Upper crust velocities beneath Nekor fault and Al-Hoceimas region

Tomografía sísmica local en el Rif Oriental (Marruecos)

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SUMMARY

To study the relationship between earthquakes distribution and seismic images, we have applied a tomographic method to image a strike-slip fault in North Morocco and have found that the occurrence of earthquakes is not only controlled by the state of tectonic stress but also dictated by the material heterogeneity in the crust. We have attempted to construct an integrated model of seismic, electric, magnetic as well as heat flow properties across northeast of Morocco from analysis of arrival times of 221 local earthquakes and from the previous geophysical surveys. The seismic images obtained show distinct features that may be related to the main tectonic events developed since the Miocene in the region. A pronounced low-velocity zone at 5 km depth parallels to Nekor fault, coinciding with an anomalously high conductive structure and low gravity values, which is interpreted as a fault gouge zone and/or a fluid-filled subsurface rock matrix. From 10 km depth downwards a weak positive velocity zone is imaged along the same area in accordance with the depth that fault gouge is stable. The results of the seismicity and the seismic velocity for Al-Hoceimas region may indicate that the concentration of earthquakes are confined in the high velocity area. It is interpreted to be a brittle and competent layer of the upper crust which sustains seismogenic stress in contrast with the low velocity near Nekor fault, where deformation is aseismic, even if the slip occurs. In the eastern coast line of Morocco, from geological, magnetic and thermal features we can infer that at the shallowest layers of the upper crust exists a high density body probably formed by Miocene volcanic rocks in relation with a large fast velocity anomaly obtained at 5 km depth.

Key words: earthquake, strike-slip fault, gouge-zone, seismicity, low-velocity zone, tomography, Alboran sea

INTRODUCTION

The study area is a part of the complex Rif chain, which runs along the northern coast of Morocco forming the southern branch of the Betic-Rif arc. This arc is the westernmost termination of the perimediterranean Alpine chains and can be considered as the result of deformation of the small Alboran block between northwest Africa and Iberia since the early Tertiary. As a consequence of the NNW-SSE convergence between Africa and Iberia this block is being expulsed to the west-southwest (Rebaï et al., 1992). The Alboran block is delimited to the north by Cadiz-Alicante fault in Spain and to the southeast by the Nekor fault (NK) in Morocco. The relative motion of the Alboran block took place first along the transform zone, and only after the late Miocene did slip occur along the Nekor fault (Frizon de Lamotte, 1987). The westward motion of the Alboran block stopped in the Pliocene, and at present we are observing the development of N-S trending normal faults with E-W extension (Morel et al., 1989; Aït Brahim and Chotin, 1989). The Nekor fault is one of the greatest discontinuities in the Rif, as has been shown by geological observations, and as such it could have played an important role in the geodynamics of the Alboran Sea and surrounding areas. At present, Nekor fault is imagined for a strongly marked topography, although it is not possible to find evidence of Quaternary slip and can not be identified on seismic reflection profiles (Gensous et al., 1986).

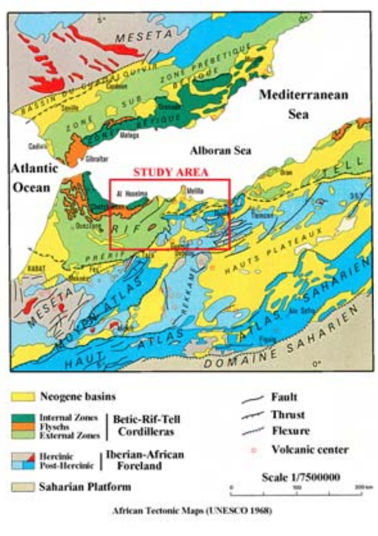

Figure 1. A geological map of southern Spain and northern Morocco. The geology and tectonic are from African Tectonic Maps (UNESCO 1968).

The northern NK region is fractured by distributed NE-SW to N-S striking high-angles faults that exhibit apparent left-lateral strike-slip offsets and by a conjugate NW-SE oriented group of more minor faults with apparent right-lateral slip component (Ait Brahim et al., 1989; Fetah et al., 1987; Saadi et al., 1984a).

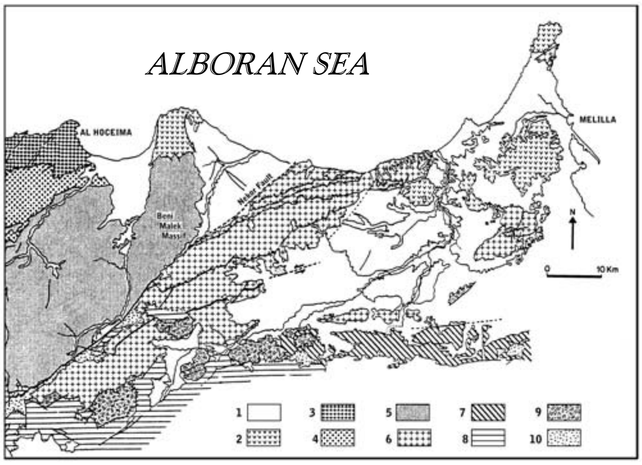

Figure 2. *Geological map of the eastern Rif showing the boundaries between the most important units. Legend: 1. Quaternary, Messinian-Pliocene sediments. 2. Volcanic rocks. 3. Internal Zones. 4. Flysch nappes. 5. Ketama unit. 6. Temsamane area. 7. African foreland. 8. Aknoul nappe. 9. Senhadja nappe. 10. Olistostromes. From Frizon de Lamotte (1985).*

DATA SELECTION

We have used P wave arrival times from digital and analog data recorded by Seismic Networks which belong to CNCPRST in Rabat (Morocco), Physique du Globe at Mohamed V University, in Rabat (Morocco), IAG in Granada (Spain), IGN in Madrid (Spain) and ROA in San Fernando (Spain). The figure 3 shows the distribution of seismic stations used in this study (triangles). We have selected exclusively the local earthquakes which have been recorded at least in five stations placed in the African continent. Finally, we selected a total of 221 earthquakes, whose hypocenters are located using the method of Lienert et al. (1986). However because of difficult availability of arrival times from seismic stations placed in north Morocco, the root mean square (rms) arrival time residual calculated from hypocenters is high, 0.75 sec., and solely the 51% of the earthquakes selected have rms smaller than 0.8 sec. Because of this reason, the database was relocated using the tomographic method of Zhao et al. (1992), after removal any arrival time differences that exceeded a certain threshold value. The events were relocated in six different velocity models from 5.8 to 6.9 km/s in the upper crust, from 6.4 to 6.8 km/s. in the lower crust and from 7.9 to 8.1 km/s. in the upper mantle. Comparing the relocated hypocenters from different models with the initial ones we can observe that the highest correlation coefficient (0.9) corresponds to the model: 6.0, 6.5 and 8.1 km/s., which coinciding with the minimum rms arrival time residual. We attain to decrease rms arrival time residual down to 0.43 sec. after the inversion.

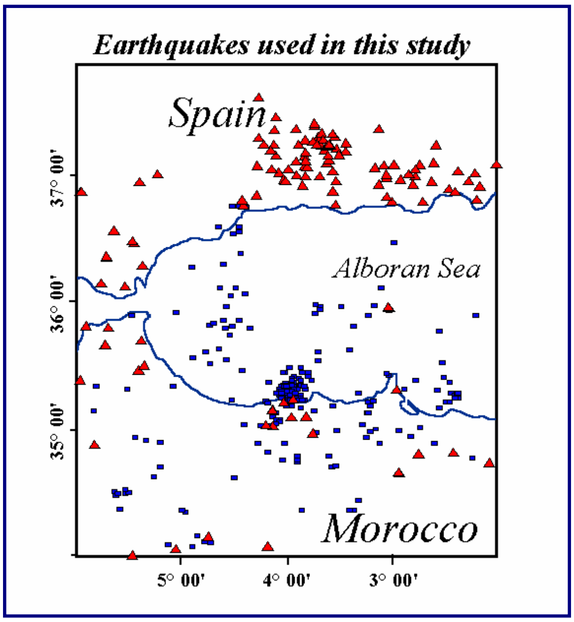

Figure 3. *Distribution of seismic stations (triangles) used in this study. The squares denote the hypocenters of earthquakes.*

METHODOLOGY AND RESOLUTION

We used the tomography method of Zhao et al. (1992, 1994) to determine the 3-D P- wave velocity structure. We set up a 3-D grid in this study with a grid spacing of 45 to 18 km in the horizontal direction and 5 to 10 km in depth. The poor seismic distribution in the area and the fact of nearly 56% earthquakes are shallower than 10 km determine the grid space. The selected initial velocity model for the tomographic inversion is derived from results of the velocity independent methods (Wadati diagram technique). Moreover some inversions were conducted by using the same tomography technique and data set, but by changing the P- velocity gradually from 5.9 to 6.1 km/s in the upper crust and from 6.4 to 6.8 km/s in the lower crust, with an interval of 0.1 km/sec. The P-velocity of 6.0 km/sec for upper crust and 6.5 km/s for lower crust give the minimum rms residual. This model is in agreement with the aforementioned model which give maximun correlation coefficient between hipocenters from location program and hypocenters from tomography program. Finally, the P-wave velocity (Vp) for the upper crust, lower crust and the uppermost mantle is 6.0, 6.5 and 8.1 km/s, respectively. Vp in the upper mantle has a vertical gradient of 0.005 km/s per km. Vp/Vs is set to be 1.7 in the initial model. A number of inversions were run with different damping values, afterward the reduction in travel time residual is compared to the variance of the solutions and we draw a trade-off curve between them. The selected value of the damping parameter is the one which gives the optimal residual reduction and the solution variance. On the other hand, a threshold of 1.0 sec. in the earthquake set was found to significantly reduce the rms residual solving the inverse problem for 1800 P- velocity prameters at the grid nodes with hit counts greater than 10. Afterwards, we applied a checkerboard resolution test (Zhao et al, 1992, 1994) to examine the resolution scale of the present data set.

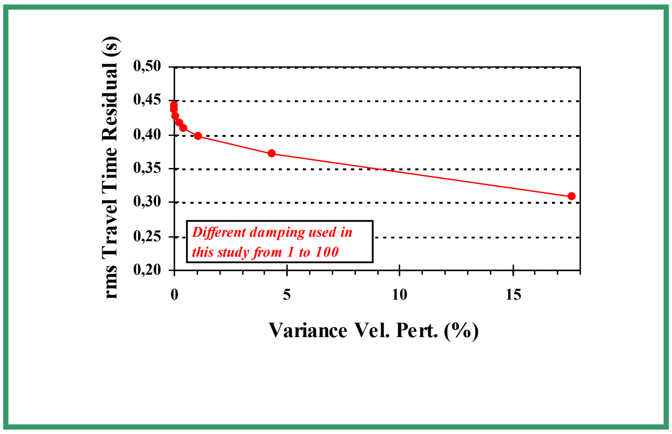

Figure 4. Trade-off curve between the variance of the solutions and travel time residuals for different damping, from 1 to 100. The selected value is 10.

NEKOR FAULT

The most robust feature imaged in the first layer, at 5 km depth, is the pronounced low-velocity region trending NE-SW in Northern Morocco. Usually low seismic velocities can be ascribed to severe fracturing and cracking or fault gouge formation, for example fault gouge is thought to lower the velocity of rock by about 20%. The place where there is significant fault gouge and/or fracturing with contained fluids, the fault zone will exhibit low velocity, low resistivity and high attenuation. In our context the electrical conductive structure detected in relation to Nekor fault can be associated with the low velocity zone and high-attenuation zone (Seber et al., 1996). Moreover the high surface heat flow and the upheaval of the isotherms in the region (Rimi et al., 1998) mean that the depth of the conductive structures do not exceed a few tens of kilometres. In addition, this velocity anomaly occupies the same relative position that NE-SW elongated part of negative gravity values extending along SE boundary of Nekor fault. Consequent these features could be interpreted as a fault gouge zone and/or a fluid-filled subsurface rock matrix in the upper crust. Otherwise it is clear that Nekor fault is a sinistral strike-slip fault that was active during the Miocene (Leblanc and Olivier, 1984) and also is widely recognized that low-velocity zones are a feature of some old or active strike-slip zones (Stern and McBride, 1998). However from 10 km depth downwards a weak positive velocity zone is imaged along SE Nekor fault in according with the results of previous tomographic studies (Calvert et al., 2000). Geological and geochemical evidence suggest that fault gouge is stable only to depth of 8-12 km (Wang, 1984) and at these depths cracks and fractures are annealed, which can explain the existence of low velocity zone only at 5 km depth. At present, we inclined to think that the low velocity zone along SE Nekor fault in the shallowest layer at 5 km can be associated to the previous activity of this important geologic accident even though that actually has not a significant seismic activity neither tectonic evidence of Quaternary motion. However, if there is no doubt that Nekor fault was one of the most great discontinuity in the Rif and played an important role in the geodynamics of the region in the recent past, it is a valid reasoning that must remain outward signs and/or geophysical evidences in relation to the slip of this fault in the region.

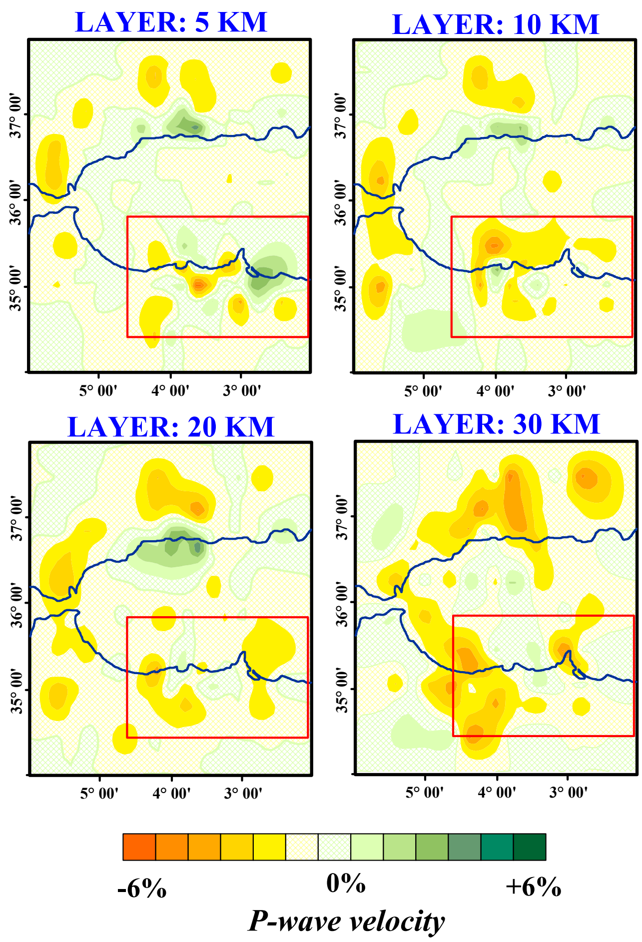

Figure 5. Fractional P-wave velocity perturbations (in percentage) at the first four depth layers. The velocity perturbation is from the mean value of the inverted velocity at each layer. Green and red colours denote fast and slow velocities respectively.

AL-HOCEIMAS REGION

In the first slice we can see important seismic velocity variations imaged in the epicentral area of Al-Hoceimas series (El Alami et al., 1994, Calvert et al., 1997, etc). The lower Nekor basin, although is occupying the same area in space that the low velocity anomaly, at present is filled with 400 m. of Quaternary sediments (Frizon de Lamotte, 1982), which indicates these sedimentary rocks are not in relation with the low velocity zone obtained at 5 km depth. Along the S-N cross section it is possible observe the main cluster of earthquakes is located in the transition zone between fast and slow velocity anomalies. Vp is low in the southern area of the earthquake zone and is high in the northern zone. The most of the earthquakes happened from low velocity limits to the south, almost inner high velocity zone. Roughly the seismicity goes deeply towards south in the Al-Hoceimas area. The high velocity zone could be associated to the seismic activity, although the relation is not very clear. However the seismic activity in this area ceases at 20 km depth, which coincide with the high-low velocity boundary. In the area where the Al-Hoceimas series happened, high velocity zone attains the end at 20 km depth and low velocity zone begin at this depth and extend downwards. The results of the seismic distribution and seismic velocity can be indicating that the most important concentration of earthquakes are confined in the high velocity area. Indeed we can interpreted this higher velocity area like a brittle and competent part of the upper crust which sustain seismogenic stress in contrast with the low velocity near Nekor fault.

HIGH VELOCITY BELOW KEBDANA MOUNTAINS

The eastern coast line Morocco spreads with a fast velocity anomaly (+3%) at 5 km depth, in relation with a disperse shallow seismic activity. However it seems clearly the NE-SW trend of this anomaly and its existence only at shallowest layer, because penetration to a deep the positive seismic values disappear. In the magnetic map of North Morocco (Demnati, 1972), we can observe a weak positive anomaly drawn in SE Melilla, and the shape of the isolines can be indicating the existence of a shallow body with NE-SW trend, coinciding with the place of the velocity anomaly. Around this area, there are important neogene volcanic outcrops and in the western part of the studied area ultramafic outcrops also exists. On the other hand we can observe the close position of a volcanic center in this area (late Miocene potassic volcanism) and the NE-SW regional trend of the volcanic outcrops in whole Ibero-Mogrebi region. Supporting this hypothesis the heat flow density and thermal gradient calculated for this area show some of the highest values, 85 mW/m2 and 37°C/Km across the North Morocco (Rimi et al., 1998). From geological, magnetic, thermal and seismic features we can infer that from at least 2.5 to 7.5 km depth exists a high density body probably formed by mid Miocene calc-alkaline or late Miocene potassic volcanic rocks.

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REFERENCES

Aït Brahim, L. and Chotin, B. A., 1989. Genèse et déformation des bassins néogènes du Rif central (Maroc) au cours du rapprochement Europe-Afrique. Geodyn. Acta 3, 295-304.

Calvert, A., Gomez, F., Seber, D., Barazangi, M., Jabour, N., Ibenbrahim, A. and Demnati, A., 1997. An integrated geophysical investigation of recent seismicity in the Al-Hoceima Region of North Morocco. Bull. Seism. Soc. Am., vol. 87, no. 3, 637-651.

Demnati, A., 1972. Krustenstructur im Rif-bereicht von Nord-Marokko aus gravimetrischen und aeromagnetischen regionalmessung. Bol. Geofis. Teor. Appl. XIV, 203-236.

El Alami, S. O., Tadili, B. A., Cherkaoui, T. E., Medina, F., Ramdani, M., Brahim, L. A. and Harnafit, M., 1998. The Al Hoceima earthquake of May 26, 1994 and its aftershocks: a seismotectonic study. Annali di Geofisica, vol. 41, nº 4.

Fetah, S. E. M., Bensaid, M. and Dahmani, M., 1987. Carte géologique du Rif, Rouadi, Notes Mem. Serv. Geol. Maroc, 347.

Frizon de Lamotte, D., 1987. Un example de collage synmétamorphe: La déformation miocène des Temsamane (Rif externe, Maroc). Bull. Soc. Géol. Fr., 3, 337-344.Gensous, B., Tesson, M. and Winnock, E., 1986. La Marge méridionale de la mer d'Alboran: caractères structure-sédimentaires et évolution récente. Mar. Geol., 72, 341-370.

Leblanc, D. and Olivier, Ph., 1984. Role of strike-slip faults in the Betic-Rifan orogeny. Tectonophysics, 101, 345-355.

Lienert, B.R., E. Berg and L.N. Frazer, 1986. AHypocenter@: An earthquake location method using centered, scaled and adaptively damped least squares. Bull. Seism. Soc. Am., 76, 771-783.

Morel, J. L., 1989. Etat de contrainte et cinématique de la chaîne Rifaine (Maroc) du Tortonien à l'actuel. Geodin. Acta, 3, 283-294.

Rimi, A., Chalouan, A. and Bahi, L., 1998. Heat flow in the westernmost part of the Alpine Mediterranean system (the Rif, Morocco). Tectonophysics, 285, 135-146.

Rebaï, S., Philip, H. and Taboada, A., 1992. Modern tectonic stress field in the Mediterranean region: evidence for variation in stress directions at different scales. Geophys. J. Int., 110, 106-140.

Saadi, S. E. M., Bensaid, M. and Dahmani, M., 1984a. Carte géologique du Rif, Al Hoceima, Notes Mem. Serv. Geol. Maroc, 302.

Seber, D., Barazangi, M., Ibenbrahim, A. and Demnati, A., 1996. Geophysical evidence for lithospheric delamination beneath the Alboran Sea and Rif-Betic mountains. Nature, vol. 379.

Stern, T. A. and McBride, J. H., 1998. Seismic exploration of continental strike-slip zones. Tectonophysics, 286, 63-78.

Wang, C. Y., 1984. On the constitution of the San Andreas fault zone in central California. J. Geophys. Res., 89, 5858-5866.

Zhao, D., Hasewaga, A. and Horiuchi, S., 1992. Tomographic imaging of P and S wave velocity structure beneath northeastern Japan. J. Geophys. Res., 97, 19909-19928.

Zhao, D., Hasewaga, A. and Kanamori, H., 1994. Deep structure of Japan subduction zones as derived from local, regional and teleseismic events. J. Geophys. Res., 99, 22313-22329.