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The Deep Structure of Corsica as inferred by a Broad Band Seismological Profile

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Abstract

To investigate the influence of inherited inhomogeneity in a lithosphere under extension, we studied the deep structure of Corsica, an island in the Mediterranean sea, at the boundary of the extensional Tyrrhenian basin, using a temporary array of eight broad-band seismographs. Between the stations in the western Hercynian part of the island and the stations in eastern Alpine Corsica, an average static station delay of 0.4 s was observed for P waves, and 0.7 s for S waves. The crustal structure is obtained through seismic data, gravity modeling and the receiver function method. The difference in crustal structure between the west and east of Corsica can explain only about half of the anomaly. Consequently we postulate a sharp increment in the thickness of the lithosphere to account for the remaining 0.2 s of P anomaly.

Introduction

As a consequence of the geodynamical evolution reported for example in *Facenna et al.*, [1996], Corsica, an island which forms the northwestern border of the Tyrrhenian sea, is morphologically divided into two parts by the central depression of Corte (Fig. 1). The western region consists mainly of Variscan granitoids, intruding metamorphic rocks overlain by volcanic and sedimentary upper Paleozoic series. The northeastern part of the island is referred as Alpine Corsica. This part consists of a stack of nappes, well-known for the occurrence of high-pressure, low-temperature metamorphic rocks [*Caron*, 1981] and clear evidence of extension [*Jolivet*, 1991]. We present here results on the deep structure of this island obtained through the study of P and S arrival times recording during a broad-band seismological survey and a gravity modeling. We show that the discontinuity between the western Hercynian part and the eastern Alpine part must extend into the deeper portion of the lithosphere. The knowledge of this structure brings new constraints to the kinematics of the regional extension.

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Study of P and S arrival times.

We installed during two months a seismologic line of eight stations perpendicular to the Alpine/Hercynian boundary (Fig. 1). The sensors were broad-band velocity sensors (50-.018Hz).

We selected teleseismic events in a range of distance from 30° up to 90° in order to study P phases with almost vertical incidence under the stations. The short length of the array allows us to assume that the effects of deep heterogeneity do not play a significant role and that the observed travel time anomalies originate at a shallow level under the stations. Two examples of P wave recordings in different stations are displayed in Fig. 2, where CURZ, EXTR, ASCO (C, E, A) are western stations and PLEC, VOLP, and LUCI (P, V, L) are eastern stations (Fig. 1). We performed cross-correlations between the different P phases and S phases recorded at each station available for a given event in order to compute the arrival time differences of P and S waves, between the stations, using the method of *VanDecar and Crosson* [1990]. Fig. 2 displays cross-correlation of P phases using CURZ as reference and obtained after applying a lowpass filter (0.7 Hz).

For the P waves we have:

$$C_{ij}^P = T_{ij}^P - S_i^P = P_{ij}^P + \Delta P_{ij}^P + \Delta T_{ij}^P - S_i^P \qquad (1)$$

where C_{ij}^P is the observed delay for event i in station j, which equals the true travel time T_{ij}^P minus an unknown time shift S_i^P. The time shift arises because the time baseline is undetermined from the measurement of time *differences*, but may also include source time errors. The true travel time can be decomposed in a term P_{ij}^P predicted for the background model (IASP91), which includes corrections for station elevation and ellipticity, an error ΔP_{ij}^P in this prediction due to event mislocation (the error being positive if the true event location is closer to the station) and a residual ΔT_{ij}^P, which represents the variation respect to the reference model.

The residual, consists of two time terms: $\Delta T_{ij}^P = \Delta T_j^P + \Delta M_{ij}^P$, where we consider a static station delay ΔT_j^P, associated with a crustal delay, and a 'mantle' contribution ΔM_{ij}^P.

We use a similar relation for S waves. The simultaneous use of P and S terms insures a better stability in the inversion. We set up a system of linear equations

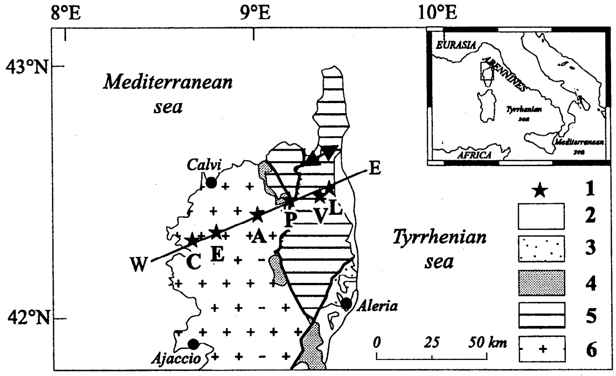

Figure 1. Geological map of northern Corsica. 1: The stars show the seismologic stations The line (W-E) shows the gravity profile. 2: quaternary units, 3: Miocene units, 4: ophiolite units, 5: schistes lustres, 6: W Corsica granitoids. The arrow denotes the fast polarization direction of SKS waves (after Margheriti et al., 1996).

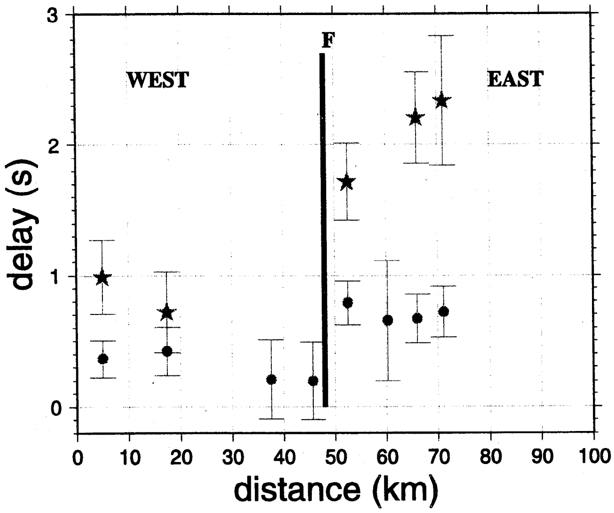

Figure 3. Lateral variation of static terms of the relative residuals for P waves (dots) and for S waves (stars) with 2σ error bars. The distance is relative to the western coast (point W on Fig. 1) The location of the Hercynian/Alpine is indicated as the bar labeled F.

to resolve the static station term, the mantle residual, and the source relocation terms:

$$\Delta T_j^{P(S)} + \Delta M_{ij}^{P(S)} - S_i^{P(S)} + \Delta P_{ij}^{P(S)} = C_{ij}^{P(S)} - P_{ij}^{P(S)} \quad (2)$$

We solve the overdetermined system of equations with 100 iterations of the LSQR solver [*Page and Saunders*, 1982]. Uncertainties were estimated with a bootstrap approach, in which we randomly removed 10% of the data and added Gaussian random errors to the remainder (using a standard deviation of 0.1 s for P and 0.5 s for S). This was repeated 30 times, from which conservative formal estimates of the standard deviations were obtained.

We selected 18 events well recorded by at least 5 stations and which provided cross-correlation factors larger than 0.9, and retrieve the unknown station delays with small standard deviations. Lateral variations of the static station term of P and S residuals are plotted in Fig. 3. Cross-correlation and corresponding inversion of the differents terms of delays were carried out for different lowpass frequencies (< 0.2 Hz, < 0.7 Hz, < 2.0 Hz). This showed the static terms to be rather stable and discrepancies smaller than the error bars of Fig. 3.

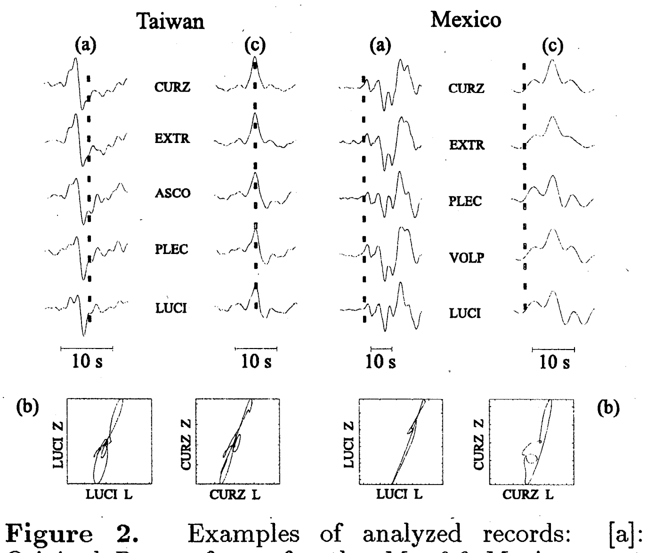

Figure 2. Examples of analyzed records: [a]: Original P waveforms for the M_s=6.8 Mexico event of 1996/02/25 and the M_s=6.4 Taiwan event of 1996/03/05. [b]: Polarization of P phases in the plane (Z, L). [c]: Filtered, cross-correlated P phases, using CURZ as reference.

For the P waves, a difference of around 0.4 s (0.7 s for S waves) was found between the western stations and the eastern stations: the waves reaching the eastern part of the island are late with respect to those recorded in the western part. This discrepancy is very sharp and seems to corresponds with the Alpine/Hercynian fault that divides clearly two domains of different propagation times.

Crustal structure

We first investigated if the observed relative P and S residuals can be explained by heterogeneities in the crust. The superficial structure of Corsica has been extensively studied (see for example, references in *Jolivet* [1991]). The deeper crustal structure was deduced from seismic refraction profiles (see [*Ponziani et al.*, 1996] for a review). The Moho depth is about 30 km under northern Corsica, whereas, 70 km off the western coast of the island, the Moho depth is only 18 km, and 25 km in the Tyrrhenian basin, east of the island [*Ponziani et al.*, 1996].

Because these refraction data provided only the velocity structure but not the detailed layer thicknesses, we carried out a 2D short-wavelength gravity modeling along our seismological profile, taking into account the constraints brought by the interpretations of these seismic profiles to refine the geological structures (the Birch's law providing a relation between the density and the velocity). We used the Bouguer anomalies measured in Corsica by *Bayer et al.* [1977] for which the station density was about 1 station/km^2. The data around the profile were projected and interpolated at an interval of 3 km. As reference density model, we used a 30 km thick crust with a starting density of 2800 kg/m^3. The regional anomaly was removed from the Bouguer anomaly, in order to avoid large wavelength perturbations. The main characteristics of this profile are to the west the influence of the volcanic Monte Cinto, 2710 m high, and to the east a large positive gravity anomaly which corresponds to the presence of heavy metamorphosed oceanic rocks [*Jolivet et al.*, 1991]. Fig. 4 shows the lateral heterogeneity of the structure (note strong vertical exxaggeration).

To provide better constraints for the structure beneath the eastern part of the profile, we inverted the receiver functions for station LUCI and VOLP. Receiver functions are produced by a time domain deconvolution. and we applied the inversion technique of *Ammon et al.* [1990]. The results are plotted in Fig. 5. This inversion first confirms the depth of the Moho and the rough crustal structure obtained by gravity anomaly, but led us to add a thin low-velocity layer in the middle of the crust to fit the receiver function. This thin layer is compatible with the gravity anomaly as shown in Fig. 4. It could be interpreted as the trace of a detachment fault

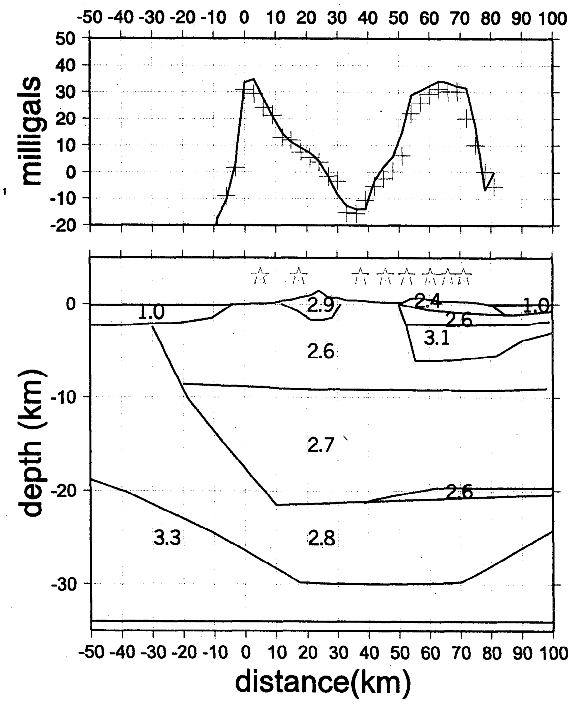

Figure 4. [a]: Observed and computed Bouguer anomaly along the profile W-E displayed on Fig. 1. [b]: Crustal structure deduced from seismic and gravimetry results. The numbers denote density in Kg/m^3, the stars indicate the station locations.

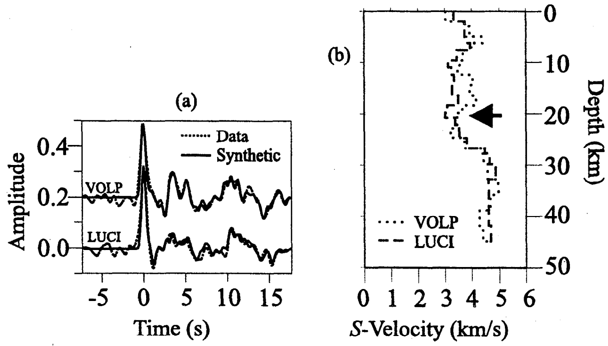

Figure 5. [a]: Receiver function at stations VOLP and LUCI. [b]: Corresponding best 1D model obtained by Ammon's inversion. The arrow shows the thin low-velocity layer.

linked to extensional processes in the region. Our refined crustal model was thus in good agreement with the Bouguer anomalies and with the P waveforms. For the westernmost stations, the significant dip of the crustal layers did not permit the computation of the receiver function in a 1D model.

To interpret the delay obtained between the western and the eastern stations we first verified that the teleseismic P waves reaching Corsica with incidence angle of around 10° to 25° (with respect to the reference earth model postulating flat crustal layers) keep an almost vertical ray path through the crust. Consequently, we computed the polarization direction of P waves at CURZ (the westernmost station) and at LUCI (the easternmost station) (see examples on Fig. 2) and verified that the P waves kept a quasi-vertical ray path in the crust, beneath each station, despite the lateral crustal heterogeneity.

In our computation, we took into account the gentle slope of the Moho and of the deep crust towards the western coast, and the presence of dense and rather high velocity oceanic crust which comprises the main part of alpine Corsica, approximately 4 km thick. We thus obtained, between 30 km depth and the surface, a travel time of 4.5 s for a P wave reaching the station CURZ and 4.7 s corresponding to the station LUCI. Even if we postulate a lateral change of velocity in the upper crust, from 6.0 km/s in the west to 5.7 km/s in the east, the value obtained in the Tyrrhenian basin by *Ponziani et al.* [1996], the maximum shift obtained in the crust from west to east is 0.25 s. Consequently, the propagation time of almost vertically incident P waves computed in this crustal structure does not explain the full delay observed for the eastern part.

Lithospheric anomaly

Since variations in relative P (or S) delay could not be explained by heterogeneities in the crust it results most probably from a difference in lithospheric thickness. Using surface waves, the thickness of the lithosphere was estimated by *Panza et al.* [1983] to be only 40 km in the

Tyrrhenian sea and 70 km under the western margin of Corsica. If we assume that this discrepancy originates under northern Corsica, a thinning of the lithosphere from west to east, we obtain an extra delay of 0.16 s for eastern Corsica (20/7.7 - 20/8.2), which is sufficient to explain the delay observed for teleseismic P waves.

An alternative explanation would be that the eastern lithosphere is on average much slower (5% if its thickness below the Moho is about 30 km), but such a large contrast is less likely.

Discussion and Conclusion

The heat-flow distribution in the Tyrrhenian sea and surrounding areas [*Mongelli et al.*, 1991] is in qualitative agreement with this lateral variation of lithospheric thickness. Values of 50 mWm^{-2} were measured in Hercynian Corsica, whereas values higher than 80 mWm^{-2} were found in Alpine Corsica, and values higher than 160 mWm^{-2} in Tuscany.

A lateral variation of thickness or/and velocity in the lithosphere could produce a lateral change in SKS wave splitting and in the apparent fast shear wave polarization azimuth. This analysis requires recording of SKS waves with good signal-to-noise ratio. During our experiment we recorded too few such data to obtain reliable results. *Margueriti et al.* [1996] obtained a fast SKS polarization azimuth ($\phi = 30°$, $\delta t = 1.2\ s$) for a station located in the northeast of the island (see Fig. 1). These authors associated the ENE-trending anisotropy, which they found in the region between Corsica and Tuscany with an asthenospheric flow, which results from the E-W extension in the lithosphere and its thinning.

However, our results based on an analysis of teleseismic P travel time residuals clearly show a sharp transition between the two parts of the island. The analogy (through a much smaller scale) of this lithospheric structure, beneath a high topography region (the topography often exceeds 2000 m in Corsica), at the boundary of the extensional lithosphere of Tyrrhenian-Apennine system, and that described by *Wernicke et al.* [1996] under the Sierra Nevada, close to the extensional Basin and Range, is striking. Strong contrasts in lithospheric thickness, heat flow, lateral change of crustal velocity, anisotropy, and the presence of asthenospheric flow are indicators of a recent thinning of the lithosphere. The tectonic implications of such a deep structure beneath Corsica are to be discussed in a future paper, in the context of the geodynamic evolution of the Tyrrhenian sea and the Apennine range.

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