFSIS profiles (Figure 4a), which revealed a large Moho step and an area of crustal thickening both in EW and NS directions, grossly coincident with the Bouguer gravity anomaly (Figure 1b). The RIFSIS EW profile shows a thin crust beneath NE Morocco, with thickness around 30 km depth which increase West of Nekkour fault, to reach 52 km. The EW01 profile here presented, is located about 30 km north and show similar overall results. However, EW01 evidences an even thicker crust northwards of the main EW profile, in the area between shot-points R3 and R4. Along the NS profile, the new profile NS01 shows Moho depths in the central part of the profile exceeding 50 km, consistent with the image retrieved from profile EW01 at the crossing area.

Figure 4b shows some examples of the PmP phases identified in the different fan gathers, used to estimate crustal thickness offline of the main profiles. The PmP arrivals from shot R4 recorded along line 5000 sample a zone located at 4°W and arrive at 3-4s reduced time, suggesting a crustal thickness around 30 km and marking the eastern limit of the thickened area. The PmP phases from the same shot recorded along line 4000 arrive at 3-6 s reduced time for distances around 130 km, marking a clearly thickened area (Figure 4b, upper panel). The fan-like section from shot R4 recorded along line 3000 shows remarkable strong variations in the PmP arrival times, hence in crustal thickness (Figure 4b, lower panel). PmP arrivals are identified at about 2 s reduced times in station 3011, located at 135 km offset from shot-point, then travel times increase steeply,

reaching unusual values of 7 s at about 145 km offset. This corresponds to crustal depths of 50-55 km for midpoints located in the area already sampled by pseudo-profile EW01.

Data from the PmP phases from the GASSIS Profile 21 (see Figure 1) provide clear evidences of a deep Moho beneath the coastline and extending few kilometers offshore, with depths exceeding 55 km. On the other hand, the NW-SE oriented profiles 17 and 19, sampling eastern Morocco, show a Moho deepening smoothly beneath the coastline to depths of about 40-45 km. The crustal thickness beneath the Alboran Sea varies between 17 and 20 km. Data from the N-S oriented WestMed profile in eastern Morocco show a Moho gently deepening from 18 km in the center of the Alboran Sea to 28 km inland, consistent with the depth estimates reported here.

As a final step, all the Moho depth estimations have been integrated in a grid file using a the nearest neighbor algorithm included in the GMT package (Wessel et al., 2013), using a small search radius to avoid extrapolations. The resulting map is presented at Figure 6a for comparison with the one resulting from the RF analysis (see next section). The thickest crust zone is not limited to the central Rif zone but extends northwards up to the coastline, within a limited region close to the Beni Moussera peridotites. A significant variation in the Moho depth estimation appears at this zone, as the deep Moho imaged derived from the land recording of profile 21 is closely followed northwards by a much thinner crust derived from PmP arrivals of shot R1. We interpret that in the first case we are sampling the thickened Rif crust, while in the second case the origin of the observed phases is the lower limit of the thin Alboran crust that probably indents the thicker Rif crust. The Moho map derived from controlled source seismic data also evidences the progressive thinning to the East already described by Gil et al. (2014).

4.2 Natural seismicity

344 Figure 5 presents some representative examples of the HK analysis. PM07 (Figure 5a) is a good
345 example of the HK results for stations located in the central part of the Rif domains, illustrating
346 the thick crust observed under this region. Ps arrives at 5.6s, a delay consistent with the 44 km
347 crustal thickness derived from the HK grid search. M416, located also in the Rif Domain, shows a
348 more complex image (Figure 5b). The stacked RF shows two maxima at 4.2s and 6.4s,
349 corresponding to depths of approximately 34 and 54 km. Taking into account the consistency of
350 the Ps arrival over the different backazimuths, we have identified the Moho with the first
351 conversor. M418 (Figure 5c), located close to the Nekkora Fault area, shows a clear maximum in
352 the grid search, resulting in a crustal thickness of 30 km and illustrating the eastward thinning
353 already inferred from active seismic results. Finally, station PM20 (Figure 5d), located in the
354 southern part of the investigated area, close to the Middle Atlas, shows again a clear result, with
355 the Moho conversor located at 30 km, thus marking the southern termination of the thickened
356 crust.

357 Consistently with results from active source experiments, the RF analysis evidences a very
358 thick crust beneath the central part of the Rif Cordillera, with Moho depths close to 50 km.
359 Although the results are somehow ambiguous for some sites, well-defined converted phase
360 arriving with large time delays are often observed, supporting the existence of this significant
361 crustal root. The results presented here show an overall similarity with those published by
362 Mancilla et al. (2012), Thurner et al., (2014) and Mancilla and Diaz (2015), even if significant
363 differences arise at some areas. Mancilla et al. (2012) present two alternative interpretations for
364 stations in central Rif and they favor the model attributing thickness of 27 - 41 km to stations
365 M013 and M006. Under this zone, RF's determined from the additional data provided by the
366 new deployments favor an interpretation in which Moho is associated to the latest
367 arrival/conversor. This results in crustal thicknesses over 50 km. Further East, Mancilla et al.
368 (2012) estimated a crustal thickness of 26 km beneath M007, but the contribution of the new

data sets favor a thicker value of approximately 42 km. The later is more consistent with the result inferred for PM36, located a few kilometers to the north. M007 is located close to the Nekkor fault area, a sharp limit between thick and thin crusts. These large differences between the interpretations are mainly due to the existence of the two conversors. Either of them can be interpreted as being the Moho. This is only relevant for the precise mapping of the eastward crustal thinning, but does not change the global image derived from those results.

The good regional coverage and fairly dense station spacing (~60 km for TopoIberia stations, and ~30 km for PICASSO stations) allows interpolating and extending single station measurements into a continuous map of crustal thickness for the entire study area (Figure 6b). To allow for a direct comparison, we have used the same interpolation scheme and color scale than for the map derived from active source experiments (Figure 5a). Both maps are remarkably similar, taking into consideration that they come from completely independent data sets and methodologies.

4.3 Joint interpretation

Results from active seismics and RFs are joined to obtain the final crustal thickness map of north Morocco, presented in 2D and 3D views at Figure 7. As previously stated, the main feature is the large crustal root beneath the central Rif Domain that reaches, at least, 50 km. This root is in good agreement with the area presenting large negative Bouguer anomaly values reaching values close to -150 mGal. The crustal thickness estimations arising from RF and active seismic show generally differences laying in the usually admitted error range (e.g. Spada et al., 2013). The main exception occurs beneath the central Rif Domain, where the differences are significant even if both methodologies consistently show a crustal root. Those differences can be related to the complex crustal geometry, resulting in weak and complex RFs and PmP phases which do not allow simple evaluations based in oversimplified hypotheses. Therefore, the absolute values of

the crustal thickness in this area can not be resolved precisely. The controlled source seismic data extend this root until the coastline in a limited region close to 5° W, near the Beni-Boussera peridotites (Azdimousa et al., 2013, Romagny et al., 2014). This shallow peridotitic body has only a moderate expression in the Bouguer map, clearly smaller than the anomaly observed in the Ronda peridotites, located in the Betic side of the Gibraltar Arc. We attribute this difference to the effect of a large crustal root below BeniBoussera, that counteracts the high density bodies close to the surface.

Most of the available tectonic reconstructions of the Gibraltar Arc (Vergès and Fernandez, 2012, van Hinsbergen et al., 2014, Chertova et al., 2014) support the hypothesis of a west directed slab rollback in the western Mediterranean. Recent teleseismic body-wave tomographic models (Bezada et al., 2014, Bonnín et al 2014) show that the Alboran slab can hardly be identified above depths around 100 km beneath the Betics, while it is clearly imaged beneath the Rif, where it seems to be connected to the surface. This geometry supports the presence, already pointed out by Spakman and Wortel (2004), of slab tearing beneath the eastern Betics but not beneath the Rif. Palomeras et al. (2014) have presented a surface wave tomography that shows evidences of an attached slab beneath the central part of the Rif. Pérouse et al. (2010) and Petit et al. (2015) reached a similar conclusion, based respectively in the modeling of GPS data and in the analysis of the degree of isostatic compensation of the Rif topography. The thickened crust area mapped by our data is coincident geographically with the area where an attached slab has been proposed.

The limited lateral dimension of the thickened area, altogether with the large thickness observed, exceeding 50-55 km, seems to favor the hypothesis presented by Petit et al. (2015), suggesting that the crustal thickening is a local, dynamic response to the sinking of the Alboran slab. In this model, the slab, still attached beneath the Rif but progressively detaching and sinking into the mantle nearby, promote lower crust flow that results in local thickening as the crust is sucked to overcome the void created above the mantle hinge.

To the East, the Nekkora fault area shows a major and rather sharp change in crustal thickness. This surface feature denotes the limits of the overthickened zone and can be associated with the position of the Neo-Tethys passive margin created during the Mesozoic rifting (Gomez et al., 2000, Tesón, 2009) connected with the TransAlboran Shear Zone. This feature marks the boundary and/or sharp change of other geophysical observables. For example, it is coincident with the limit of the seismic activity, the margin of the Bouguer anomaly and/or is a localized marker of the change in the anisotropic parameters. These characteristics or boundary markers suggest that the Nekkora fault is, most probably, a lithospheric-scale structure.

The limit of the seismicity in the area can be observed in Figure 7, where the hypocentral distribution during the period 2000-2014, as reported in the IGN catalogue, is overlaid on the determined map of crustal thickness. Main points are the presence of a well defined, N-S oriented, alignment of deep seismicity in the westernmost Alboran Sea (approx. 4.6°W) and a large amount of superficial seismicity distributed around the Alhoceima region (4 °W, 36 °N approx.) and south of Nador (3°W, 36°N). To the West a horseshoe/arcuate alignment of seismicity, including both superficial and deep events can be defined from about 5.5°W, 34.5°N to 7°W, 35.5°N. The origin of this seismicity remains unclear, and is, currently, under investigation. The installation of several permanent stations in Morocco should help in resolving correctly the location of these hypocenters. It is worth to point out that the zone with thickened crust lacks seismicity and corresponds to the area in-between the seismically active regions. Few events have been located so far inside the region defined by the 40km depth isoline. The relationship between the crustal thickening, the seismic gap and the presence of an attached slab is still an open issue to be explored in the next future.

5 Conclusions

The analysis presented here of new seismic data including controlled source wide-angle and natural seismicity places constraints on the 3 dimensional geometry of the base of the crust beneath northern Morocco. The Moho depth map built up by joining the two independent datasets provide a remarkably consistent image of the 3D crustal variations, clearly dominated by the presence of a large crustal root beneath central Rif.

Offline data from controlled source seismic profiles has been processed in order to obtain information on the crustal thickness variations offline the main seismic profiles, thus extending to 3D the 2D crustal models presented by Gil et al. (2014). CMP sorting of the records corresponding to the offline shots of the RIFSIS transects results in pseudo-profiles sampling intermediate zones. Low fold wide-angle stacks were then obtained after applying a hyperbolic move-out to the shot records. The Moho geometry can then be extracted from these images. We also estimated the crustal thickness from PmP phases identified in fan gathers of the RIFSIS land shots and in the stations deployed inland to record the offshore shots of the marine MCS profiles of the GASSIS experiment. At the same time, teleseismic RFs in the Rif domain area were analyzed, to determine the crustal thickness beneath northern Morocco. We reprocessed data from both the TopoIberia and PICASSO experiments and installed some additional stations to densify the data in the more complex region of interest. The technique of H- κ stack was used to extract the depth location of the Moho discontinuity beneath each seismic station obtaining an independent crustal thickness map. Even if some differences do exist, the two crustal thickness maps are remarkably consistent, taking into account that two completely independent methods were used. The controlled source wide-angle seismic data sample the Moho Moho discontinuity from above using reflected phases and in the RFs approach the depth of the Moho is probed from below.

Both maps resolve the 3D geometry of the Moho. The major achievement of this study is that the geometry of the large crustal root is well documented in the central part of the Rif Cordillera. The area with thicker crust is located around 4.5°W, 35°N, a zone not directly imaged by the RIFSIS models. Both controlled source and natural seismicity data suggest that a crustal root extends to the coastline in a limited region close to 5° W, around the Beni-Boussera peridotites. The global image is consistent with the Bouguer anomaly map, even if the location of the crustal thickness maximum seems shifted to the Northeast. The area with larger crustal depth is coincident geographically with the zone where independent studies based on P-wave and surface wave tomography, and GPS modeling have suggested that the Alboran fast velocity slab can be attached to the crust. Therefore, we interpret that the observed crustal thickening is directly related to the pull exerted by the high velocity Alboran slab.

Furthermore, the Moho-depth map presented reveal that the regions with crustal thicknesses of 40 km define an area with a small amount of seismicity, between the arcuate seismicity beneath western Alboran Sea and the more superficial seismicity in the Alhoceima area. Therefore, the presence of a crustal root seems to play a major role in the seismicity distribution in northern Morocco.

Acknowledgements

Funding for this project has been available from Spanish Ministry of Science and Innovation under grants: CGL2009-09727 (RIFSIS), CSD 2006-00041 (TopoIberia), CGL2007-63889 (SIMA), CGL2008-3474 (TopoMed), and by Generalitat de Catalunya grant: 2009SGR996. We have also used data from the PICASSO project, founded by the U.S. NSF grant EAR0808939.

491 We thank Bureau Gravimétrique International (BGI)/IAG International Gravity Field Service
492 (<http://bgi.obs-mip.fr>) for facilitating the gravity data in the North Morocco and Iberia.
493 reau

References

- Alpert, L.A., Miller, M.S., Becker, T.W., and Allam, A. (2013). Structure beneath the Alboran from geodynamic flow models and seismic anisotropy, *J. Geophys. Res.*, 118, 4265-4277, doi:10.1002/jgrb.50309.
- Ayarza, P., R. Carbonell, A. Teixell, I. Palomeras, D. Martí, A. Kchikach, M. Hanafi, A. Levander, J. Gallart, M.L. Arboleya, J. Alcalde, M. Charroud and M. Amrhar (2014), Crustal thickness and velocity structure across the Moroccan Atlas from long offset wide-angle reflection seismic data: the SIMA experiment, *Geochem. Geophys. Geosyst.*, 15, 1698–1717, doi:10.1002/2013GC005164.G3.
- Azdimousa, A. J. Bourgois, G. Poupeau, M. Vázquez, L. Asebriy and E. Labrin (2013), Fission track thermochronology of the Beni Bousera peridotite massif (Internal Rif, Morocco) and the exhumation of ultramafic rocks in the Gibraltar Arc, *Arab. J. Geosci.*, doi:10.1007/s12517-013-0924-3
- Bezada, M.J., E.D. Humphreys, D.R. Toomey, M. Harnafi, J.D. Dávila, and J. Gallart, (2013), Evidence for slab rollback in westernmost Mediterranean from improved upper mantle imaging, *Earth and Planetary Sciences Letters*, 368, 51-60. doi: 10.1016/j.epsl.2013.02.024
- Blanco MI, Spakman W (1993) The P wave velocity structure of the mantle below the Iberian Peninsula: evidence for subducted lithosphere below Spain. *Tectonophysics* 221, 13–34, doi:10.1016/0040-1951(93)90025-F.
- Buontempo, L., G.H.R. Bokermann, G. Barruol and J. Morales, (2008). Seismic anisotropy

beneath southern Iberia from SKS splitting, *Earth Planet. Sci. Lett.*, 273, 237-250.

Calvert, A., E. Sandvol, D. Seber, M. Barazangi, S. Roecker, T. Mourabit, F. Vidal, G. Alguacil, and N. Jabour (2000a), Geodynamic evolution of the lithosphere and upper mantle beneath the Alboran region of the western Mediterranean: Constraints from travel times tomography, *J. Geophys. Res.*, 105, 10,871-10,898.

Calvert, A., E. Sandvol, D. Seber, M. Barazangi, F. Vidal, G. Alguacil and N. Jabour (2000b). Propagation of regional seismic phases [Lg and Sn] and Pn velocity structure along the Africa–Iberia plate boundary zone: tectonic implications. *Geophys. J. Int.* 142, 384–408

Carbonell, R., J. Gallart and A. Pérez-Estaún (2002). Modelling and imaging the Moho transition: the case of the southern Urals. *Geophys. J. Int.*, 149, 134-148

Cembrowski, M., J. Gallart, M. Schimmel, J. Díaz, R. Carbonell, E. Garcia, C. Ranero, J. Scmaltz, C. Thomas, D. El Ouai, and I. Palomeras (2013), Mapping the onshore/offshore crustal trnasiction at the Westernmost Mediterranean from seismic profiling, *Geophys. Res. Abs.*, Vol 15, EGU 2013-8209 presented at 2013 spring Meeting EGU, Vienna, Austria, April.

Chalouan, A., A. Michard, H. Feinberg, R. Montigny, and O. Saddiqi, (2001), The Rif mountain building (Morocco): a new tectonic scenario, *Bull. Sec. geol. France*, 172(5), 603-616.

Chalouan, A., A. Michard, Kh. El Kadiri, F. Negro, D. Frizone de Lamotte, J.I. Soto, and O. Saddiqi, The Rif Belt. (2008) In: Michard, A., O. Saddiqi, A. Chalouan, and D. Frizone de

Lamotte (eds), *Continental Evolution: The Geology of Morocco*. Lecture Notes in Earth Sciences, Springer, Berlin, 203-302.

Díaz, J., A. Villaseñor, J. Gallart, J. Morales, A. Pazos, D. Córdoba, J. Pulgar, J.L. García-Lobón, M. Harnafi and the TopoIberia Seismic Working (2009). The IBERARRAY broadband seismic network: a new tool to investigate the deep structure beneath Iberia. *Orfeus Newsl.* 8, 2.

Díaz, J., Gallart, J., Villaseñor, A., Mancilla, F., Pazos, A., Córdoba, D., Pulgar, J.A., Ibarra, P., Harnafi, M., (2010). Mantle dynamics beneath the Gibraltar Arc (western Mediterranean) from shear-wave splitting measurements on a dense seismic array, *Geophys. Res. Lett.*, 37(L18304), doi:10.1029/2010GL044201

Díaz, J., A. Gil, and J. Gallart, (2013), Uppermost mantle seismic velocity and anisotropy in the Euro-Mediterranean region from Pn and Sn tomography, *Geophys. J. Int.*, 192, 310-325

Díaz J., and J. Gallart, (2014), Seismic anisotropy from the Variscan core of Iberia to the Western African Craton: New constraints on upper mantle flow at regional scales. *Earth Planet. Sci. Lett.*, 394, 48-47, doi:10.1016/j.epsl.2014.03.005

El Moudnib, L., Villaseñor, A., Harnafi, M., Gallart, J., Serrano, I., Córdoba, D., Pulgar, J.A., Ibarra, P., Himmi, M.M., Chourak, M. (2015), Crust structure of the Betic-Rif system, western Mediterranean, from local earthquake tomography. *Tectonophysics*, 643, 94-115, doi:10.1016/j.tecto.2014.12.015

Faccenna, C., C. Piromallo, A. Crespo-Blanc, L. Jolivet, F. Rossetti (2004). Lateral slab deformation and the origin of the Western Mediterranean arcs. *Tectonics* 23. doi:10.1029/2002TC001488.

Fadil, A., P. Vernant, S. McClusky, R. Reilinger, F. Gomez, D. B. Sari, T. Mourabit, K. L. Feigl, and M. Barazangi (2006), Active tectonics of the western Mediterranean: GPS evidence for roll back of a delaminated sub-continental lithospheric slab beneath the Rif mountains, *Geology*, 34, 529–532, doi:10.1130/G22291.1.

Fullea, J., et al., Perturbing effects of sub-lithospheric mass anomalies in GOCE gravity gradient and other gravity data modelling: Application to the Atlantic-Mediterranean transition zone. *Int. J. Appl. Earth Observ. Geoinf.* (2014), doi:10.1016/j.jag.2014.02.003

Gallart, J., Vidal, N. and Dañobeitia, J.J. (1995). Multichannel seismic image of the crustal thinning at the NE Iberian margin combining normal and wide angle reflection data. *Geophysical Research Letters*, 22, 4, 489-492.

Galvé, A., Gallart, J., Díaz, J., Fernández, M., Grevemeyer, I., Ranero, C.R. and the Westmed Team (2007). “Probing the deep structure of the Eastern Alboran Basin (Western Mediterranean) by wide-angle seismics”. EGU General Assembly. Wien.

Garcia-Castellanos, D., and A. Villaseñor, (2011), Messinian salinity crisis regulated by competing tectonics and erosion at the Gibraltar Arc. *Nature* 480, 359-363.

Gracia, E., C.R. Ranero, I. Grevemeryer, The WestMed, TopoMed, and GEomargen-1 cruise parties (2012), Seismic Images and Wide-angle Velocity constrains of the structure and geodynamic origin of the Gibraltar Arc system: A geological interpretation of the Gulf of Cadiz imbricated wedge, the western and eastern Alboran basins, and the South-Balearic basin. Geophys. Res. Abs., Vol 14, EGU 2012-8209 presented at 2043 spring Meeting EGU, Vienna, Austria, April

Gil, A., J. Gallart, J. Díaz, R. Carbonell, A. Levander and M. Harbafi (2014) Crustal structure beneath the Rif Cordillera, North Morocco, from the RIFSIS wide-angle reflection seismic experiment. *Geochem. Geophys. Geosyst.*, 15, 4712–4733, doi:10.1002/2014GC005485.

Gutscher, M.A., J. Malod, J.P. Rehault, I. Contrucci, F. Klingelhoefer, L. Mendes-Victor, and W. Spakman (2002), Evidence for active subduction beneath Gibraltar, *Geology*, 30, 1071-1074

Hatzfeld, D., and D. Bensari (1977), Grands profile sesmiques dans la région de l'arc de Gibraltar, *Bull. Sec. Géol. France*, 7 (XIX-4), 749-756

Hildenbrand, T. G., R. P. Kucks, M. F. Hamouda, and A. Bellot (1988), Bouguer gravity map and related filtered anomaly maps of Morocco, *U.S. Geol. Surv. Open File Rep.*, 88-517.

Jolivet, L., C. Faccenna and C. Piromallo (2009). From mantle to crust: Stretching the Mediterranean. *Earth Planet. Sci. Lett.*, 285, 198–209.

Koulali, A., D. Ouazar, A. Tahayt, R.W., King, P. Vernant, R.E. Reilinger, S. McClusky, T. Mourabit, J.M. Davila, and N. Amraoui, (2011), New GPS constraints on active deformation

619 along the Africa-Iberia plate boundary, *Earth and Planetary Science Letters*, 308, 211-217.

620
621 Lonergan, L., and N. White (1997), Origin of the Betic-Rif mountain belt, *Tectonics*, 16, 504-
622 522, doi:10.1029/96TC03937

623
624 Mancilla, F.L., Diaz, J., High resolution Moho topography map beneath Iberia and Northern
625 Morocco from receiverfunction analysis, *Tectonophysics* (2015), 203-211,
626 <http://dx.doi.org/10.1016/j.tecto.2015.06.017>

627
628 Mancilla, F.L., D. Stich, J. Morales, J. Julià, J. Díaz, A. Pazos, D. Córdoba, J.A. Pulgar, P.
629 Ibarra, M. Harnafi, and F. Gonzalez-Lodeiro (2012), Crustal thickness variations in Northern
630 Morocco, *J. Geophys. Res.*, 177, B02312, doi:10.1029/2011JB008608

631
632 Miller, M.S., A. Allam, T.W. Becker, J.F. Dileo, and J. Wookey (2013), Constraints on the
633 tectonic evolution of the westernmost Mediterranean and northwestern Africa from shear wave
634 splitting analysis. *Earth Planet. Sci. Lett.* doi:10.1016/j.epsl.2013.05.036

635
636 Palano, M., P. Gonzalez, J. Fernandez (2013). Strain and stress fields along the Gibraltar
637 Orogenic Arc: constraints on active geodynamics *Gondwana Res.*, 23 (2013), pp. 1071–1088
638 doi:10.1016/j.gr.2012.05.021

639
640 Palomeras, I., S. Thurner, A. Levander, K. Liu, A. Villaseñor, R. Carbonell, M. Harnafi (2014),
641 Finite-frequency Rayleigh wave tomography of the western Mediterranean: Mapping its
642 lithospheric structure, *G3*, 15 (1), 140-160, doi:10.1002/2013GC004861

Pérouse, E., P. Vernant, J. Chery, R. Reilinger, and S. McClusku, (2010), Active surface deformation and sub-lithospheric processes in the western Mediterranean constrained by numerical models, *Geology* 38(9), 823-826, doi: 10.1130/G30963.1

Petit, C., Le Pourhiet, L., Scalabrino, B., Corsini, M., Bonnín, M. and Romagny, A. (2015). Crustal structure and gravity anomalies beneath the Rif, northern Morocco: implications for the current tectonics of the Alboran region. *Geophys. J. Int.* 202 (1): 640-652. doi: 10.1093/gji/ggv169

Platt, J.P. and R.L.M. Vissers (1989). Extensional collapse of thickened continental lithosphere: A hypothesis for the Alboran Sea and Gibraltar arc, *Geology*, 17, 540-543.

Platt, J.P., Th.W. Becker, R.L. Evans, E.D. Humphreys, C.T. Lee, and A. Levander (2008), PICASSO: testing models for upper mantle processes beneath the Alboran Basins and the Gibraltar Arc (Western Mediterranean), *Geol. Soc. Am. Abstrat. Prog.*, 40(6), 273.

Platt, J.P., Behr W, Johanesen, K., and Williams R. (2013) The Betic-Rif Arc and Its Orogenic Hinterland: A Review. *Annual Review of Earth and Planetary Sciences* Vol. 41: 313-357 doi: 10.1146/annurev-earth-050212-123951

Romagny, A., Ph. Münch, J.-J. Cornée, M. Corsini, A. Azdimousa, M.C. Meline-Dobrinescu, H. Drinia, M. Bonno, N. Arnaud, P. Monié, F. Quillévéré and A. Ben Moussa (2014), Late Miocene to present-day exhumation and uplift of the Internal Zone of the Rif Chain: Insights from low temperature thermochronometry and basin analysis, *Journal of Geodynamics*, 77, 39-55, doi:10.1016/j.jog.2014.01.006

- Rosenbaum, G., Lister, G.S., (2004). Neogene and Quaternary rollback evolution of the Tyrrhenian Sea, the Apennines, and the Sicilian Maghrebides. *Tectonics* 23, TC1013. doi:10.1029/2003TC001518.
- Royden, L.H (1993), Evolution of retreating subduction boundaries formed during continental collision, *Tectonics*, 12, 629-638, doi:10.1029/92TC02641
- Seber, D., M. Barazangi, B. A. Ibenbrahim, and A. Demnati (1996), Geophysical evidence for lithospheric delamination beneath the Alboran Sea and Rif-Betic Mountains, *Nature*, 379, 785-790
- Serrano, I., T.M. Hearn, J. Morales and F. Torcal (2005). Seismic anisotropy and velocity structure beneath the southern half of the Iberian Peninsula. *Phys. Earth and Planet. Int.*, 150, 317-330.
- Spada, M., Bianchi, I., Kissling, E., Piana Agostinetti, A., Wiemer, S. (2013). Combining controlled-source seismology and receiver function information to derive 3-D Moho topography for Italy. *Geophys. J. Int.*, 194, 1050-10698, doi: 10.1093/gji/ggt148
- Spakman, W. and M.J.R. Wortel, (2004). A tomographic view on western Mediterranean geodynamics. In: Ziegler, P. [Ed.], *The TRANSMED Atlas — The Mediterranean region from crust to mantle*. Springer, Berlin Heidelberg, pp. 31–52
- Turner, S., I. Palomeras, A. Levander, R. Carbonell and L. Cin-ty (2014), Evidence for

Ongoing Lithospheric Removal in the Western Mediterranean: Ps Receiver Function Results from the PICASSO Project, G3, doi:10.002/201GC005124

Torné, M., M. Fernández, M. C. Comas, and J. I. Soto (2000), Lithospheric structure beneath the Alboran Basin: Results from 3D gravity modeling and tectonic relevance, *J. Geophys. Res.*, 105(B2), 3209–3228, doi:10.1029/1999JB900281.

Vergés, J., and M. Fernández (2012), Tethys-Atlantic interaction along the Iberia-Africa plate boundary: The Betic-Rif orogenic system, *Tectonophysics*, 579, 144-172, doi:10.1016/j.tecto.2012.08.032

Vernant, P., A. Fadil, T. Mourabit, D. Ouazar, A. Koulali, J.M. Davila, J. Garate, S. McClusky, and R. Reilinger, (2010), Geodetic constraints on active tectonics of the Western Mediterranean: Implications for the kinematics and dynamics of the Nubia-Eurasia plate boundary zone, *Journal of Geodynamics*, 49, 123-129

Wessel, P., W. H. F. Smith, R. Scharroo, J. F. Luis, and F. Wobbe, (2013) [Generic Mapping Tools: Improved version released](#), *EOS Trans. AGU*, 94, 409-410.

Wigger, P., G. Asch, P. Giese, W. D. Heinsohn, S. O. E. Alami, and F. Ramdani (1992), Crustal structure along a traverse across the Middle and High Atlas mountains derived from seismic refraction studies, *Geol. Rundsch.*, 81(1), 237–248, doi:10.1007/BF01764552.

Working Group For Deep Seismic Sounding In Alboran 1974, (1978). Crustal seismic profiles in the Alboran sea—preliminary results. *Pageoph*, 116, 166–180.

719

720 Zeck, H.P. (1996). Betic-Rif orogeny: Subduction of Mesozoic Tethys lithosphere under
721 eastward drifting Iberia, slab detachment shortly before 22 Ma and subsequent uplift and
722 extensional tectonics, *Tectonophysics*, 254, 1-16
723 Zelt, C.A, and R.B. Smith (1992), Seismic
724 traveltime inversion fro 2-D crustal velocity structure, *Geophys. J. Int.*, 108, 16-34

724

725 Zeyen, H., P. Ayarza, M. Fernàndez, and A. Rimi (2005), Lithospheric structure under the
726 western African-European plate boundary: A transect across the Atlas Mountains and the Gulf
727 of Cadiz, *Tectonics*, 24, TC2001, doi:10.1029/2004TC001639

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Figure Captions

Figure 1: a) Geometry of the wide-angle seismic reflection experiments. Shot point locations are marked by yellow stars. The red dots indicate the location of the seismic recorders while the black dots indicate the CMP (Common Mid Points) used for the low-fold wide-angle stacks. Dashed black lines labeled p17-p19-p21 show the contributing GASSIS offshore profiles. b) Bouguer anomaly map. White squares denote BB seismic stations from the TopoIberia experiment, yellow circles are from PICASSO stations and black squares are for the new stations deployed within the RIFSIS project.

Figure 2: Low fold wide-angle stacks along profiles EW (upper panel) and NS (lower panel). Data is presented using an hyperbolic time reduction $HTR = (t - \sqrt{t^2 - x^2/v^2})$ with $v=6.2$ km/s. Dashed red lines indicate the Moho reflected energy (PmP phases) along each profile.

Figure 3: Low fold wide-angle stacks of the offline shot R2 recorded along profile EW (upper panel) and of the offline shot R4 recorded along profile NS (lower panel). Data presented using an hyperbolic time reduction $HTR = (t - \sqrt{t^2 - x^2/v^2})$ with $v=6.2$ km/s. Dashed red lines indicate the Moho reflected energy (PmP phases) along each profile.

Figure 4: a) Ray tracing modeling of the main N-S and E-W wide angle profiles (Gil et al., 2014). b) Upper panel: Shot R3 recorded at the NW-SE lines 4000 and 5000 shown in the inset. Lower panel: Shot R5 recorded at the NE-SW line 3000 shown in the inset. Numbers ontop the traces show offsets. Times are reduced using $v=6.0$ km/s.

Figure 5: H- κ analysis for some characteristic stations. a) Station PM07, located in the internal Rif. b) station M416, showing a complex case in the thickened area c) Station M418, located close to the Nekkore fault area and depicting a thinner crust d) PM20, close to the Middle Atlas, also showing a rather thin crust. The inset map shows the position of the stations.

Figure 6: Moho depth maps inferred from wide-angle experiments (a) and RF analysis (b) beneath Northern Morocco. Numbers show the Moho depth values at the points where a measurement is available. Color grid interpolates those points using a nearest neighbor algorithm.

Figure 7: a) Moho depth map as inferred from the combined results from controlled source experiments and RF data. b) 3D view of the same map. Reddish colors show the thinner zones beneath the Alboran Sea and the east Morocco. Deep blue colors show the deep crustal thickening beneath the Rif, where crustal thickness exceeds 50 km.

Figure 8: Earthquakes with magnitude > 2 , as reported by the Instituto Geográfico Nacional catalogue in the period 2000-2014, overprinting the new crustal thickness map. White dots are for event with hypocenters above 40 km depth, black dots denote deeper events.

Figure 1 (with caption below and on the same page)

a)

b)

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Figure 4 (with caption below and on the same page)

Figure 4

a) Ray tracing modeling of the main NS and E-W wide angle profiles (Gil et al., 2014)

b) Examples of PmP picking on the auxiliary profiles. Upper panel: Shot R3 recorded at the NW-SE lines 5000 and 4000 shown in the inset. Lower panel: Shot R4 recorded at the NE-SW line 3000 shown in the inset. Numbers ontop the traces show offsets. Times are reduced using $v=6.0$ km/s

Figure 5 (with caption below and on the same page)

Figure 5: H- κ analysis for some characteristic stations. a) Station PM07, located in the internal Rif. b) station M416, showing a complex case, in the thickened area. c) Station M418, located close to the Nekor fault area and depicting a thinner crust d) PM20, located close to the Middle Atlas, also showing a rather thin crust. The inset map shows the position of the stations.

Figure 6 (with caption below and on the same page)

Figure 6: Moho depth maps inferred from wide-angle experiments (a) and RF analysis (b) beneath Northern Morocco. Numbers show the Moho depth values at the points where a measurement is available. Color grid interpolates those points using a nearest neighbor algorithm.

Figure 7 (with caption below and on the same page)

a)

b)

Figure 7: a) Moho depth map as inferred from the combined results from controlled source experiments and RF data. b) 3D view of the same map. Reddish colors show the thinner zones beneath the Alboran Sea and the east Morocco. Deep blue colors show the deep crustal thickening beneath the Rif, where crustal thickness exceeds 50 km.

Figure 8 (with caption below and on the same page)

Figure 8: Earthquakes with magnitude > 2, as reported by the Instituto Geográfico Nacional catalogue in the period 2000-2014, overprinting the new crustal thickness map. White dots are for event with hypocenters above 40 km depth, black dots denote deeper events.