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# New fault-plane solutions of Moroccan earthquakes for the 2005-2008 period

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**Abstract**. We present new fault-plane solutions, based on P wave first motion, of 10 moderate shocks that occurred in Morocco during the period 2005-2008. In the Middle Atlas and adjacent area, the 3 fault-plane solutions correspond either to reverse or to strike-slip faulting with a normal component, in good agreement with the state of stress determined in this area, reflected by NW-SE horizontal pressure axes. In the central and eastern Rif area, the 3 strike-slip and normal solutions (with ENE-WSW T-axes) are in agreement with the local state of stress. Finally, in the western Rif front, which is undergoing increased seismic activity, the 2 fault-plane solutions obtained (reverse faulting) show unusual NE-trending P-axes that support the model of lateral escape of the Central Rif.

**Key words:** Seismotectonics, Morocco, fault-plane solution

**Nouveaux mécanismes au foyer pour les séismes marocains pour la période 2005-2008.**

**Résumé**. Nous présentons de nouveaux mécanismes au foyer, basés sur le premier sens de mouvement des ondes P, pour 10 séismes de magnitudes modérées ayant eu lieu de 2005 et 2008. Dans le Moyen Atlas et les régions avoisinantes, les 3 mécanismes correspondent soit à un jeu inverse, soit à un jeu décrochant à composante normale, en bon accord avec l'état de contrainte déterminé dans cette région, reflété par l'orientation NW-SE des axes de pression. Dans le Rif central et oriental, les 3 mécanismes déterminés, à jeu décrochant ou normal, avec des axes de tension orientés ENE-WSW, sont également compatibles avec l'état de contrainte local. Enfin, au front du Rif occidental, qui a enregistré une activité sismique accrue au cours des dernières années, les solutions montrent des axes P orientés NE-SW. Cette direction inhabituelle conforte le modèle tectonique d'échappement du Rif.

**Mots clés :** Sismotectonique, Maroc, mécanismes au foyer

## INTRODUCTION

The determination of focal mechanisms of earthquakes has become a routine task since the development of the Moroccan and international seismological networks, which allowed colleting a larger and improved data set. For moderate to strong earthquakes (M≥4), moment tensor solutions can be easily obtained from Harvard CMT solutions (http://www.globalcmt.org), USGS (http://neic.usgs.gov), ETHZ (http://www.seismo.ethz.ch), INGV (http://www.bo.bo.ingv.it), and IGN (http://www.ign.es). For the Ibero-Maghrebian region, due to the small to moderate (in general less than 5) magnitudes of earthquakes, it is difficult to find solutions in special for Morocco. However, in the last years the installation of new seismological broad band stations at the region for permanent (Western Mediterranean) or temporary (Siberia) networks permits the estimation of fault-plane solutions from polarities for earthquakes with magnitudes 3.0 to 5.0.

We present in this paper new fault-plane solutions of 10 moderate shocks that occurred in the period 2005-2008 (3 events in 2005; 4 in 2007 and 3 in 2008).

## METHODOLOGY

First, we have selected the events of magnitude M ≥4 (period 1990-2010) recorded by the national seismological networks in Morocco and neighbouring areas, such as southern Spain, Moroccan Atlantic margins and Algeria (Fig. 1). The hypocentral relocations were determined using the revised version of the HYPO71 computer program (Lee and Valdes, 1985), and a standard crustal model for Morocco with $V_p/V_s$ = 1.74 (Frogneux 1980). Magnitudes were calculated from seismogram duration using the formula:

$$M_d = a + b \log(\tau) + c\,\Delta \qquad (1)$$

Where $\tau$ is the signal duration (in seconds), $\Delta$ is the epicentral distance (in km), and *a, b, c* are constants which were calculated for each station by the least squares method, using data recorded by the seismic permanent network of Morocco. Magnitudes $M_d$ were calibrated against magnitudes $m_b$ determined by ISC and USCG (Cherkaoui 1991).

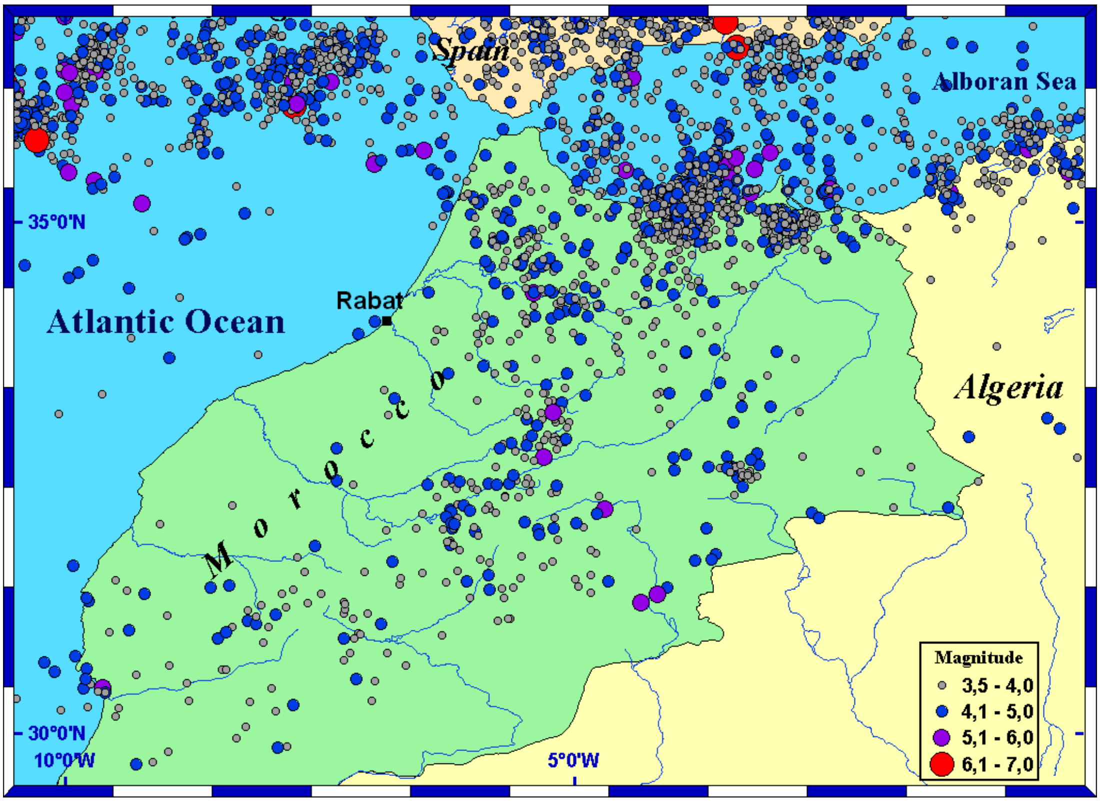



Figure 1. Seismicity of Morocco (M>3.5) and neighbouring areas for the period 1990-2010.

First motions of P waves were read on paper records (Institut Scientifique and CNRST networks) and from digital files of permanent stations of the Western Mediterranean network (AVE, IFR), and IGN network (Spain), completed with the TOPOSIBERIA temporary network installed in Northern Morocco.

Fault plane solutions have been obtained using the algorithm developed by Brillinger *et al.* (1980) to estimate fault plane orientation, their errors and score. A crustal specific model for Morocco, formed by two flat layers (15 km and 15 km) with constant velocity 6.10 km.s$^{-1}$ and 6.70 km.s$^{-1}$, has been used to estimate the take-off angles for stations at regional distances (less than 1,000 km). For stations at larger distances, we have used the IASPEI model. In table I we show the obtained solutions. We have included an index according to the quality of the solution: (a) indicates a well-constrained solution (most errors less than 15º), (b) medium-quality solutions (errors between 15º and 40º) and (c) poor-quality solutions with large errors.

## RESULTS

Hypocentral parameters and fault plane solutions of the selected earthquakes are given in Table I and Figures 2 and 3. Solutions obtained are described according to the geographical location of epicentres.

### Atlas chain

Three mechanisms were determined for the moderate shocks recorded in the Atlas chains, among which 2 were recorded in the Middle Atlas and one in the Central High Atlas (Table I and Fig. 2; mechanisms 2, 4 and 5).

***11 August 2007 (event 5)***. This event (*Md*=5.1) was largely felt in central Morocco including Rabat. The epicentre was located in the central Middle Atlas (33.14°N; 5.21°W) at a depth of 7.0±3.7 km. The obtained solution corresponds to strike-slip motion with a normal component. A plane is vertical and oriented in WNW-ESE direction (strike 108°) and the second one is oriented in NNE-SSW direction (strike 14°) and dipping to the east. The pressure and tension axes are nearly horizontal and oriented in NNW-SSE and NE-SW direction respectively. The solution is not very well constrained with estimation of errors for some parameters such as rake of plane A or plunge of T axis near or larger than 30°. These errors are due to the lack of observations of azimuth from 45° to 225°, with only 1 observation (ZFT at 146°). The score is 91%.

***25 January 2008 (event 2).*** The epicentre of this event (Fig. 2, n° 2) is located in the southern Middle Atlas (33.01°N; 5.36°W) at 5.6 ± 3.5 km depth. The solution has been obtained using 12 P-wave polarities and corresponds to almost-pure reverse faulting with planes oriented approximately in ENE-WSW direction and dipping to the north and to the south. The P-axis is horizontal and oriented in NNW-SSE direction. The solution is well constrained, with low values of errors, and a score of 100% (Fig. 2).

***18 December 2007 (event 4).*** The epicentre of this event was located in the Central High Atlas (Fig. 2, n° 4), at 32.12°N, 6.26°W, at a depth of 25.8 ± 3.4 km. The obtained

Table I. Parameters of the studied earthquakes (latitude, longitude, magnitude and depth) and their focal mechanism solutions. $\Phi$=strike ; $\delta$= dip ; $\lambda$=slip. Tr.= trend; Pl.= plunge; N= number of stations used; Q= quality of solution: a, well constrained solutions (error < 15°); b, medium-quality solutions (errors between 15° and 40°); c, poorly constrained solutions (error > 40°).

| Ref | Date (D/M/Y) | Lat. N Lon. W | Mag | Depth (km) | Fault plane(°) ($\Phi$, $\delta$, $\lambda$) | P axis (°) (Tr; pl) | T axis (°) (Tr; pl) | N | Score (%) | Q |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 28/09/08 | 33.59 ; 5.89° | 4.5 | 22±3 | A: 80±7; 21±2; 66±8<br>B: 234±4; 71±2; 99±3 | 331±4; 25±2 | 130±7; 63±2 | 13 | 85 | a |
| 2 | 25/01/08 | 33.01 ; 5.36° | 4.3 | 6±4 | A: 80±6; 40±4; 69±13<br>B: 233±24; 53±4; 107±16 | 335±7; 7±3 | 90±30; 75±10 | 12 | 100 | a |
| 3 | 21/01/08 | 35.12°, 3.94° | 4.1 | 8±3 | A: 200±9; 70±12; –9±20<br>B: 293±12; 82±19; –159±12 | 158±9; 20±16 | 65±11; 8 ± 15 | 19 | 95 | a |
| 4 | 18/12/07 | 32.12 ; 6.26° | 4.1 | 26±3 | A:276±38; 32±11; –107±156<br>B:116±80; 60±18; –80±93 | 52±114; 73 ± 26 | 199±62; 14±15 | 11 | 82 | c |
| 5 | 11/08/07 | 33.14 ; 5.21° | 5.1 | 7±4 | A:14±13; 59±20; –7±35<br>B:108±24; 84±29; –149±21 | 336±14; 26±19 | 237±24; 17±31 | 23 | 91 | b |
| 6 | 23/06/07 | 34.30 ; 5.65° | 4.5 | 15±8 | A:97±15; 55±12; 136±19<br>B:338±9; 55±7; 136±19 | 38±9; 1±7 | 308±5; 54±16 | 14 | 86 | a |
| 7 | 18/05/07 | 35.29 ; 6.26° | 4.6 | 59±5 | A:161±30; 7±4; –26±35<br>B:277±22; 87±3; –96±5 | 181±22; 48±3 | 13±22; 42±3 | 14 | 79 | b |
| 8 | 26/05/05 | 34.60 ; 5.88° | 4.2 | 59±11 | A:120±22; 32±13; 104±83<br>B:317±37; 59±33; 99±121 | 41±27; 13±10 | 251±55; 75±17 | 14 | 79 | c |
| 9 | 22/03/05 | 35.05°; 2.97° | 4.7 | 5±5 | A:33±59; 40±38; –44±53<br>B:160±35; 63±20; –121±52 | 25±43; 59±45 | 272±37; 13±19 | 29 | 97 | c |
| 10 | 18/02/05 | 34.95°; 2.99° | 4.4 | 3±3 | A:43±20; 67±35; 164±14<br>B:306±18; 76±13; 24±37 | 356±24; 6±26 | 263±13; 27±26 | 22 | 73 | b |

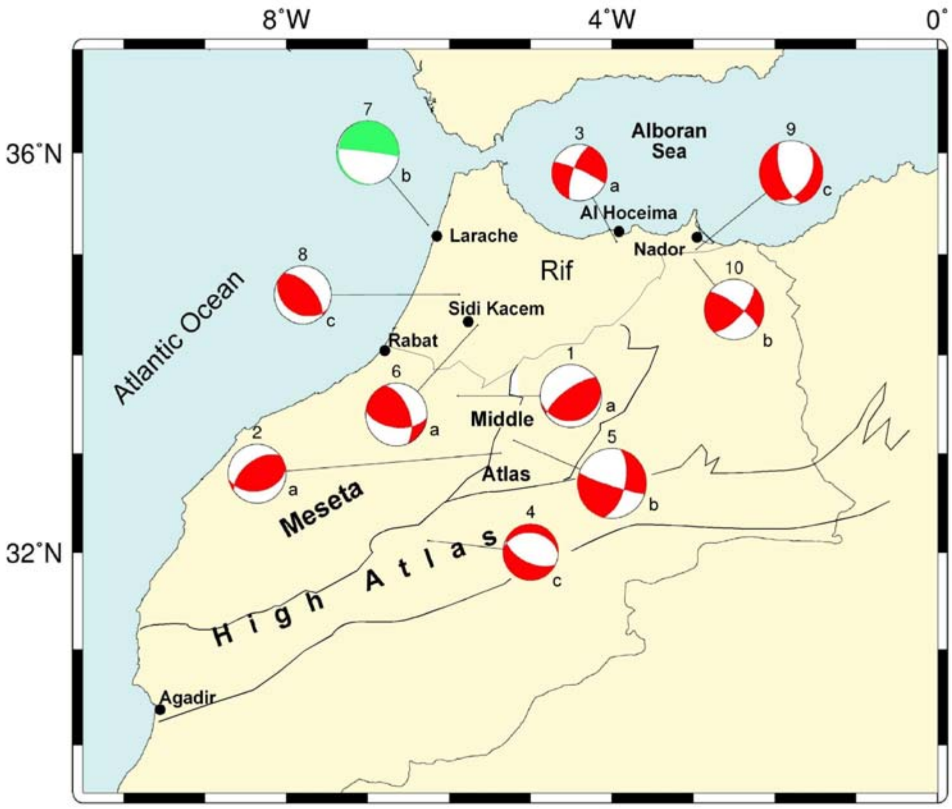



Figure 2. Fault plane solutions studied. The numbers correspond to those in Table I. a, well constrained solutions (error < 15°); b, medium-quality solutions (errors between 15° and 40°); c, poorly constrained solutions (error > 40°).

solution corresponds to normal faulting with planes oriented in E-W direction, and the horizontal tension axis oriented in N-S direction. We have a poor azimuthal coverage of the focal sphere, with all stations concentrated at the first and fourth quadrants and an azimuth gap larger than 180°. In consequence, the solution is very poorly constrained, with large estimation of errors (between 11° and 118°) of fault-plane and Pressure and Tension axis. The high score (82%) is not representative of the quality of this solution.

### Rif front

***26 May 2005 (event 8).*** The region of Sidi Kacem, located along the Rif front (34.60°N; 5.88°W), was affected on 26 May 2005 by a moderate shock of magnitude 4.2. The focal depth was about 59.0 ± 10.9 km. The fault-plane solution (N=14) corresponds to almost-pure reverse faulting (Fig. 2, n° 8), with planes oriented in NW-SE direction. The pressure axis is horizontal and trending in the NE-SW direction. The solution is not well constrained with a large estimation of errors on fault plane parameters (83° and 121° for the rake of both planes). The score is low (79%).

***23 June 2007 (event 6).*** The same area of Sidi Kacem, where event 8 occurred, was affected on 23 June 2007 by another moderate shock of magnitude 4.5. The epicentre was located at 34.30°N; 5.65°W, 40 km SE of the previous one, but, in opposite to event 8, it was at shallow depth (14.8 ± 7.5 km). The fault-plane solution is similar to that of event 8 (Fig. 2, n°6), and corresponds to reverse faulting, with planes oriented in E-W and NNW-SSE direction. In this case, the solution is well constrained, with estimation of errors for planes and Pressure and Tension axes less than 15°. The score is 86% (Fig. 3).

***28 September 2008 (event 1).*** The Meseta area east of Rabat (33.59°N; 5.89°W) was affected by a moderate earthquake (M=4.5) with a shallow depth (21.8 ± 2.7 km). The fault-plane solution has been obtained using 13 P-wave polarities and it corresponds to reverse faulting with plane oriented in NE-SW and E-W directions and horizontal pressure axis oriented in NW-SE direction. The solution is well constrained with low values of errors (less than 15°) and a score of 85% (Table I; Fig. 3).

### Western Rif Atlantic margin

***18 May 2007* (*event 7*).** The epicentre of this intermediate earthquake (58.7 ± 4.6 km) was located in the Atlantic margin of Asilah at 35.29°N; 6.26°W (Fig. 2, n° 7). The fault-plane solution obtained from 14 P-wave polarities, shows dip-slip motion, with a vertical plane oriented in E-W direction, and a horizontal plane. The pressure and tension axes are dipping about 45° to the south and north respectively. The solution is poorly constrained due to the lack of observations on the first and second quadrant. In consequence, we have obtained large estimates of error for planes and pressure and tension axis (Table I).

### Central Rif

***21 January 2008 (event 3).*** This event is located near Al Hoceima region (35.12°N; 3.94°W), at a shallow depth of 8.2 ± 3.0 km. The fault-plane solution (N=19) corresponds to strike-slip faulting (Fig. 2- n°3), and is well constrained with nearly vertical planes trending to the NNE-SSW and to the WNW-ESE directions. The pressure axis is horizontal and trends to the NE-SW direction. Estimations of error for stress axis and fault-plane are less than 15° and the score is 95% (Table I).

### Eastern Rif

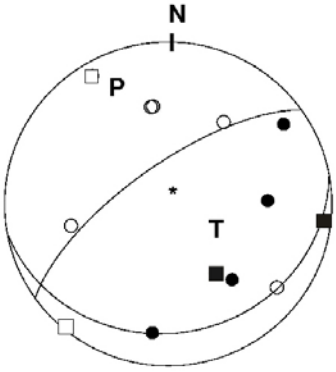
***18 February 2005 (event 10).*** This shock is located south of Nador (34.95°N; 2.99°W), at a shallow depth (2.6 ± 3.1 km). The fault-plane solution shows strike-slip motion with planes oriented in NE-SW and NW-SE directions. Pressure and Tension axes are horizontal and trending to the N-S and E-W directions. However, due to the lack of observations, with an azimutal gap between 20° and 220°, solution is poorly constrained, with large estimation of errors (Table I) and a low score (73%).

***22 March 2005 (event 9).*** The epicentre of this event (35.05°N; 2.97°W) is located 20 km SW of Nador and very close to the epicentre of event 10. Two contradictory Moment tensor solutions were determined by IGN (normal faulting) and IAG (reverse faulting) for this event (Medina 2008). In this study, we have obtained a solution based on 29 P-wave polarities (Fig. 2, n°9 and Fig. 3). It corresponds to normal faulting with planes oriented in N-S direction and dipping to the east and west. The tension axis is horizontal and trending on E-W direction. The solution is poorly constrained with large estimation of errors of planes and stress axes (Table I), due to the concentration of observations at the second and third quarters of the focal sphere.

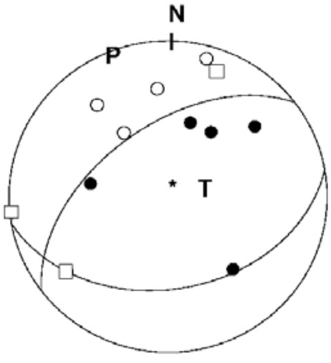
## TECTONIC IMPLICATIONS

Our study permits to complete the data collected previously on the fault-plane solutions of the earthquakes in Morocco (e.g. Medina, 2008 and references therein), and to have a new view on the seismotectonics of areas where no (or a few) fault-plane solutions were available, as in the southern Middle Atlas, the western Prerif (Sidi Kacem), and the Eastern Rif (Nador) regions.

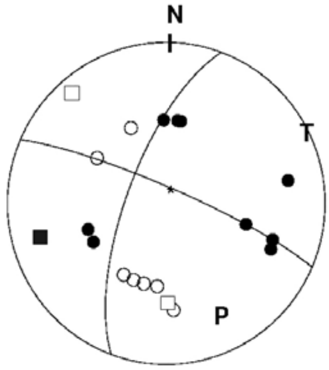
In the Middle Atlas, where the previous fault-plane solutions indicate normal faulting in the north-west (Tadili & Ramdani 1981, Medina & Cherkaoui 1992) and reverse faulting in the south-east (Medina & Cherkaoui 1992) the new fault-plane solutions correspond either to reverse (solutions 1 and 2) or to strike-slip faulting (event 5) with a normal component. These mechanisms are in good agreement with the state of stress determined in this area, which may be undergoing crustal partitioning (Gomez *et al.* 1998).



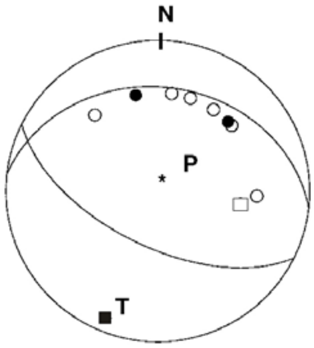

**N°1-** 28 September 2008



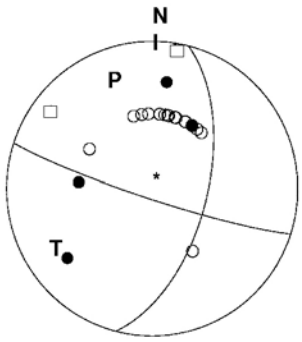

**N°2-** 25 January 2008



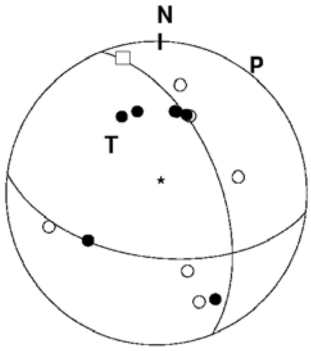

**N°3-** 21 January 2008



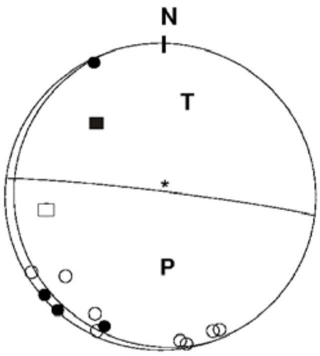

**N°4-** 18 December 2007



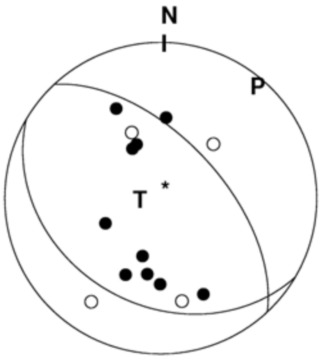

**N°5-** 11 August 2007



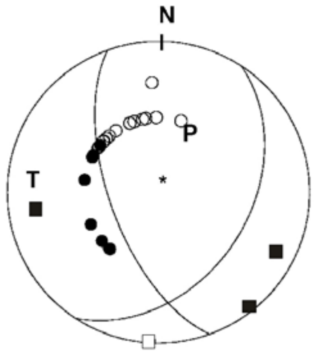

**N°6-** 23 June 2007



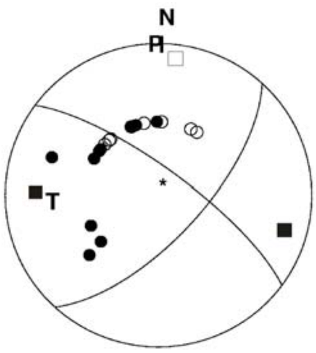

**N°7-** 18 May 2007




**N°8-** 26 May 2005




**N°9-** 22 March 2005




**N°10-** 18 February 2005

Figure 3. Detailed fault plane solutions (Schmidt net, lower hemisphere). Circles=stations; solid=upward first motion; empty=downward first motion; P=Pressure axis; T=Tension axis. Circles=refracted waves; squares=direct waves.

The only fault-plane solution determined for the Central High Atlas (event 4) is not well constrained (solution quality c), and indicates normal faulting with NNE-SSW trending T-axis, which is not in conformity with the general compressional state of stress, but it may be related to the uplift by thermal doming of the High Atlas (Frizon de Lamotte *et al.* 2009).

In the eastern Rif, the normal fault solution of the 22 March 2005 event in Nador has a larger vertical component than the previous solutions determined in the area, although the solution is in agreement with the regional state of stress (Medina & El Alami 2006).

Finally, the most interesting solutions are those determined in the Sidi Kacem area at the Rif front, which is undergoing increased seismic activity, reflected by repetitive small earthquakes which led to some panic within the population as reported in the daily press. Geologically, it corresponds to a regional arc along which the anticlinal “Rides prérifaines”, consisting of Jurassic limestones covered by Neogene deposits, overthrust the Neogene deposits of the Gharb plain (Zizi 1996). In this part of the Rif front, recent structural (e.g. Chalouan *et al.* 2006) and GPS (Fadil *et al.* 2006, Vernant *et al.* 2010) data point to lateral escape of the Central Rif reflected by NE-SW state of stress. The two fault-plane solutions obtained for this area show NE-trending P-axes, which supports this state of stress, although the focal depth of one is too large to account for surface deformations.

From these solutions, we observe in the Rif horizontal compression in NNW-SSE direction and horizontal E-W extension in conformity with the regional stress pattern in this area. In the Middle Atlas, there is horizontal compression in NNW-SSE direction but in the high Atlas the stress regime changes to horizontal NNE-SSW extension. However, this result is supported for only one fault-plane solution and it corresponds to a low quality solution (c, for event 4). In the Sidi Kacem region, solutions show a change of the horizontal compression which is rotated to a NNE-SSW direction, this result is supported by two events (6, quality a and event 8, quality c). Finally, it is important to remark the occurrence of two earthquakes at intermediate depth (events 7 and 8).

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