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Three-dimensional upper mantle structure beneath the intraplate Atlas and interplate Rif mountains of Morocco

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Abstract. We integrate observations based on teleseismic *P* wave travel times and available geologic data to infer that the lithosphere beneath the intraplate Atlas mountains is thin and/or it is characterized by lower *P* wave velocities, while beneath the interplate Rif mountains and the adjacent Alboran Sea a previously thickened lithosphere has been delaminated into the upper mantle. Using surface geology and geochronology data, previous studies have proposed that lithospheric delamination took place in this region. In this study we show through analysis of teleseismic *P* wave residuals the existence of a high-velocity (> 3%) upper mantle body, which is interpreted to be the delaminated, rigid lithosphere. This high-velocity layer is overlain by a very low velocity uppermost mantle material (Pn velocities of about 7.6-7.7 km s^{-1}) interpreted to be asthenospheric material replacing the delaminated lithosphere. Teleseismic *P* waves recorded by a recently installed digital seismic network and an older analog network in Morocco provide the residuals database. A total of 734 *P* wave residuals from 92 selected teleseismic earthquakes are used to document the spatial pattern of upper mantle velocity structure beneath northern Morocco and the Alboran Sea. Subsequent use of these residuals in a tomographic inversion scheme produced a three-dimensional velocity image of the upper mantle. We infer from the *P* residuals that strong upper mantle velocity anomalies exist beneath both the Rif and Atlas regions. The Rif stations show negative residuals (~ 1-1.5 s) for ray paths from the east and northeast and show positive residuals (~ 1-1.5 s) for ray paths from the northwest and southwest. Tomographic results indicate the existence of a high-velocity body (~ 3% higher velocities) in the upper mantle beneath the eastern Rif and Alboran Sea, extending approximately from subcrustal depths down to a depth of at least 350 km. In the western Rif, however, 1-2% lower velocity material is imaged in the upper mantle. The residuals of the Atlas stations also show azimuthal variations. In general, most of the *P* waves that travel beneath the High and Middle Atlas have about 0.5-1.0 s delays. In contrast, the rays that travel beneath the northwestern margin of the Atlas mountains and the adjacent Moroccan Meseta area show negative residuals (~ 1 s), suggesting that higher velocity material exists beneath the platform area adjacent to the Atlas mountains. Tomographic results indicate that beneath most of the Atlas system the uppermost mantle has about 1% lower velocities. Beneath the Alboran Sea region, however, reported low uppermost mantle Pn velocities contrast strongly with higher velocity upper mantle velocities obtained by our analysis. Low-velocity uppermost mantle beneath the Alboran Sea underlain by a high-velocity upper mantle material is used to support earlier interpretations of lithospheric delamination beneath the Rif and Alboran Sea regions. The enigmatic occurrence of subcrustal earthquakes in these regions is also consistent with this active delamination mechanism.

Introduction and Geologic Framework

The intraplate Atlas mountains of Morocco, consisting of the E-W oriented High Atlas mountains and the NE-SW oriented Middle Atlas mountains, are an integral part of the African Atlas system that stretches for a distance of about 2000 km from the Atlantic coast of Morocco in the west to the Mediterranean coast of Tunisia in the east (Figure 1). The High Atlas mountains constitute the highest elevated region in this mountain chain with a maximum elevation of about 4100 m. The Rif mountains in the north, however, are interplate mountains and show very different structural styles compared to the Atlas mountains [*Pique et al.*, 1987].

Two major geological events that took place in the Mesozoic and Cenozoic affected the geologic history and present-day tectonics of Morocco: Opening of the North Atlantic and the Western Tethys in the early Mesozoic, and the Africa-Europe continent-continent collision in early Cenozoic time [e.g., *Schaer*, 1987; *Jacobshagen et al.*, 1988].

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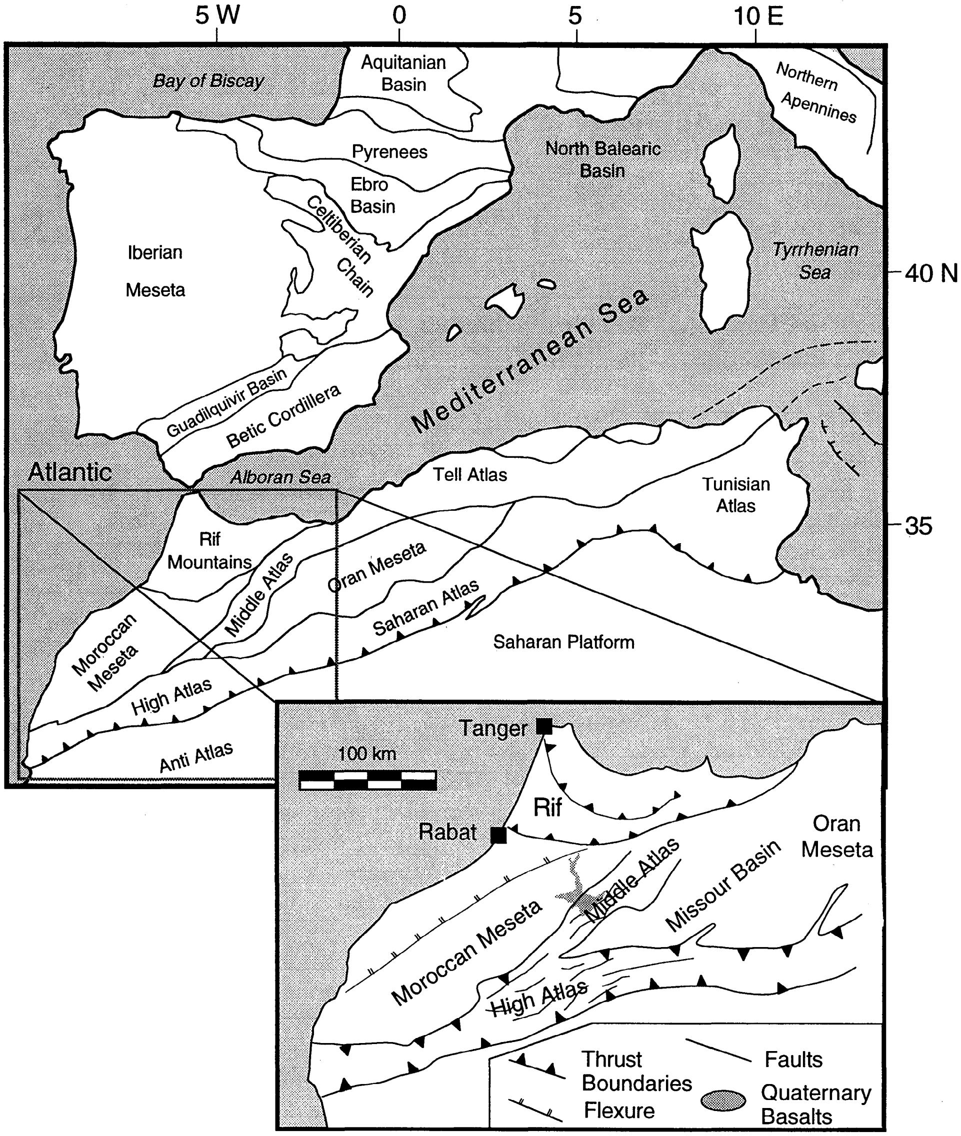


Figure 1. Generalized tectonic map of the western Mediterranean region, and the location of the study area. The Atlas system stretches from the Atlantic coast of Morocco to Tunisia totaling about 2000 km in length (modified from *Dewey et al.* [1989]).

These two events resulted in four major mountain ranges in NW Africa: The Rif, High Atlas, Middle Atlas, and Anti Atlas ranges (Figures 1 and 2). The Rif mountains, which are an integral part of the "Gibraltar arc" surrounding the Alboran Sea, are characterized by numerous, well-mapped, asymmetric, Alpine-type, complex nappe structures [e.g., *Morley*, 1987; *Doublas and Oyarzun*, 1989; *Ait Brahim*, 1991]. The High Atlas mountains, however, are located at an intraplate setting and exhibit a structural symmetry. They were formed over the site of a Mesozoic rift [*Dresney,* 1975]. Although much of the inversion was accomplished during Neogene time, some authors suggested that the initiation of uplift in the High Atlas was as early as Late Jurassic- Early Cretaceous time [*Sichler et al.,* 1980; (W. Beauchamp et al., Intracontinental rifting and inversion: The Missour basin and Atlas mountains of Morocco, submitted to *American Association of Petroleum Geologists Bulletin*, 1995)]. The geological evolution of the Middle Atlas mountains is similar to that of the High Atlas. Rifting in early Mesozoic time was followed by intense compression, mostly transpressive, in the Cenozoic [*Dresney*, 1988]. The Anti Atlas mountains, however, are located between the High Atlas and the Saharan craton. Uplift history of the Anti Atlas goes back to the Hercynian orogeny (300-340 Ma) [*Pique et al.*, 1987]; but the most recent phase of uplift is from Pliocene to present [*Jacobshagen*, 1992].

Being intracontinental in nature, the Atlas mountains are fundamentally different from the typical orogens located along convergent/collisional plate boundaries, like the Himalayas, Andes, or the Alps. The Atlas mountains (both Middle and High Atlas) lack many of the observed diagnostic geological features of interplate mountains. Flyschs, nappes, regional metamorphism, ophiolites, granitoid intrusions and large-scale asymmetric deformation are missing in the Atlas mountains. Very little is known about the crustal and upper mantle structures beneath the Atlas, making the comparison of the deeper structures of the Atlas and interplate-type mountains infeasible. The occurrence of earthquakes in and around Morocco is among the signatures of active tectonics in this region. A seismicity map by *Ramdani et al.* [1992] shows the active deformation (seismogenic) belts in Morocco, which include the Rif, the Middle Atlas, and central

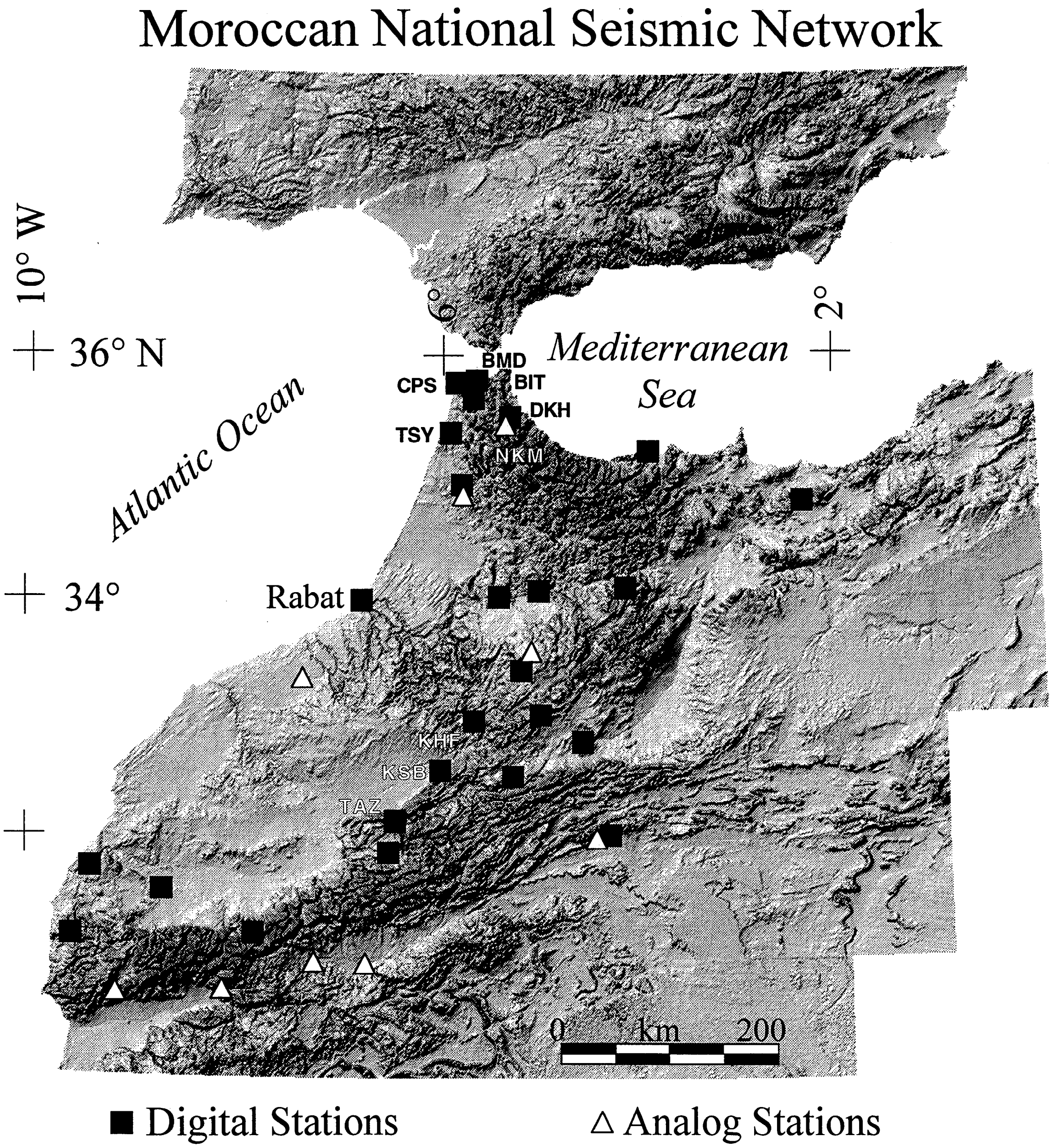


Figure 2. Map showing both digital and analog seismic stations in Morocco. Background image is a topographic shaded-relief map generated using a high-resolution digital elevation model showing the extent and dimensions of the Atlas and Rif mountains. Names of the stations that are referred in the text and in the following figures are also shown.

High Atlas mountains. Furthermore, the existing information on the focal mechanism solutions of shallow earthquakes in the High and Middle Atlas indicates strike-slip and/or thrust deformation [*Medina and Cherkaoui,* 1991]. In the Rif region mainly strike-slip focal mechanisms dominate [*Medina and Cherkaoui,* 1992]. Of special interest is the reported occurrence of intermediate-depth earthquakes beneath the central High Atlas and Middle Atlas [*Hatzfeld and Frogneux*, 1981; *Tadili and Ramdani*, 1983; *Cherkaoui*, 1991]. All of the intermediate-depth events are small in size ($M < 4.5$) with a maximum depth of about 160 km. *Hatzfeld and Frogneux* [1981] state that there is a seismic gap between depths of about 30 and 55 km. This intermediate-depth seismicity is not related to any subduction zone in the Atlas, as indicated by surface geology. Neither is a well-developed Wadati-Benioff zone observed. Kinematic models, although limited in resolution in the western Mediterranean region, show transcurrent plate motions followed by limited north-south convergenge since the Cretaceous [*Dewey et al.*, 1973]. The Atlas and the Rif regions are the only places known to us where intermediate-depth seismicity is observed without any apparent Neogene and/or Quaternary subduction. Mapping the upper mantle structure beneath the Atlas would significantly improve our understanding of the mechanism that is responsible for the intermediate-depth seismicity.

In addition to earthquake data collected in the past two decades, the available geophysical data in Morocco include seismic refraction profiles and gravity data. Numerous reversed and unreversed refraction profiles transect the Rif, Middle Atlas, and western segment of the High Atlas [*Hatzfeld and Ben Sari*, 1977; *Makris et al.*, 1985; *Schwarz and Wigger*, 1988; *Wigger et al.*, 1992; *Ramdani*, 1993]. Analysis of refraction profiles suggests that the uppermost mantle velocity, Pn, ranges from 7.8 to 8.0 km/s beneath the Atlas mountains. However, the data range where Pn is the first arrival is limited and very emergent in character. Both refraction and gravity studies suggest that the Moroccan crust is relatively thin (~ 30 km) beneath the Rif, Middle Atlas and Anti Atlas and reaches its maximum thickness (about 40 km) beneath the High Atlas [*Demnati*, 1972; *Van Den Bosch*, 1981; *Tadili et al.*, 1986; *Ben Sari*, 1987; *Wigger et al.*, 1992].

At least three different geodynamic evolution models have been proposed for the Atlas mountains, and three others for the Betic-Rif mountains. The geodynamic models proposed for the Atlas evolution include (1) crustal scale block uplift of the Mesozoic Atlas Gulf [*Stets and Wurster*, 1982]; (2) transpressive forces reactivating preexisting structures [*Froitzheim et al.*, 1988]; and (3) inversion of a midcrustal, subhorizontal detachment system which was developed in the early Mesozoic rifting stage [*Giese and Jacobshagen*, 1992]. A common ground in these proposed models is that they all accept the reactivation of older structures as the main mechanism of uplift. The geodynamic models proposed for the evolution of the Betic-Rif system and the extension in the Alboran Sea include (1) emplacement of a mantle diapir beneath the Alboran Sea uplifting the lithosphere and forming the Gibraltar Arc and nappe structures in the Betic-Rif system [*Loomis*, 1975; *Weijermars*, 1985]; (2) reactivation of the normal faults of the passive margins of the Alboran block into complex thrust sheets along the Gibraltar arc [*Duran-Delga and Oliver*, 1988]; and (3) convective removal of a thickened lithospheric root (delamination) and subsequent uplift resulting in the Gibraltar arc and nappe structures in the Betic-Rif system [*Platt and Vissers*, 1989].

A recently installed, 30-station, short-period seismic network in Morocco [*Ben Sari,* 1991] provides reasonably dense teleseismic ray coverage beneath the Moroccan Atlas and Rif mountains. Data collected by these stations allow us to bring additional constraints to the structure and geodynamic evolution of the intracontinental Atlas mountains and to compare the upper mantle structures of an intraplate and interplate mountain systems. In this study we analyze teleseismic *P* wave residuals to map the three-dimensional upper mantle velocity structure beneath the Rif and Atlas mountains.

Data and Results

The new seismic network in Morocco provides most of the seismic data used in this study. Additional data were provided by analog recordings of nine other seismic stations, which have been operational for about the past three decades in Morocco [*Tadili and Ramdani*, 1983; *Ben Sari*, 1987; *Cherkaoui*, 1991]. Figure 2 shows the locations of both the digital and analog stations. The natural frequency of all receivers is 1 Hz. Data from the digital network are recorded on a trigger basis with 100 samples per second sampling rate, and also on analog drums continuously. Arrival times of *P* and *PKP* waves generated by teleseismic earthquakes (Figure 3) are used to obtain the teleseismic residuals for each station. The residuals were obtained by subtracting the calculated travel times of the International Association of Seismology and Physics of the Earth's Interior (IASPEI-91) earth model of *Kennett and Engdahl* [1991] from the observed travel times. A total of 734 first arrival times from 92 teleseisms at distances between 20 and 90 degrees and 150 and 180 degrees were read from the seismograms and used in this study. We took considerable care in selecting these 92 teleseisms. More than 250 teleseismic events were analyzed initially. We eliminated the majority of these data because either first arrivals were emergent in character or the number of recording stations was not adequate. Most of the selected events show impulsive first arrivals; for these events we read the arrival times. In order to take advantage of station distribution and provide additional data coverage beneath the Atlas and Rif mountains, it was necessary to utilize additional analog data. The analog data prevented the use of the waveform correlation technique to pick relative arrival times [*Evans and Achauer,* 1993]. Each seismic record had the same British Broadcasting Company radio time signals that formed a uniform time base for all records. All of the residuals were corrected for the station elevations and then for each teleseismic event a network average was calculated, and this average residual was subtracted from the individual residuals in order to eliminate errors in locations and origin times. This averaging may bias the residuals, since the number of the readings used for each teleseismic event varies. This would reduce the magnitude of the residuals, but locations of the anomalies would not change.

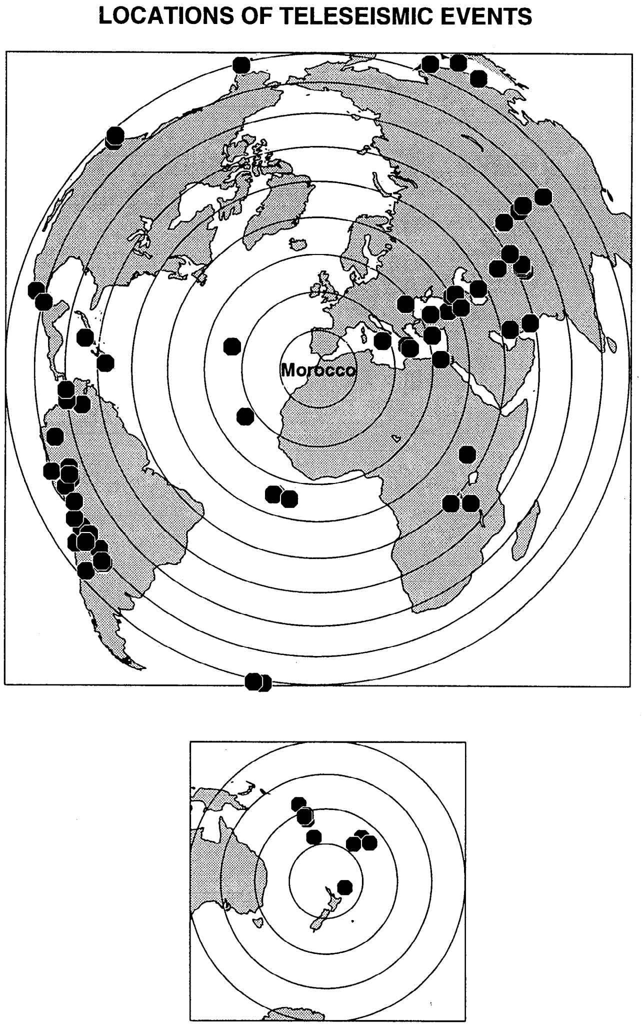

LOCATIONS OF TELESEISMIC EVENTS

Figure 3. Azimuthal distribution of teleseismic events and their distances from the Moroccan network. Concentric circles are drawn at 10° distance intervals. The total number of teleseismic events used in this study is 92.

Residual Analysis

Some of the teleseismic *P* wave travel time residuals are shown as composite plots in Figure 4. For the Rif stations we have compiled all the readings from stations CPS, BIT, BMD, NKM, DKH, and TSY in one plot (Figure 4a), since these stations are only a few tens of kilometers away from each other. Similarly, we compiled readings of stations TAZ, KSB, and KHF into one plot (Figure 4b) to present a general trend of the residual anomalies in the Atlas ranges. First-order observations from these plots are that (1) beneath the eastern Rif there is a strong high-velocity anomaly, (2) to the west of the Rif there is a low velocity, and (3) beneath the Atlas ranges, especially beneath the Middle Atlas, there is a lower velocity. In the Moroccan Meseta area a relatively higher velocity material exists in the uppermost mantle. Negative residuals of up to 1.0-1.5 s are obtained for some of the stations in the Rif region from the easterly azimuths (Figure 4a). A relatively sharp change to positive residuals is observed when the rays arrive from the westerly azimuths (Figure 4a). This low-velocity anomaly extends toward the Azores-Gibraltar plate boundary and is probably a reflection of this complex plate boundary processes [*McKenzie*, 1972]. These significant differences in the teleseismic residuals indicate that the upper mantle beneath the Rif region has strong heterogeneities. The Atlas region shows upper mantle heterogeneities as well. Most of the rays that travel beneath the Middle Atlas range (i.e., 30°-60°N azimuth) show late arrivals. However, the rays traveling beneath the platform area to the northwest of the Atlas ranges (the Moroccan Meseta) have negative residuals up to 1 s (Figure 4b), suggesting that higher velocity upper mantle material exists beneath this region.

To show the lateral extent of the upper mantle heterogeneities responsible for these residuals, we projected the teleseismic ray paths to the surface from a depth of 350 km (Figures 5 and 6), which is estimated to be the base of major velocity variations and/or depth limit in our database as will be discussed below. Only those rays with residuals greater than 0.5 s (slow rays) and less than -0.5 s (fast rays) are projected to the surface and shown in Figure 6. The eastern Rif is clearly marked by faster rays (Figure 6a). The

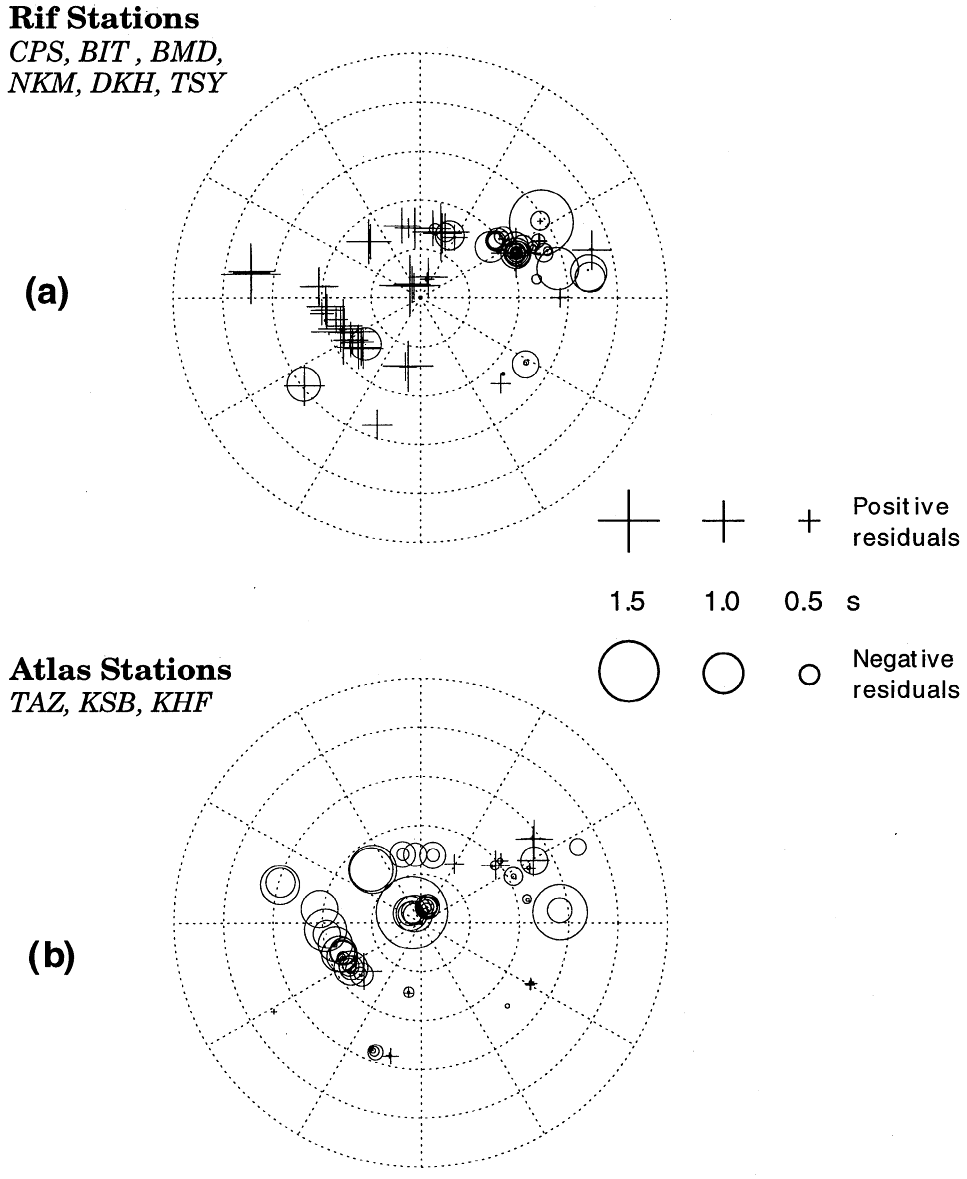


Figure 4. Teleseismic P wave residuals of some selected stations in Morocco plotted with respect to their incident angles and azimuths. Concentric circles representing incident angles are drawn at 10° increments, azimuth lines drawn at 30° increments. Positive residuals are marked with pluses and negative residuals are marked as open circles. The size of the anomaly is proportional to symbol size. (a) Composite residuals of six Rif stations. (b) Composite residual plots of three Atlas stations. See Figure 2 for location and codes of stations shown.

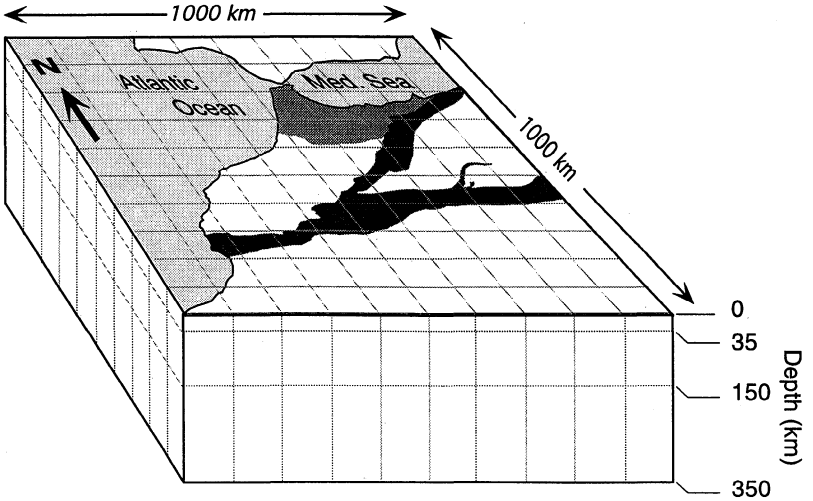


Figure 5. Three-dimensional view of the block geometry used in tomographic inversion in Figure 7. For the tomographic inversion the region was divided into three layers each consisting of 100 blocks. The boundaries of the Rif and Atlas ranges are marked in the figure.

northernmost limit of this higher velocity upper mantle material is beyond our resolution limit. This anomaly, however, probably extends well into southern Spain as shown by the studies of *Plomerova et al.* [1993] and *Blanco and Spakman* [1993]. The western Rif upper mantle low-velocity anomaly is also evident in Figure 6b as slow rays dominate the western part of the Rif. Also evident from Figure 6b is that the Middle Atlas is mostly dominated by slow rays.

Teleseismic Tomography

Teleseismic *P* wave residuals clearly indicate that there are strong velocity variations in the upper mantle beneath Morocco. Upper mantle velocities change considerably, even at short distances (~ 50 km), beneath the Rif and Atlas regions. However, residuals alone only give a qualitative picture of the velocity anomalies. To obtain quantitative images of these velocity anomalies we applied a tomographic inversion technique [*Aki et al.*, 1977] to the existing residuals. This inversion technique has been successfully applied to many regions [e.g., *Aki et al.*, 1977; *Oncescu et al.*, 1984; *Plomerova et al.*, 1993; *Amato et al.*, 1993] and details of the technique will not be repeated here. The technique requires the region of interest be divided into layers and the layers into blocks, each block having a uniform initial velocity. The velocity perturbation within each block that explains the observed residuals are then calculated in a damped least squares scheme. The technique does not yield

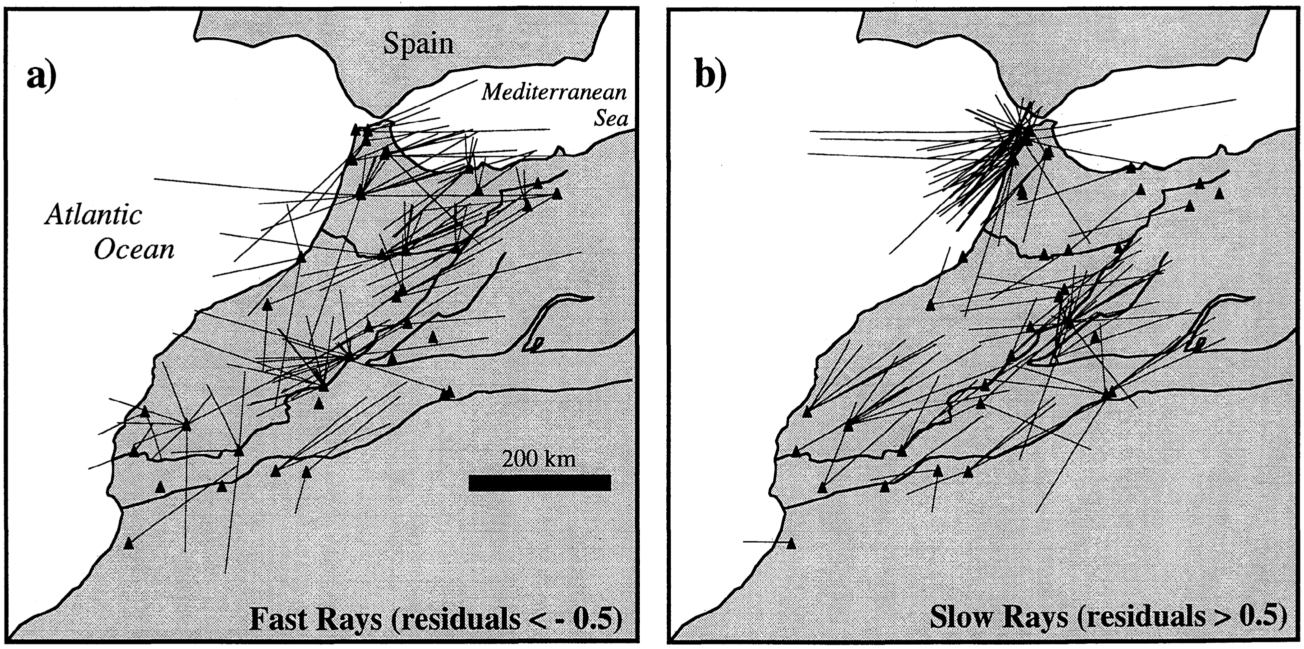


Figure 6. Surface projections of those ray paths having residuals (a) less than -0.5 s and (b) larger than 0.5 s. Rays were projected to the surface from a depth of 350 km (see Figure 5). These figures show the lateral extent of each ray path in the upper mantle. Faster rays dominate in the Rif and Meseta areas, while slower rays dominate to the west of the Rif and in the Atlas ranges.

absolute velocities; only variations from an initial model can be calculated.

The Moroccan seismic network covers an area of approximately 600 x 500 km^2 (see Figure 2). We chose an area of 1000 x 1000 km^2 around the seismic network and divided the area into 10 x 10 blocks, each block having 100 x 100 km dimensions (Figure 5). A three-layer model to a depth of 350 km was constructed. To a first-order approximation, the first layer in the model represents the crust (0-35 km) with a velocity of 6.5 km/s. The underlying layer represents the mantle lithosphere (35-150 km) with 8.1 km/s velocity, and a final layer (150-350 km) with 8.5 km/s average velocity. Our initial tests and resolution analyses showed that below 350 km, significant velocity perturbations cannot be resolved. Hence the maximum depth of the blocks was kept at 350 km. The coverage of ray paths is not uniform beneath the region of interest (Figures 6 and 7d). Since there are not many stations in the Moroccan Meseta and High Atlas, the sampling at shallow depths is especially poor beneath these regions. A more uniform ray path coverage is obtained below the crust.

One of the critical questions in constructing a model for teleseismic inversion is the size of the blocks to be used and their positions. The block size is limited by the station distribution [*Aki et al.*, 1977] and was fixed to be 100 x 100 km in the inversion. This limits the horizontal resolution in our inversion results. Also, the positions of the blocks are arbitrary. Since the size of the blocks are fixed, care must be taken when positioning these blocks. If a block encloses a region where there are strong velocity variations, velocity perturbations obtained after the inversion are some average over the region: hence results will not reflect the real velocity structures, even at the scale of the block size. To minimize the effects of this phenomenon and to estimate the degree of smoothing, a general procedure is to change the center of the blocks slightly (~ 10-20 km) and then average the solutions. If no major velocity boundary is crossed by a single block, velocity perturbations obtained by this change in block locations should be very similar to that of the original block location, and the variance of these velocities averaged over many such offsets should be small. The variance, then, can be used as a check on the parameterization artifacts. We calculated 81 different solutions from the same residuals data set. The central points of these blocks were varied by 10 km in each step up to 40 km in all directions. The maximum shift of a block, then, was little less than one-half the size of each block. An average over these 81 solutions gives the final velocity image shown in Figure 7a, and contours of the diagonal elements of the resolution matrix are shown in Figure 7b. Standard deviations, in percentage, due to block shifting and averaging is shown in Figure 7c, and ray hit counts for each block is shown in Figure 7d.

In order to select an accurate damping value we performed a series of inversions using a number of damping values and decided to use a damping value of 300 throughout the inversion procedure (Figure 8). This damping value provided a reasonable constraint in the resultant velocity anomalies while constraining the effects of the noise in the data. Although smaller damping values provided better rms errors, the velocities obtained from these values were unrealistically high or low.

The velocity anomalies in the crustal layer (0-35 km) is not well resolved due to the relatively small thickness of the crust and the relatively nonuniform ray path coverage from teleseismic events. For this reason a geological interpretation will not be given for the crustal layer. The second layer (35-150 km), generally representing the lithosphere, shows quite significant lateral velocity variations (Figure 7a). Similar to our residual analysis, teleseismic tomography images high-velocity uppermost mantle material in most of the Rif region. Velocity perturbations in this region reach > 2%. Velocities up to 2% lower are obtained in the northwestern part of the Rif, again confirming our residual analysis interpretation. A Meseta block (see Figures 5 and 7) shows about 2% higher uppermost mantle velocities, and the Atlas ranges show about 0.5 -1% slower velocities. In the third layer, which is assumed to represent the asthenosphere (150 - 350 km), the eastern Rif high-velocity anomaly becomes quite strong (~ 2 - 3%), suggesting that no widespread asthenospheric material is present at this depth. The high-velocity material covers the eastern half of the Rif and the Alboran Sea. The western Rif low-velocity anomaly is still present at this depth with 1.5 - 2.0% slower velocity anomalies. Along the Atlas ranges no significant velocity perturbations are imaged at this depth. These results suggest that there are no lithospheric roots to the Atlas mountains.

Contour maps of the resolution matrix shown in Figure 7b indicate that the poorest resolution in our inversion is in the crustal layer, a common problem in teleseismic inversion. However, solutions for the other two layers are reasonably well constrained. Standard deviations of velocity perturbations obtained by sliding block locations and averaging over the results obtained give an idea about possible errors due to the ambiguity of placing the blocks in the space domain. Figure 7c shows that positions of the blocks affect mostly the crustal layer's solution, since the highest standard deviation is observed there (± 0.5%). In the next two layers, however, standard deviations vary between 0.1 and 0.2 %. A velocity perturbation anomaly of about 2%, then, would actually be in the range of 2.0 ± 0.2%. The new three-dimensional velocity model obtained from tomography provides a variance improvement over 50% to the residuals (Figure 9). There are still significant variations left in the data which cannot be improved further due to a number of limitations such as limited number of stations, azimuthal distribution of teleseismic earthquakes, and large block sizes.

Teleseismic Inversion Resolution Tests

A concern in all inversion studies is the resolution, accuracy, and uniqueness of the imaged anomalies. One has to show either statistically or through modeling that the obtained anomalies are not artifacts of the technique and/or noise in the data. All of the velocity perturbations that we calculated using the teleseismic inversion are consistent with the anomalies seen in the residual plots. The teleseismic inversion, then, helps in constraining the depth distribution of these anomalies and provides quantitative information about the magnitude of the anomalies.

We performed two different resolution tests using synthetic data. In the first test we generated a model with a checkerboard pattern velocity anomalies (+2 % and -2 % both in the horizontal and vertical directions). A synthetic residuals data set was calculated using the same event-station pairs as are observed. This noise-free data set was then inverted using the same parameters that we used in our inversion calculations. The results obtained from this test are shown in Figure 10a. Anomalies in the middle and third layers are reasonably well resolved. Velocity perturbations show a similar checkerboard pattern as in the input model, although the magnitudes of the imaged velocity anomalies (~ 1-1.5 %) are slightly less than those of the input values. The crustal layer, as expected, does not show any significant anomalies except in northern Morocco where the station distribution is the densest.

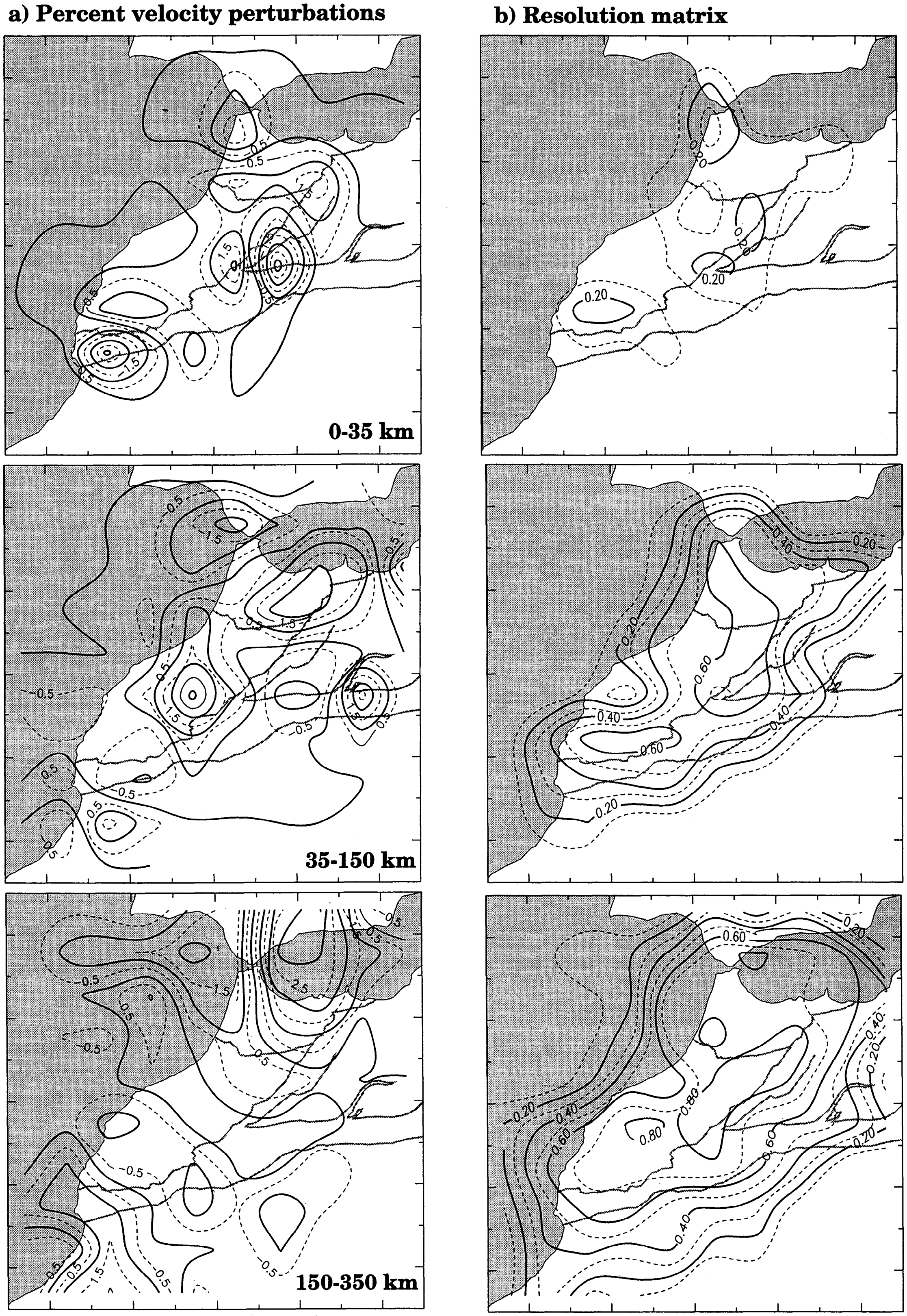
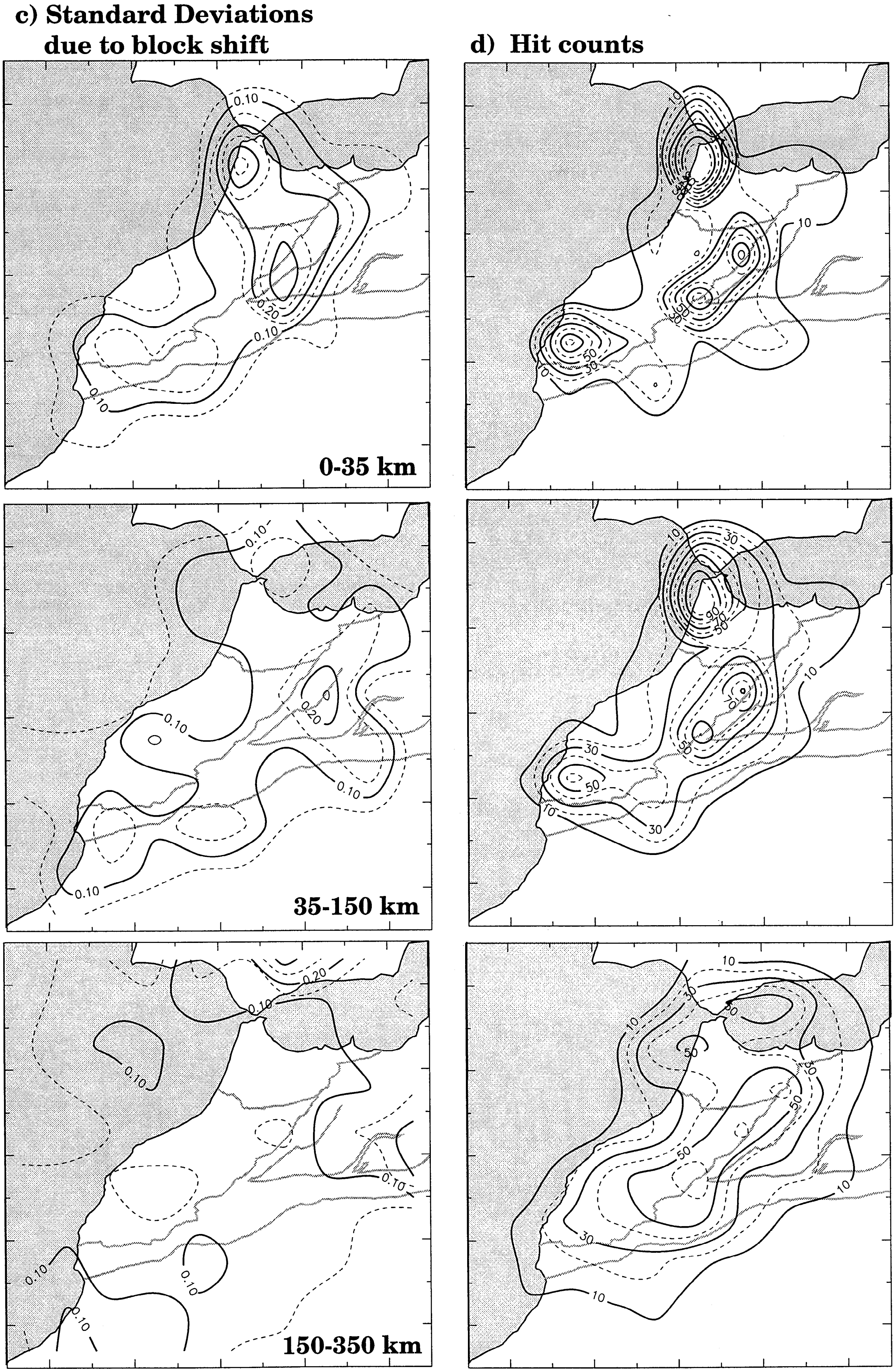


Figure 7. Map showing results of tomographic inversion. (a) velocity perturbations in percentage are contoured with 0.5% increments. High (negative residuals) and low (positive residuals) velocity anomalies in the eastern and western sides of the Rif, respectively, extend deep into the upper mantle. The Atlas ranges show slower velocity anomalies in the second layer. The upper mantle beneath the Rif and Alboran Sea is characterized by high-velocity anomalies, whereas to the west of the Rif the upper mantle is characterized by low velocities. (b) Contour representations of the resolution matrix diagonal elements. (c) Standard deviations of velocity perturbations in each block determined by shifting the block centers and averaging the results of 81 different inversions. Large standard deviations (~ 0.5%) are obtained for the first layer indicating that velocity perturbations obtained for this layer strongly depend upon parameterization of blocks. The remaining two layers show reasonably low standard deviations. Contour interval is 0.05%. (d) Hit counts for each block. Contour interval is 10.



c) Standard Deviations due to block shift

d) Hit counts

Figure 7. (continued)

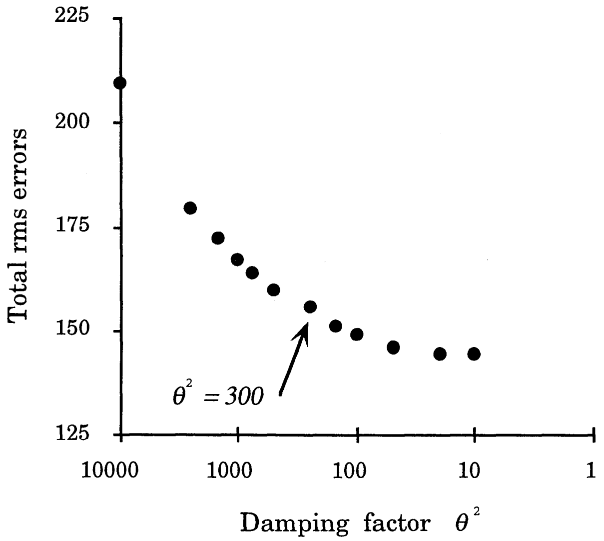


Figure 8. Plot showing total rms values versus different damping values used in teleseismic inversion. A value of 300 was chosen for the analysis.

The second inversion test involved a spike anomaly in the model. We constructed a model in which only one block had a 3% higher velocity anomaly and examined the effects of smearing of velocity anomalies in the resultant images. The anomaly was placed in the second layer in the Rif area where a high-velocity anomaly is observed. The test results show (Figure 10b) that the anomaly is resolved, and there is no significant smearing of velocity anomalies into adjacent blocks in both vertical and horizontal directions. The magnitude of the original anomaly is slightly underestimated due to both the damping value used in the inversion and the lack of sufficient ray coverage.

Discussion

Existence of a weak and probably thinned lithosphere beneath the intraplate Atlas mountains is inferred from the analysis of teleseismic *P* wave residuals and available geologic data. Slightly lower velocities beneath the Atlas, at a depth range of 35-150 km, most likely indicate a weak lithosphere. We argue that there are no lithospheric roots beneath the Atlas mountains, since no high-velocity material is imaged beneath the Atlas ranges. Both the Middle and High Atlas are recognized as sites of early Mesozoic rifting [*Dresney*, 1975]. Although no ocean was formed at that time, the rifting must have been significant as evidenced by the widespread and thick Triassic basalts in these areas [*Saadi et al.*, 1985]. The rifting processes undoubtedly affected the lithosphere and probably weakened it. It is unlikely that a low velocity layer would remain intact since the Triassic; however, the zones of weakness in the mantle lid due to rifting may have been reactivated by the Cenozoic collision of Africa and Europe. The occurrence of intermediate depth earthquakes beneath the Atlas ranges [*Hatzfeld and Frogneux*, 1981; *Tadili and Ramdani*, 1983] could be attributed to reactivation of lithospheric structures. A

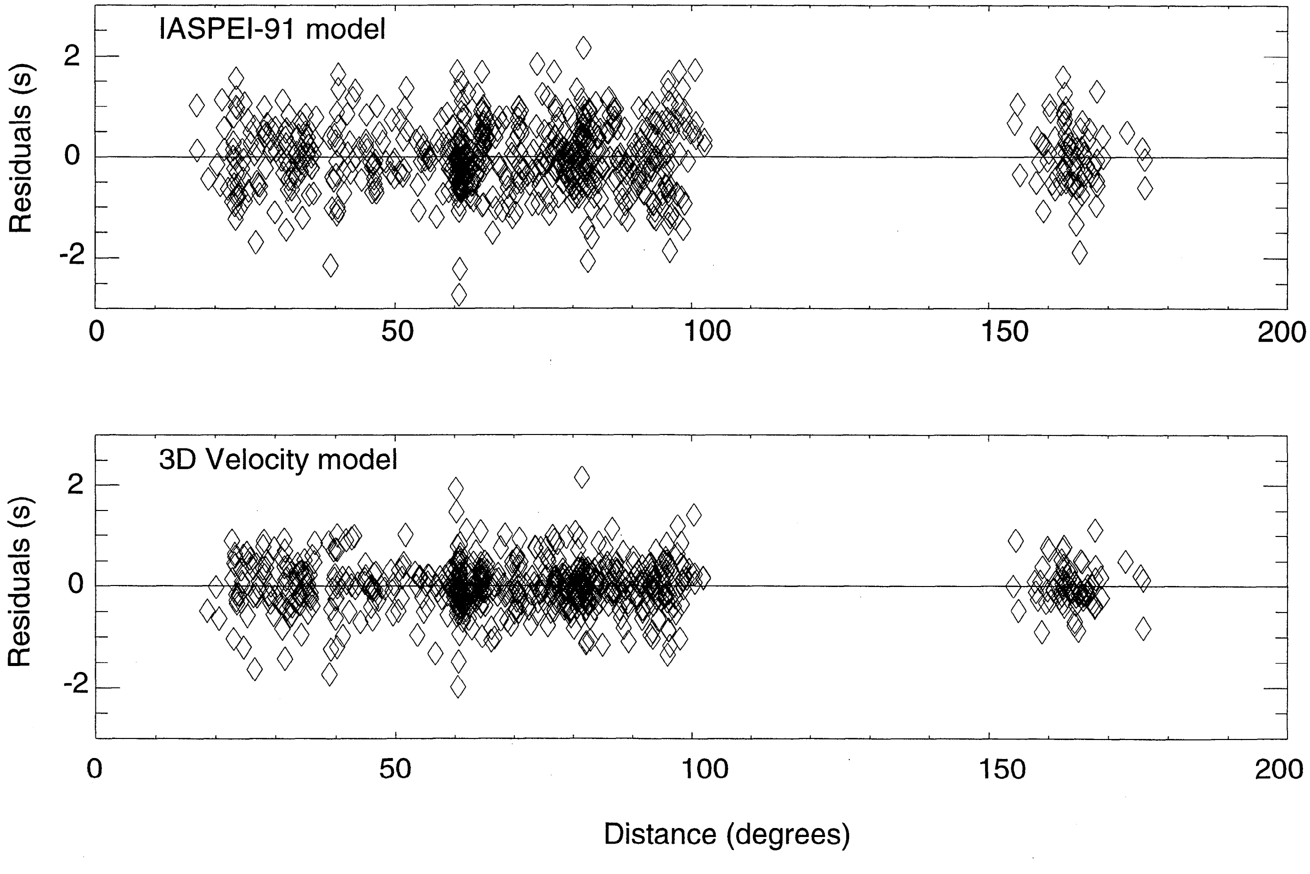


Figure 9. Plots showing teleseismic *P* wave residuals. (Top) Teleseismic residuals calculated from IASPEI-91 model; (bottom) same dataset residuals calculated using the new three-dimensional model obtained from tomography. Variance improvement is over 50%.

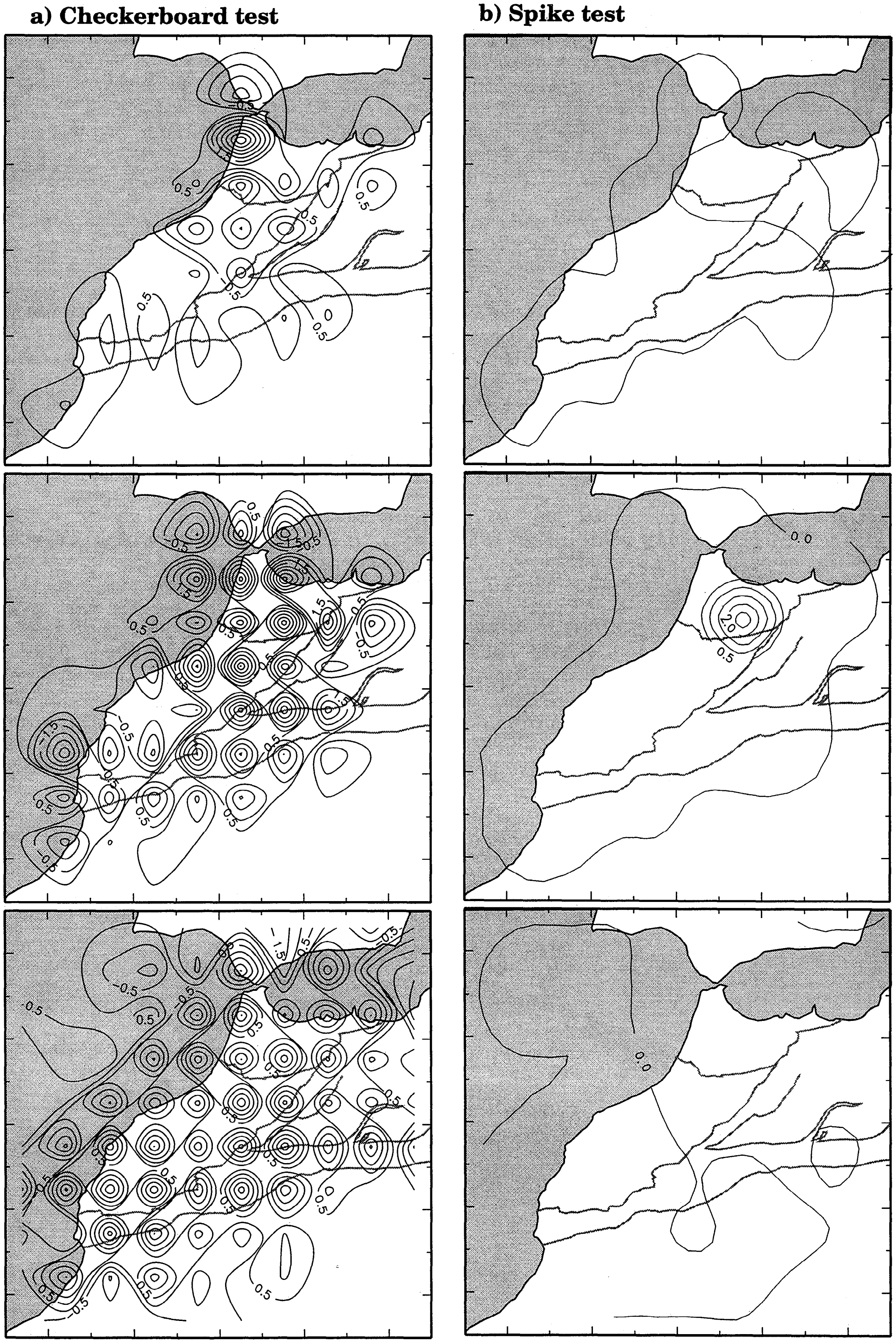


Figure 10. Maps showing inversion test results of the synthetic residuals. (a) Successive blocks both in horizontal and vertical direction were assigned +3% and -3% velocity perturbations, forming a checkerboard velocity pattern. Synthetic residuals were generated using the same number and locations of the teleseismic earthquakes as in the case of the observed data set, and inverted to obtain these images. The lowest resolution, as seen from the inversion results, is in the crustal layer. Contours are drawn at 0.5 % increments. (b) Resolution test for a spike model. A block with 3% higher velocity is placed in the second layer beneath the Rif region where we image a high-velocity anomaly from the observed data set. Synthetic residuals were calculated and these images were obtained upon inversion. The block with higher velocity is successfully imaged.

maximum of 20% shortening is reported for the High Atlas [e.g., *Giese and Jacobshagen*, 1992], which corresponds to a little over 20 km of shortening in the central High Atlas, and less elsewhere. This is consistent with our teleseismic tomography results suggesting that the lithosphere did not thicken. It seems unlikely that ~ 20 km of shortening would form a mountain range as extensive as the High Atlas, a few hundred kilometers long with high peaks reaching close to 4000 m at some localities. The lower velocity (higher temperature) material in the upper mantle beneath the Atlas ranges suggests that there may be a positive buoyancy force contribution to the uplift of the Atlas mountains (Figure 11). In a similar study, using teleseismic and local earthquakes, *Roecker et al.* [1993] showed that beneath the intracontinental Tien Shan mountain belt of central Asia there is also a low-velocity zone in the upper mantle reaching a maximum depth of about 300 km. The low-velocity upper mantle material may be a common feature for intracontinental mountain belts. That is, weakness zones in the lithosphere and below may be a major factor in the formation of intracontinental deformation and mountain building processes.

Beneath the Rif region and to the northeast beneath the Alboran Sea, however, high-velocity material extends to at least to 350 km depth in the upper mantle. This strong upper mantle high-velocity anomaly contrasts with the western Rif/Azores-Gibraltar low-velocity upper mantle anomaly. A sharp vertical transition boundary near the strait of Gibraltar separates these anomalies. *Platt and Vissers* [1989] suggested that extentional collapse of a thickened continental lithosphere beneath the Alboran Sea is responsible for the present-day extension in the Alboran Sea and thrusting along the Gibraltar arc. *Watts et al.* [1993] using seismic reflection data in the Alboran Sea concluded that crustal and lithosphere thinning occurred in this region. A thickened continental lithosphere, now present in the upper mantle but detached from the overlying crust, is the most likely candidate for the higher velocity body imaged based on teleseismic residuals (Figure 11). As a result of this hypothesized delamination episode, low-density asthenospheric material would have replaced the cold and denser lithosphere at shallower depths. Although our velocity models do not have the necessary resolution to decipher the relatively thin low-velocity layer overlying the high-velocity detached lithosphere, seismic refraction data in the Alboran Sea show extremely low (7.5-7.9 km/s) Pn velocities [e.g., *Banda*, 1988].

The high-velocity upper mantle body that we interpret to be the delaminated lithosphere beneath the Rif was also mapped to extend in a northeasterly direction beneath the Alboran Sea and southern Spain. Analysis of teleseismic data recorded by the Spanish seismic network suggests up to a 6% velocity increase in the upper mantle beneath southeastern Spain [*Plomerova et al.*, 1993] . *Blanco and Spakman* [1993] also showed the presence of a similar high-velocity anomaly in the upper mantle beneath the Alboran Sea and Southern Spain. They used both local and teleseismic *P* wave arrival times, as reported by the International Seismological Centre bulletins, and interpreted this high-velocity anomaly in the upper mantle as detached subducting lithosphere. Inferring from the deep seismicity beneath southern Spain, earlier researchers also speculated on the presence of a lithospheric body located deep in the mantle beneath this region [*Udias et al.*, 1976; *Buforn et al.*, 1991]. Our results show that this high-velocity lithospheric body extends into the Rif area as well. Although it is difficult to differentiate between the geophysical signatures of a subducted lithosphere and a previously thickened and then delaminated lithosphere,

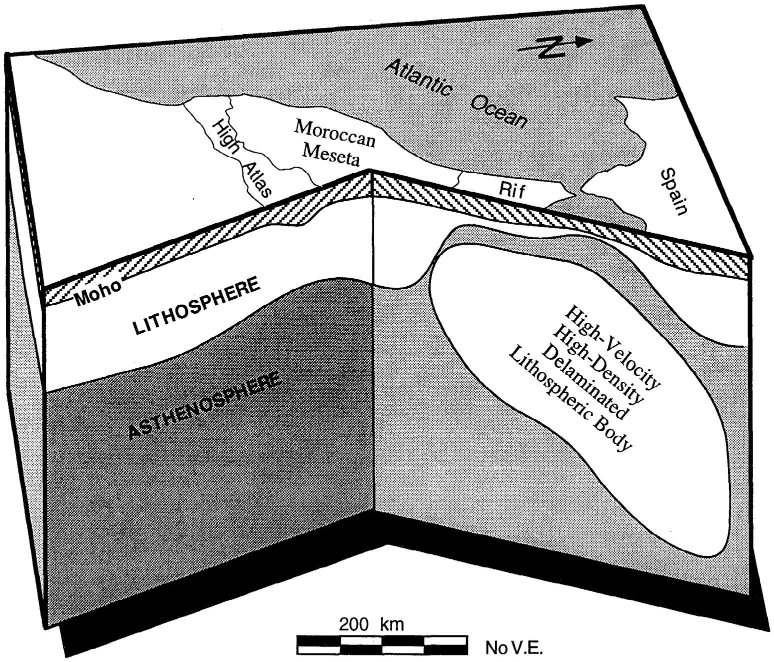


Figure 11. A schematic representation of the interpreted cross section across the Atlas and Rif/Betic regions. This interpretation is meant to show a gross upper mantle structure based on analysis of teleseismic residuals. Lithospheric thinning beneath the Atlas is inferred from the positive residuals. Beneath the Rif and Alboran Sea regions teleseismic *P* wave residuals and tomographic inversion results show that high-velocity material exists in the upper mantle. Very low Pn velocities in the uppermost mantle are overlain by high-velocity upper mantle material. In a recent study *Seber et al.* [1996] discussed the occurrence of intermediate-depth earthquakes beneath the Alboran Sea and surrounding regions and the presence of a seismic gap in the uppermost mantle beneath the Alboran Sea region.

several factors suggest that this anomaly is a result of delamination of a thickened continental lithosphere rather than simple subduction: the width of the anomaly (~ 200 km) and its oblique orientation to any plate boundaries, and also the fact that it extends beneath continental regions of both Africa and Iberian plates. The Alboran Sea, where the proposed delamination episode most likely initiated, is now underlain by a thin continental crust and has subsided 2-4 km since the Middle Miocene [*Platt and Vissers*, 1989]. Extensive Neogene/Quaternary volcanism and normal faulting, probable consequences of delamination processes, characterize the Alboran Sea at the present time. Radial thrusting around the Alboran Sea (Betic and Rif thrusts) probably developed as a result of a thermal uplift between 22 and 15.5 Ma as evidenced by very high cooling and uplift-exhumation rates obtained from radiometric and paleontological dates [*Zeck et al.*, 1992]. This type of geometry, that is, subsidence at the center and thrusting along the edges, has been shown by thermomechanical modeling to be an expected consequence of delamination [*Burgess and Nur*, 1994].

Our results suggest that among the proposed models for the evolution of the Betic-Rif system, the delamination of a previously thickened continental lithosphere is the most likely geodynamic model. Additional geophysical data are also presented in a most recent study by *Seber et al.,* [1996]. The mantle plume model of *Loomis* [1975] and *Weijermars* [1985] would predict a lower velocity upper mantle beneath the Alboran Sea, which contradicts the observed high velocity body in the upper mantle. Similarly, the Alboran block model of *Duran-Delga and Oliver* [1988] does not predict any special upper mantle processes and is insufficient to explaining the present-day extension in the Alboran Sea. It only accounts for the thrusting along the Gibraltar arc. A typical subduction idea is discarded on the basis of the extent of the high-velocity upper mantle anomaly, as it extends both into southern Spain and northern Rif continental areas, and the lack of geologic evidence for a Neogene subduction zone.

Finally, teleseismic residuals and tomographic inversion results suggest that there is low-velocity upper mantle material to the west of the strait of Gibraltar. This anomaly does not seem to extend toward the south. It is restricted to a narrow zone extending mostly toward the west. Because of its location, this low-velocity zone is most likely related to plate boundary processes along the Azores-Gibraltar seismic zone [e.g., *Grimson and Chen*, 1986].

Conclusions

A recently installed seismic network in Morocco has provided an opportunity to study upper mantle structure beneath the intracontinental Atlas and interplate Rif mountains of Morocco. Based on our interpretation of teleseismic P wave residuals, we conclude that the lithosphere beneath the intracontinental Atlas mountains is relatively thin (Figure 11) and characterized by low-velocity upper mantle material below a depth of about 150 km. This low-velocity layer probably represents upwelling of asthenospheric material beneath the Atlas mountains. Since only about 20 km of shortening is documented across the Atlas mountains, which is relatively small to form a mountain range like the Atlas, a positive buoyancy force generated by the low-velocity (high temperature) material might be contributing to the uplift of the Atlas mountains.

Beneath the interplate Rif mountains a high velocity body in the upper mantle is imaged using teleseismic P wave residuals. We infer from both velocity anomalies and geologic evidence that this high velocity body corresponds to a delaminated continental lithosphere beneath the Rif-Betic mountain belts (Figure 11). We suggest that the high-velocity upper mantle body is overlain by a low-velocity, low-density asthenosphere beneath both the Alboran Sea and the Rif region of Morocco. Present-day extension in the Alboran Sea, accompanied by extensive Neogene volcanism, is probably a consequence of this inferred delamination episode. Thrusting along the Gibraltar arc, which formed the Rif and Betic mountains, was contemporaneous with the extension in the Alboran Sea. The thrusting may have developed as a response to the sudden thermal uplift resulting from the lithospheric delamination episode in the Alboran Sea region, and radially propagated away from the center, as the center collapsed and started subsiding.

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