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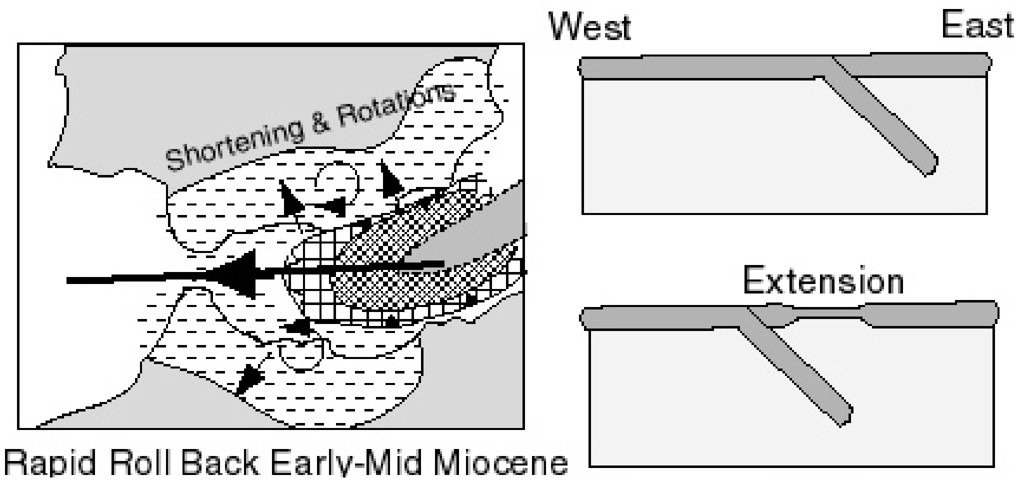
We discuss mantle structure and dynamics under the Gibraltar/Alboran Sea region. That region has been much studied, and a wealth of information is available about its crust. Nevertheless, there is no consensus yet on the type of model that best explains the geodynamic situation and evolution in the region. Figure 1 shows the two models that are most frequently invoked to describe the geodynamic situation of the region. These are, on one hand, the subduction-rollback (SR) model, and on the other, continental delamination or convective removal (CDCR).

a) Oceanic model (retreating subduction)



b) Continental model (convective removal)

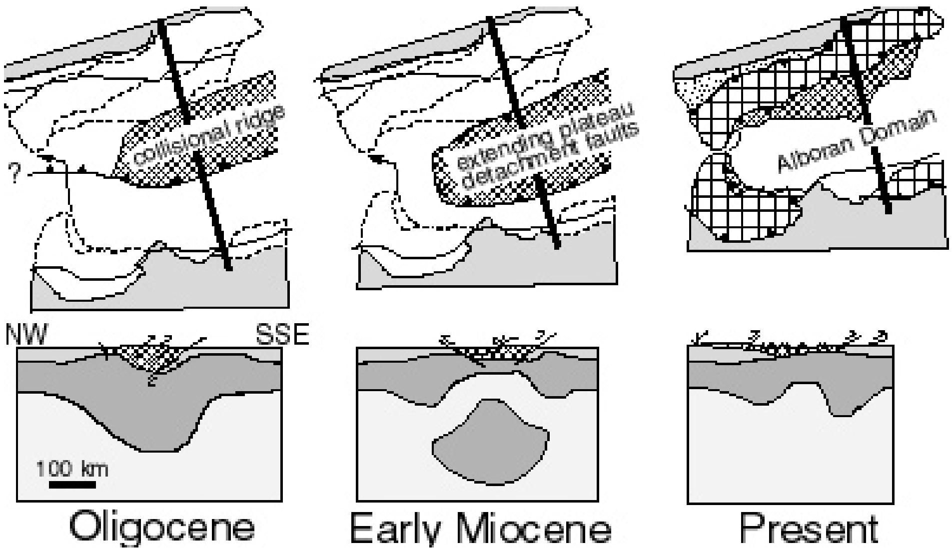


Figure 1 (redrawn from Calvert et al., 2000): The two types of geodynamic models that we test, a) the retreating subduction model of Lonergan and White (1997) and Gutscher et al (2002), and b) the convective removal model of Platt and Vissers (1989).

We attempt to direct test the geodynamic models, using adapted seismological techniques. The new constraints are based on observations of P-wave dispersion that are indicative of anomalous (layered) structure along the propagation path, and also seismic anisotropy, since it is capable of constraining the geometry of mantle flow, which is also rather indicative of the kind of geodynamic environment.
We propose that distinguishing the two types of models requires resolving two questions, 1) what is the *nature* of

that high-velocity anomaly, e.g., is it composed of oceanic or of continental lithospheric material?, and 2) what is the *shape* of the anomaly? It appears that up to recently, neither of these two questions has been well-resolved. We will thus propose techniques that are designed to directly address these questions.

The first technique that we use is based on observations of dispersed P-wavetrains that are expected for certain ray directions. Figure 2 shows waveforms from two teleseismic events observed at two stations, MTE in Portugal and CEU in Ceuta. The latter station has a fortunate location, in that it is positioned along the continuation of the high-velocity anomaly in tomographic models (see for example Gutscher et al., 2002). That station is thus at the ideal location for looking for the described dispersion phenomena. On the other hand, the station in Portugal (MTE) serves as a reference station, so that we can assure that any observed dispersion is really due to the anomalous upper mantle under the Alboran Sea, and not due to effects at larger distance or due to the earthquake source.

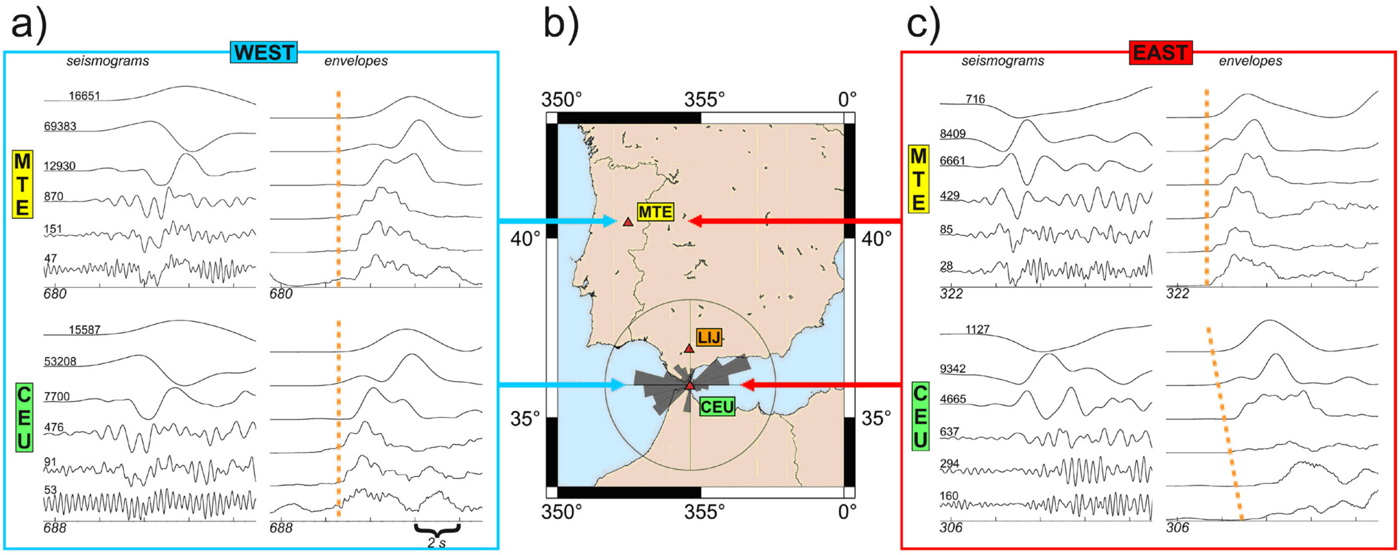


Figure 2: Dispersion observations. Waveforms of P-waves arriving at two stations a) from the West (earthquake in Columbia, 15.11.2004, Magnitude 7.2, lat. 4.69 Thursday, 11 February 2010Thursday, 11 February 2010deg, long -77.5 deg, distance 72.8 deg) and b) from the West (earthquake in Crete, 17.3.2004, magnitude 6, lat. 34.59 deg, long. 32.32 deg, distance 23.45 deg). Each seismogram is shown filtered in a series of filter bands (from the top: < 0.5 Hz, 0.05 - 0.5, 0.5 - 1.5, 1.5 - 2.5, 2.5 - 3.5, and 3.5 - 4.5 Hz), and corresponding smoothed envelopes. Amplitudes are given by numbers, and ticks give time intervals of 2 second. The observed dispersion is illustrated by a dashed line (after Bokelmann and Maufroy, 2007).

Figure 2c shows P-waves arriving from the East, for an earthquake occurring in Crete. The seismograms were filtered in a series of frequency bands. Waveforms are complicated, and smoothed envelopes are useful for tracing the arrival time across the different frequencies. The envelopes show an interesting difference between the two stations. While all frequencies arrive at about the same time at the reference station MTE, there is a clear dispersion at station CEU. High frequencies arrive up to about one second after the low-frequency arrivals. This effect has been observed in numerical modelling, and also in observations from known subduction zones around the Pacific (Abers and Sarker, 1996; Abers 2005). The P-waves arriving from the West, in Figure 2a, do not show such a difference between the two stations. In fact, there is hardly any frequency dependence of arrival times at the two stations, somewhat similar to the arrival from the east at MTE. The anomalous behaviour that requires explanation is the Eastern arrival at CEU that is passing through the upper mantle under the Alboran Sea.
We have studied a larger number of events, and we frequently find the dispersion behaviour for rays arriving at Ceuta from eastern direction, but never from Western direction, and neither do we find dispersion for the reference station in Portugal. This observation is consistent with a presence of a subducted slab under the Alboran Sea (to the east of Gibraltar).

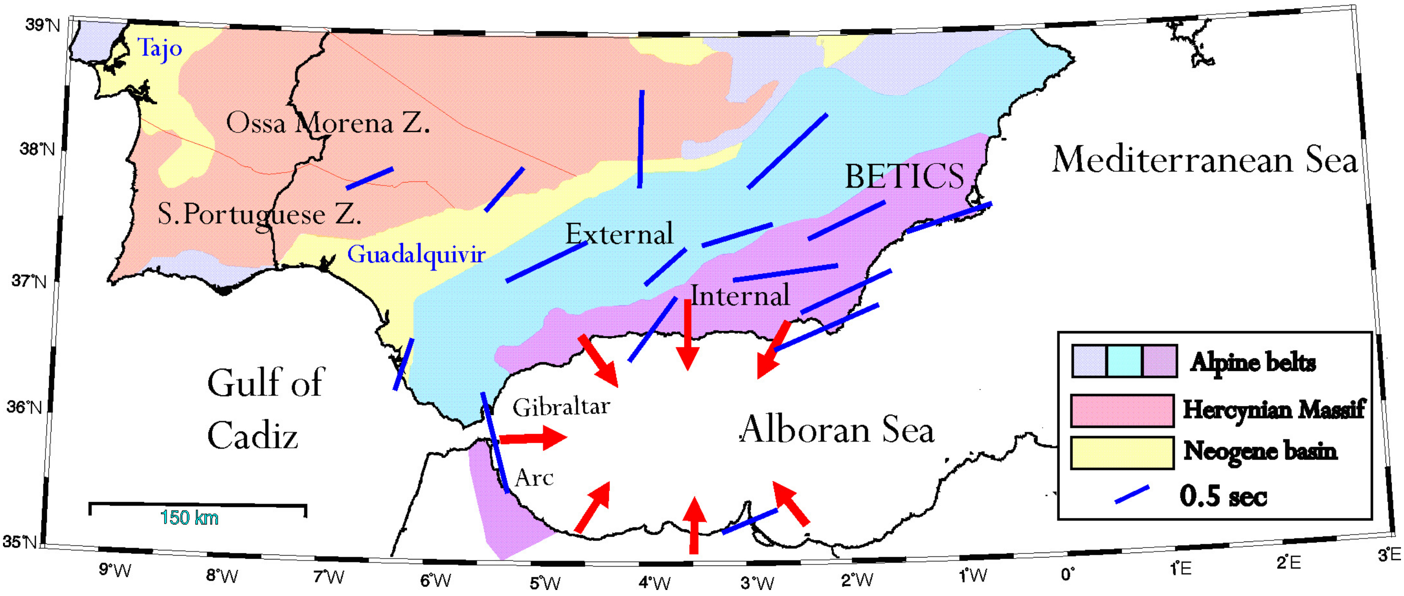


Figure 3: Map showing an illustration of the expected radial for the continental model (shown by red arrows), towards the Alboran Sea. Also shown is shear-wave splitting at each of the 16 stations: Weighted-mean fast orientations are given by the direction of the line. Splitting delays are given by its length (after Buontempo et al., 2008).

The continental model presented in Figure 1b proposes that a gravitationally unstable continental root has separated from the upper portion of the lithosphere and has foundered into the deeper mantle. The lithospheric root is thus replaced by asthenospheric material, which must be brought in from the side. In idealized theoretical models (Houseman and Molnar, 1997), this flow occurs simultaneously from all directions. Obviously, any lateral difference in 'boundary conditions' in the real Earth, as well as heterogeneity in temperature and material properties will perturb this symmetry. In a real Earth, such a radial replacement flow would probably occur preferentially from one side. The occurrence of radial flow thus represents a necessary feature for any continental-type model (also for continental delamination), and we can use it to critically test the continental model.

We do not know from which side that flow comes in, but it must necessarily be present at one of the edges of the model. Figure 3 thus shows a prediction of radial flow (red arrows). In a channel flow model, we are dealing with simple shear deformation with a horizontal flow direction. Seismic fast azimuths will match the (horizontal projection of) flow direction. This allows us to directly compare those predicted directions of radial flow with observed fast orientations.

Upper mantle seismic anisotropy can be detected from the splitting of teleseismic shear waves: a polarized shear wave propagating through an anisotropic medium is split into two perpendicularly polarized waves that travel at different velocities. From three-component seismic records, two parameters can be measured to quantify anisotropy: the difference in arrival time (∂t) between the two split waves, which depends on the thickness and on the degree of intrinsic anisotropy of the medium, and the azimuth Φ of the fast split shear wave polarization plane that is related to the orientation of the pervasive fabric (foliation and lineation) in the anisotropic structure.

We have analyzed shear-wave splitting at a set of 16 stations around the Alboran Sea. Details of data and results are given in Buontempo et al (2008). These are coherent with results from earlier studies (e.g., Diaz et al. 1998; Schmid et al., 2004). We show weighted-means for each station in Figure 3. Since fast orientations should be identical with the horizontal flow direction, we can directly compare the predicted flow directions (arrows) and the observed fast orientations. We note that there is little indication, in the available splitting data, of such a radial flow toward the Alboran Sea. Essentially, all stations show fast orientations that are more or less tangential to the Alboran Sea, rather than radial. Particularly in the Betics, the fast split orientations are trending parallel to the crustal large-scale tectonic structures, suggesting some coherence between crustal and mantle deformation. This suggests that a convective removal model is not supported by the SKS splitting data that are available so far. First results (Diaz et al., 2009) from the IBERARRAY broadband seismic network seem to confirm our observations.

The two observational constraints allow to critically test the geodynamic models that are most frequently discussed for the Alboran Sea region (Figure 1). An oceanic model (retreating subduction) predicts that some P-waves should have a characteristic type of dispersion. We have searched for this phenomenon in waves at two stations, and have found that this occurs frequently (and exclusively) for waves propagating through the mantle under the Alboran Sea. This is strongly indicative of the presence of a subduction zone under the Alboran Sea. The second type of constraint was based on seismic anisotropy, which allows to critically test the continental model (convective removal) since that model predicts radial flow to occur towards the Alboran Sea. This phenomenon does not appear in the observations, given the current station distribution. On the other hand, a subduction-induced toroidal flow is quite consistent with the observations.

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