PRESENT-DAY STRESS FIELD AND TECTONIC REGIME IN ALGERIA FROM INVERSIONS OF EARTHQUAKE FOCAL MECHANISMS

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ABSTRACT

Estimation of stress field orientations is essential for understanding mechanisms of crustal deformation and seismotectonics. Previous studies in Algeria have primarily focused on regional studies; however, this study provides a comprehensive analysis of stress field variations across the entire country. By applying stress inversions to a dataset of 631 earthquake focal mechanisms sourced from international databases and previous studies, we determined the principal stress axes (σ1, σ2, and σ3), SHmax, SHmin, and the stress ratio (R). The results confirm the overall SHmax orientation and stress regime, which are consistent with previous regional studies. However, a more detailed analysis, achieved by dividing the study area into smaller subregions, reveals spatial heterogeneity in stress conditions. A transition from a compressive-transpressive to a strike-slip stress regime is evident from the western to the eastern Tell Atlas, with the Great Kabylia block emerging as a transitional zone marked by a predominantly pure compressive stress field. The Beni Slimane region shows local perturbations in the stress field, likely linked to the reactivation of underlying structures. Moreover, the analysis of neotectonic data and the P-axis of large events across Algeria shows a clear correlation with the distributed SHmax, indicating that future earthquakes will likely be generated along the reactivation of these faults. These findings have critical implications for seismic hazard assessment, offering insights that can refine seismogenic zone definitions and improve hazard mapping in Algeria.

Keywords: Stress field, Focal Mechanisms, SHmax, Stress Tensor Inversion.

1. INTRODUCTION

Estimating stress field orientations is essential for understanding crustal deformation mechanisms and the underlying physics of seismic activity. Variations in the stress field across different regions are critical for identifying geodynamic and seismotectonic characteristics. Focal mechanism inversion, a widely used seismological technique, plays a key role in determining stress orientations by analyzing earthquake source mechanisms. This method typically assumes that the in-situ stress orientation can be approximated by the azimuth of the maximum horizontal compressive stress (SHmax) (Zoback, 1992). In Algeria, previous studies have examined the distribution and spatial variation of the stress field, but they have predominantly focused on regional-scale patterns, with limited attention to localized stress field variations. These studies have provided valuable insights into broad regional trends but have not fully addressed the complexities on the local scale. Building on these earlier efforts, the current study aims to offer a more comprehensive analysis of stress field orientations across Algeria. By analyzing 631 earthquake focal mechanisms from various sources. This research seeks to map the stress field variations across the entire country, with a particular focus on sub-regional and local differences. This work will enhance our understanding of neotectonic and active tectonic processes, contributing to more accurate seismic hazard assessments and informing disaster prevention strategies.

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2. DATA

We compiled data from various international organizations such as the Global Centroid Moment Tensor (GCMT) (Dziewonski et al., 1981; Ekström et al., 2021) and the International Seismological Centre Bulletin (ISC Bulletin) (Lentas et al., 2019), including published literature and scientific papers. This dataset, encompassing 631 earthquakes (mainshocks and aftershocks) with magnitudes ranging from 2.0 to 7.3 (Figure 1) and depths ranging mainly from 0.6 to 20 km (maximum 51 km), and covers the period from 1954 to 2022 and extends across the region from west to east Tell areas and to Saharan atlas in the south. The collected database focal solutions are well distributed and encompass all active regions in Algeria, which allows for analysis of horizontal stress distributions across the studied area from west to east and north to south.

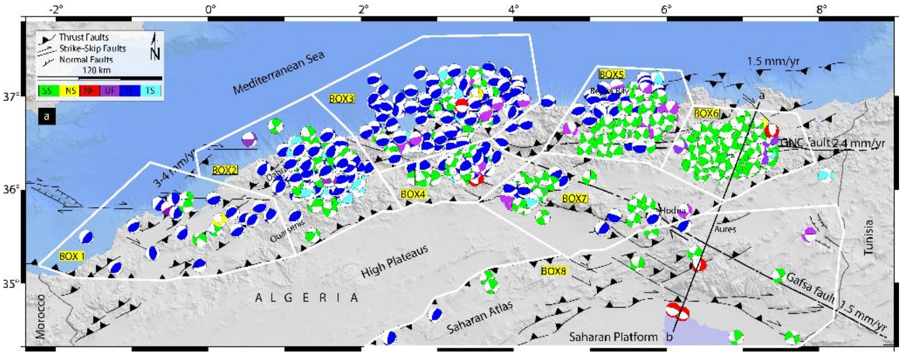

Figure 1. Box zonation (sub-areas) and the corresponding dataset were plotted on a seismotectonic map. Box 1: Oranie region, Box 2: Chellif region, Box 3: Mitidja basin, Box 4: Beni Slimane Basin, Box 5: Soummam – Babor Range region, Box 6: Constantine – Mila basin, Box 7: Front Tell – Hodna basin, Box 8: Saharan Atlas region. A-b: cross-section of figure 4.

3. METHODOLOGY

For the current study, we divided the studied area into small boxes for a better understanding of the spatial variation of the regional and local stress field distribution, taking into consideration many criteria, such as homogeneity of focal mechanisms, geological domains and structures, and seismicity distribution. Moreover, we classify the focal mechanism solutions using the Frohlich ternary diagram for a better understanding of the distribution of the compiled dataset. In this study, the Win-Tensor software (Delvaux and Sperner, 2003) was employed to invert stress tensors from earthquake focal mechanisms. The output parameters of the stress tensor inversions are the principal stress axes ($\sigma 1$, $\sigma 2$, $\sigma 3$), the stress ratio R, which is a measure of the relative magnitudes of the principal stresses in a given stress field, and it is defined by the following formula ($R = \sigma 2 - \sigma 3 / \sigma 1 - \sigma 3$), the stress index regime (R'), is used to describe the nature of the stress regime in a more qualitative way. It considers the orientation and relative magnitudes of the principal stresses to categorize the stress field. The maximum horizontal compressive stress (SHmax) and the minimum horizontal compressive stress (SHmin) were derived through an iterative process. Additionally, spatial variation of the estimated stress regime was compared with the regional tectonic regime, the Moho depth distribution, and the occurrence of moderate to large magnitude seismic events.

4. RESULTS AND DISCUSSION

4.1. The D90 distribution of seismicity

Seismicity in Algeria mainly consists of events at depths of 0 to 20 km. The D90 distribution, which indicates the depth above which 90% of seismic events occur (Omuralieva et al. 2012), is approximately

18 km (Figure 2). This suggests that most of the seismic activity is concentrated in the upper and lower crust, particularly in the upper crust (mean seismicity is 9.2 km) in the Tell Atlas regions, where the Moho depth ranges from 20 to 30 km. The shallow seismicity primarily reflects active crustal deformation driven by the interactions between the African and Eurasian plates. However, occasional deeper seismic events, reaching up to 50 km in the Saharan Atlas (where the Moho depth ranges from 36 to 44 km), point to activity along deep faults associated with the region's geological structure. Moreover, analysis of D90 in the western and eastern Tell regions reveals variations, with D90 at 18 km in the west and 15 km in the east. This difference highlights the heterogeneity and complexity of the tectonic forces and processes across Algeria.

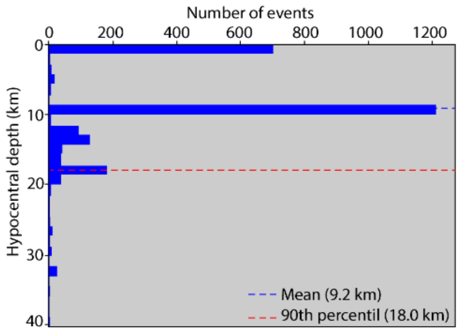

Figure 2. The D90 distribution of seismicity in depth. Seismicity data from ISC Bulletin and USGS.

4.2. Stress inversion results

The spatial variation in SHmax in the studied area (Figure 3) shows heterogeneity in the orientation and stress regime in two zones (western and eastern Tell) known by their different tectonic stress regimes and tectonic deformation models. The result revealed consistent SHmax and stress regime with previous studies, with a NW–SE to NNW–SSE SHmax orientation of 147° ± 9.7° and a compressive to transpressive regime with a stress index R′ of 2.18 ± 0.21 for the western Tell Atlas. This result was consistent with the deformation trend along this region, which exhibited more thrust mechanisms linked sometimes to strong earthquakes, e.g., earthquakes with Mw of 7.3 and 6.8 that occurred on 10/10/1988 and 21/05/2003 in El Asnam region and Zemmouri, respectively. Western Tell also experienced earthquakes generated by NE–SW to NW–SE strike-slip faults but with moderate to low magnitudes. In contrast, the strike-slip stress regime controlled the recent deformations in the eastern Tell, which was indicated by the NE-SW left-lateral and E-W right-lateral strike-slip focal solutions. The estimated SHmax is oriented NNW-SSE (165 ± 8.8) with a stress index R′ of 1.92 ± 0.27, indicating a slight transpressive component. Herein, the distribution of regional and local stress tensors was investigated by analyzing the orientation of SHmax and tectonic regime in eight sub-areas. Results revealed a clockwise rotation of the mean stress axis σ1. The Oranie region exhibited a SHmax oriented at 141° ± 12.2° and a stress ratio R of 0.23, indicating a compressive tectonic regime associated with a slight transpressive component. Such an observation was due to inverted data dominated by thrust mechanisms. In the Cheliff region, a SHmax rotates of 5° from the previous obtained in the Oranie region (SHmax = 146 ± 9.2), and the stress ratio R of 0.09 was observed, which is typical for a transpressive regime with a horizontal σ1 and σ2-σ3 of nearly the same magnitude and can easily be permutated exhibiting a transpressive movement along active faults. This phenomenon is shown by the

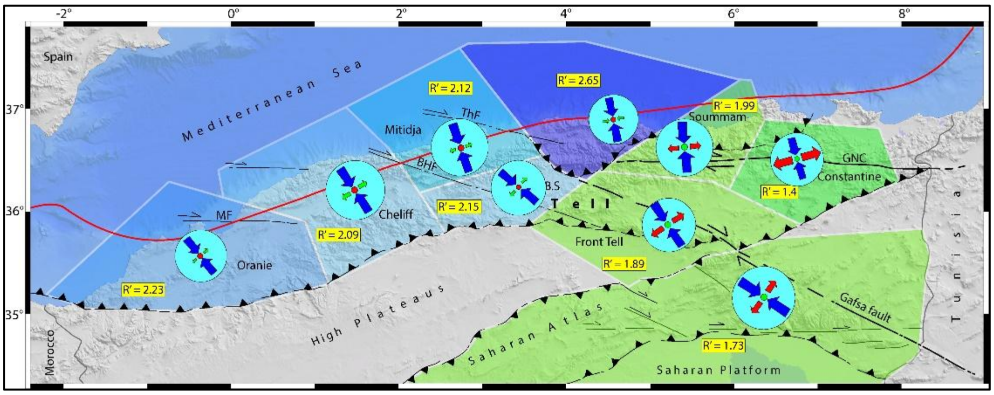

Figure 3. Obtained stress axes orientations and tectonic regime distribution along the entire Algerian area. MF: Mostaganem fault, BHF: Beni Haoua fault, ThF: Thneia fault, GNC: Ghardimaou – North Constantine fault, R': stress index.

strong event of El Asnam (Mw = 7.3) along a 40 km long thrust-sinistral fault. The third box in the western Tell is the Mitidja basin. The selected and inverted focal plane yielded a SHmax of 162 ± 12.2, with an R of 0.24, indicating a compressive regime with a slightly transpressive component. The selected and inverted focal planes in the Mitidja basin mainly exhibited thrust mechanisms, particularly in the eastern part. Strike-slip mechanisms were present, predominantly in the western part. Therefore, the data were divided into two subsets. The corresponding results showed a SHmax of 139 ± 4.5 with an R of 0.12, consistent with the transpressive regime but with a counterclockwise comparison to the SHmax obtained for the Chellif basin. In contrast, the eastern part of the Mitidja basin exhibited an SHmax of 158 ± 18.3 with an R of 0.58; this later indicated a pure compressive stress regime shown by a strong event of Mw = 6.8 in Zemmouri (21/05/2003) generated along a thrust fault with only some aftershocks indicating a slight left-lateral component. The Beni Slimane region, with thrust solutions in the western part as well as thrust and strike-slip solutions in the eastern part, exhibited the lowest SHmax of 130 ± 9.9 with an R of 0.15, indicating a transpressive regime along the basin.

In the eastern Tell, the Soummam–Babor range region exhibited heterogeneity in focal solutions, which was evident in the obtained results. The computed SHmax in this region exhibited an NNW–SSE to N-S direction (174° ± 11°) with a stress ratio R of 0.01. The derived stress regime shows a strike-slip regime with a slight transpressive component. $\sigma1$ is sub-horizontal; the axes $\sigma2$ and $\sigma3$ exhibited almost the same magnitude, allowing permutation in heterogeneous data. Therefore, the region was partitioned into two subsets. Results showed that the western box corresponding to the Great Kabylia block exhibited a pure compressive regime highlighted by an R of 0.65 and SHmax of 168 ± 31.9. The inverted focal solution for the eastern part of the Soummam–Babor range, corresponding to the Lesser Kabylia block, indicated a strike-slip stress regime with a slight transpressive component and an R of 0.26 along with an SHmax of 1.74 ± 0.29. In the Constantine-Mila basin, a seismically active zone, particularly in the last decade, the focal solutions were almost dominated by strike-slip mechanisms related to its tectonic architecture. The orientation of SHmax is 164° ± 8.4°, highlighting a counterclockwise rotation of the mean stress axis compared with the previous region. R was 0.6, typical for a pure strike-slip stress regime consistent with the reactivated NE–SW and E–W major faults in this basin. Along the Front Tell limit–Hodna basin region, the obtained SHmax was oriented NW–SE (146° ± 11.1°) with an R of 0.11, indicating a stress regime delineated by a strike-slip regime with a transpressive component. The Saharan Atlas region, characterized by an NW–SE-oriented SHmax of 128° ± 7°, exhibited the lowest value, attributed to the heterogeneity of the dataset, including NE-SW, E-W, and NW-SE trending faults with varying mechanisms. The Saharan Atlas, in the south, was delineated by a strike-slip stress regime with a transpressive component indicated by an R of 0.27.

The variations in SHmax and tectonic conditions across the region are primarily driven by the compression between the African and Eurasian plates, with local stress distributions influenced by the alignment of pre-existing geological structures. In the Northern Tell Atlas, strike-slip faults have shifted the stress regime from compressive to strike-slip, with the Great Kabylia serving as a transitional zone. This complex interplay is due to the oblique plate convergence driven by the ridge push and continental collision between Africa and Eurasia, while the heterogeneity in stress fields arises from first-order plate boundary compression, second-order shear zones, and third-order can be influenced by hydrothermal activities (eastern Tell), and pre-existing reactivated structures leading to diverse tectonic regimes across the region.

4.3. Tectonic regime and focal depth distribution in northern Algeria

The north-south cross-section (a-b) traverses the Constantine-Mila basin, Hodna basin, and the Saharan Atlas, extending to the Saharan platform. This cross-section provides a detailed distribution of focal mechanisms across various geological domains in Algeria, including the Tell Atlas, High Plateaus (Hodna-Front Tell), Saharan Atlas (Aures), and the stable Saharan platform in the south (Figure 4). In the Constantine-Mila basin, a pure strike-slip tectonic regime predominates, with focal mechanisms primarily occurring at the boundary between the upper and lower crust. Moving to the Hodna-Front Tell limit, the few observed strike-slip solutions indicate some deeper seismic events, likely related to the reactivation of deeper strike-slip faults, such as the Gafsa fault. Within the Saharan Atlas, the Moho depth becomes significantly deeper. This region is characterized by shallower thrust focal mechanisms occurring in the upper crust; strike-slip are distributed along the upper and lower crust, while normal solutions mostly indicate deformation related to deeper faults. The major E-W fault (SAF; Saharan Atlas Front), occasionally trending NW-SE, demarcates the Saharan Atlas to the north and the Saharan platform to the south. It is responsible for the deepest strike-slip and normal fault solutions observed in Figure 5. The cross-section also illustrates the intricate tectonic interplay and varying depths of fault mechanisms across different geological domains, highlighting the complexity of the region's seismicity and crustal structure.

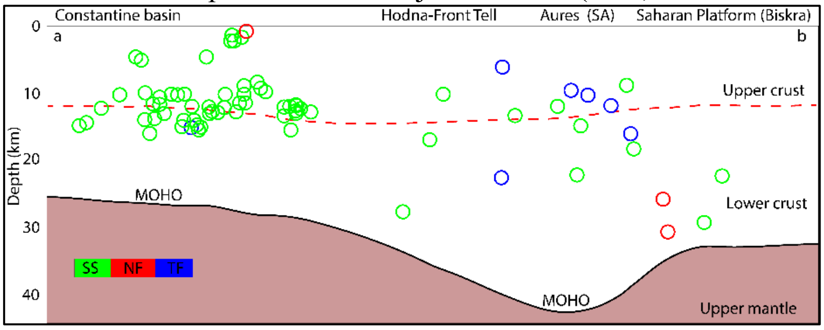

Figure 4. Focal depth distribution of the used focal mechanisms data in the Constantine-Mila basin to the Saharan Atlas regions. SS: Strike-Slip, NF: Normal Faults, TF: Thrust Faults.SA: Saharan Atlas. Moho depth data from Melouk et al. (2023). See the trait of cross-section in Figure 1.

4.4. Seismic Hazard Implications

Figure 5 illustrates the distribution of SHmax orientations across northern Algeria based on the inversion of focal mechanism data, as well as the distribution of larger instrumental seismic events and their P and T axes. Additionally, it displays the SHmax derived from in-situ stress data from neotectonic studies. This distribution highlights that thrust faults tend to produce larger seismic events compared to strike-slip faults, which is consistent with the observed focal mechanisms of significant events. The alignment of the SHmax obtained from neotectonic data with those derived from focal mechanisms in each box confirms the reliability of the stress field analysis. The P-axis orientation of larger events across the studied area generally aligns with the SHmax direction. In regions dominated by thrust faults, the P-axis is parallel to SHmax, suggesting that current stress accumulation along these faults will likely be released through their reactivation, leading to future seismic activity. This parallel orientation of SHmax with the dip-direction of thrust faults indicates that future earthquakes are likely to be generated along these orientations. In the case of strike-slip events, the SHmax orientation typically forms a 45° angle with the P-axis or the dip-direction of the faults. This relationship implies that the NNW-SSE to N-S oriented SHmax in the eastern part is responsible for reactivating NE-SW and NW-

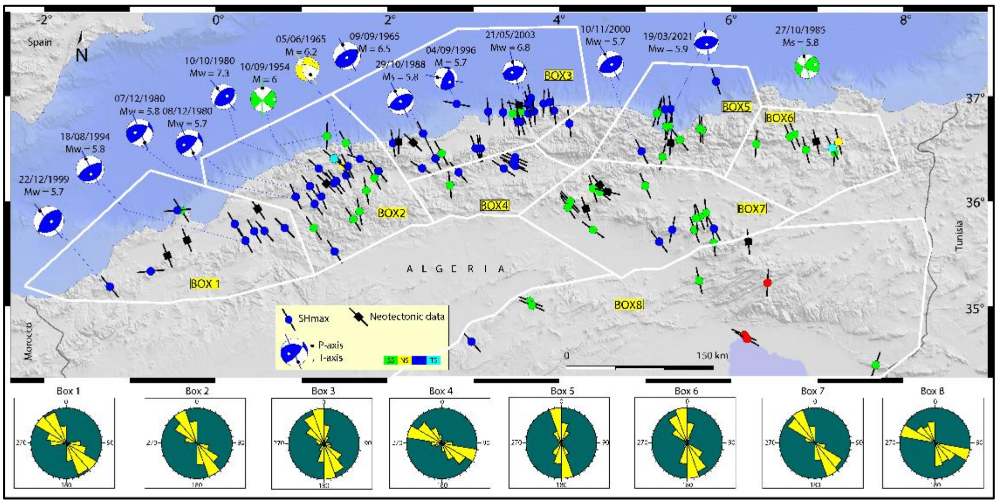

Figure 5. SHmax axis of focal mechanism data used in this study (M ≥ 4.5). A color-coded central circle indicates the stress type. Rose diagrams at the bottom show the distribution of SHmax orientations in each box. Beach balls indicate events of M ≥ 5.7 with P and T axes. Neotectonic data from Meghraoui & Pondrelli (2013).

SE strike-slip faults. The consistency of these findings across different data sources underscores the importance of region-specific seismic hazard assessments. The heterogeneity in stress fields across boxes highlights the influence of complex geological structures, including pre-existing faults and crustal heterogeneities.

5. CONCLUSIONS

The current study presents an analysis of the stress tensor derived from 631 earthquake focal mechanisms across the Tell and Saharan Atlas regions of Algeria. The findings reveal significant spatial variability in SHmax orientations and stress regimes, showing a complex pattern of stress field distribution. In the western Tell Atlas, SHmax orientations exhibit a clockwise rotation, transitioning from an NW-SE orientation in the Oranie region to an NNW-SSE direction in the eastern Mitidja basin, indicating a shift from a transpressive stress regime to a pure compressive regime. In contrast, the eastern Tell Atlas shows a counterclockwise rotation in SHmax, maintaining a strike-slip regime with a transpressive component, particularly the Constantine-Mila basin with a pure strike-slip stress regime. In the Saharan Atlas, SHmax orientations are predominantly NW-SE, with variability due to the heterogeneity of fault trends and mechanisms. The study also identifies a predominantly shallow seismicity in northern Algeria, with a D90 depth of approximately 18 km, and variations in seismic activity between the western and eastern regions. These findings have significant implications for seismic hazard assessments, as the alignment of SHmax with neotectonic fault orientations suggests ongoing strain accumulation along these faults, potentially leading to future seismic events. The detailed characterization of stress field variations underscores the importance of localized seismic risk mitigation strategies tailored to the specific tectonic behaviors of different regions within Algeria and contributes to a deeper understanding of the complex tectonic interactions along the Africa–Eurasia plate boundary in this segment of the Alpine chain (Maghrebides) in north Africa.

ACKNOWLEDGEMENTS

I am deeply thankful to my supervisor, Dr. Saeko Kita, for her invaluable support, expertise, and guidance throughout this research, which were crucial to its successful completion. I also extend my heartfelt thanks to Dr. Tatsuhiko Hara for his insightful comments. I would like to extend my thanks to the IISEE-BRI staff, JICA, and GRIPS.

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