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Seismotectonic Stress Regimes of the Nubia-Eurasia Plates Boundary and Its Kinematic Implications on the Adjoining Region

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Abstract

The tectonic stress regime of the Nubia-Eurasia plate boundaries and the adjoining region of the Strait of Gibraltar, Morocco, Azores-Cape St. Vincent, Algeria and Northern Algeria has been studied by stress tensor inversion analysis for the area bounded by latitude 27.00˚N to 40.00˚N and longitude 19.00˚W to 7.00˚E. A total of fifty-four focal mechanism solutions, pertaining to the earthquake events that have occurred in this region, were used for this study. The stress pattern of the different seismotectonic domains contained in this region was deciphered by zone-wise stress tensor inversion analysis of the Focal Mechanism Solutions (FMSs) through the algorithms of Michael and Gauss techniques. The stress tensor inversion in the five subzones of investigation shows different types of stress orientations. All of these zones are characterized by varying principal axial directions. The orientations of the principal axial direction along the Strait of Gibraltar, Northern Algeria, Algeria region, Morocco region and Azores-Cape St. Vincent zone are along N-W/S-E, NN-W/SS-E, N-W/S-E, NN-W/SS-E and N-S, respectively. The stress tensor inversion results indicate that the Strait of Gibraltar, Northern Algeria, Algeria region, and Azores-Cape St. Vincent zones are characterized by strike-slip tectonic stress regimes, while the Morocco zone is characterized by a thrust (compression) stress regime. The study concluded that for as long as the dominant compression axis of all the investigated subzones is virtually located along the N-S or along the convergent movements of the Nubia-Eurasia plates, the seismicity of the region shall continue to increase with the possibility of large magnitude events occurring anytime and anywhere within the investigated region. Hence, there is a need for precursory measures and preparedness for seismic hazards in the region.

Keywords

Stress-Tensor, Tectonic Stress Regime, Focal Mechanism Solutions, Nubia-Eurasia, Plate Boundary

1. Introduction

The Nubian and Eurasian plates' boundaries are among the few regions of the world characterized by complex geodynamic processes. This region is seismically active and consists of the following seismotectonic domains: Strait of Gibraltar, Northern Algeria, Algeria, Morocco, and Azores-Cape St. Vincent (**Figure 1**). In recent times, two of the tectonic domains have experienced devastating earthquake occurrences, namely: the Iberian Peninsula and the High Atlas Mountain range region of Morocco. Records indicate that in 1755, the Portugal earthquake was severely felt throughout the Iberian Peninsula, Northwest Africa, and some parts of Western Europe, including the southern region of France, the north of Italy, and Germany [1]. Consequently, geomorphological effects caused by this earthquake event were noticeable in spring flow variation or seiches [2]. The event was accompanied by several aftershocks that lasted for months [1]. The Atlantic Ocean's shoreline was heavily devastated by a strong tsunami moving towards the Caribbean highland and Brazil.

Recently, on 8 September 2023, there was an occurrence of a 6.8-magnitude earthquake event in the High Atlas Mountain zone of Morocco. This event echoed a seismic reawakening in a region that is historically quiescent, and approximately 2.8 million people were affected, with an estimated 3000 fatalities recorded.

Though the seismicity of Morocco is influenced by the presence of the Rif Mountains, shaped by plate convergence, the Middle-Atlas, High-Atlas, and the Anti-Atlas ranges are engineered by mantle upwelling processes [3] [4]. The Atlas rift system exhibits peak elevations exceeding 4000 m. Specifically, the crustal thickness of 32 - 40 km underlies the High Atlas mountain [4]-[6]. Seismically, Morocco is influenced by a low convergence rate of 4 mm/year along the Nubia-Eurasia plate boundary, manifesting in earthquake events near the Rif Mountains [4] [7] [8]. Conversely, the western High-Atlas Mountains display a contrasting tectonic behavior, with a lower convergence rate of 1 mm/a and aseismic to sparse seismic activity [3] [4] [7]. Considering the complex seismotectonic domain of the Nubia-

Eurasia plate boundaries, in this work, we intend to study the tectonic stress regimes of each of the seismotectonic domains of the region and determine the stress orientation of each for possible interaction in propagating a large or great magnitude earthquake in the near future. The knowledge of which will serve as a precursor and preparedness for a devastating seismic hazard in the region.

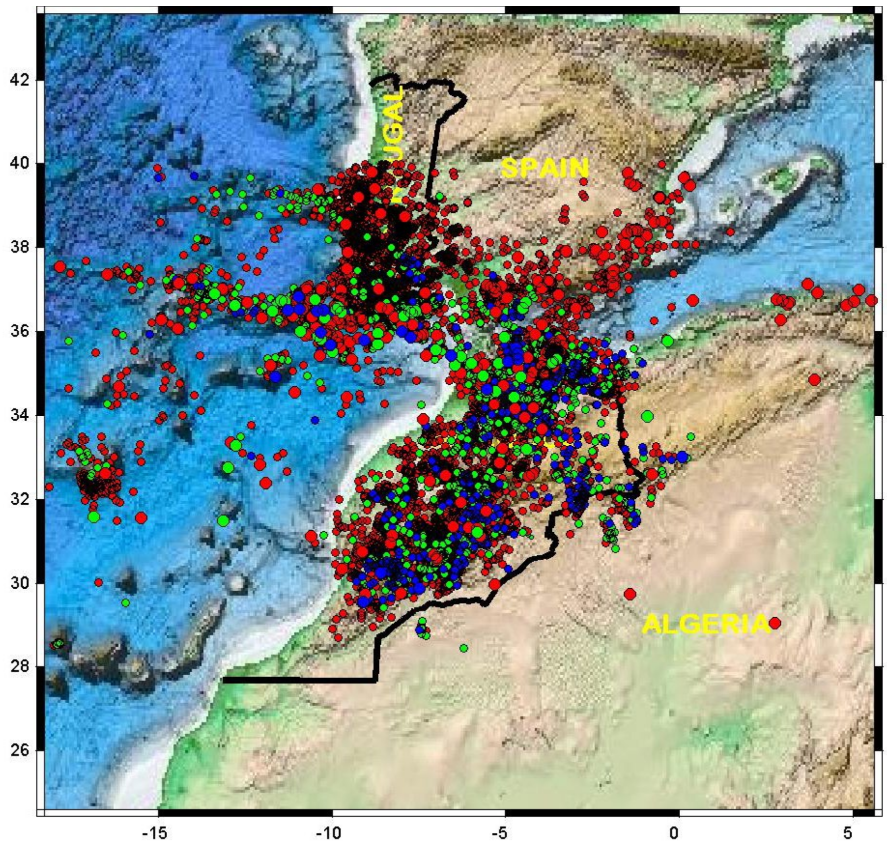

Figure 1. The red color indicates shallow (0 - 33 km) epicentral points; the green color indicates the intermediate (33 - 70 km) epicentral depth range, while the blue color indicates the deeper (70 - 150 km) depth range of the earthquakes.

2. Seismotectonic Settings of the Study Region

The westernmost end of the Mediterranean Alpine ranges at the boundary between the Nubia and Eurasian plates is situated in the Gibraltar Arc and Betic-Rif cordilleras. The present shape of the Mediterranean region is an effect of slab rollback, which is regarded as the main mechanism/process occurring over the last 25 - 30 Myr [9]-[14]. Its pertinent role in the formation of the Alboran Sea, a Neogene basin of the extensional regime [14] [15], is still controversial. Indeed, multiple geodynamical models have been proposed to explain the formation of the Alboran Sea concurrently with the compression and formation of the mountain chains of the Betics and Rif. The formation of the Alboran Basin by multiple geodynamic models—as the result of the collapse of a thick lithospheric root [14] [16] [17], crustal extrusion due to forces transmitted across the Africa-Eurasia plate boundary [14] [18], or cut-off of a subduction slab [19]—has been considered, but numerical simulations render the origin of the Alboran domain as a stretched continental fragment that emanates from the Oligocene trench zone in the Baleares margin and was dragged/stretched to its present location in the wake of slab rollback [13] [20].

3. Data Used

Both the International Seismological Data Center (ISC) and the Global Centroid Moment Tensor (GCMT) were queried for the Hypocentral and Focal Mechanisms Solutions (FMSs), otherwise known as the Fault Plane Solutions (FPSs), respectively. The Global Centroid Moment Tensor (GCMT), known as Harvard CMT [21] [22], and the International Seismological Centre (ISC) catalogue. A total number of one hundred and seventy-one thousand, eight hundred and twenty-four (171,824) hypocentral data points were obtained. In contrast, a total number of thirty-nine Fault Mechanism Solutions (FMSs) were obtained from the GCMT catalogue. An additional fifteen FMS data obtained from the literature [23], belonging to the High Middle Atlas junction of Morocco, were added to the stress tensor inversion, bringing the total FMS utilized for the study to fifty-four.

4. Methodology

The analytical methodology for the FMS utilized for the stress tensor inversion in this study can be obtained from [22]. The method is based on the linear relationship that is present between the six independent elements of a zeroth-order moment-tensor representation of an earthquake, concerning the ground motion that the earthquake generates. The relationship holds as long as the duration is small relative to the period of the seismic waves, and the dimension of the earthquake (the fault that slips) is small relative to the wavelengths of the seismic waves considered. The methodology for the hypocentral data containing the longitude, latitude, Magnitude, and Depth [24] is as follows: it uses all ak135 [25] predicted phases (including depth phases) in the location with elevation, ellipticity [26], and depth-phase bounce point corrections; obtains the initial hypocenter guess via the neighborhood algorithm; performs iterative linearized inversion using an a priori estimate of the full data covariance matrix to account for correlated model errors; attempts a free-depth solution if and only if there is depth resolution, otherwise it fixes the depth to a region-dependent default depth; scales uncertainties to 90 percent confidence level and calculates location quality metrics for various distance ranges; obtains a depth-phase depth estimate based on reported surface reflections via depth-phase stacking; and provides robust network magnitude estimates with uncertainties.

The historical and recent earthquake seismological data instrumentally recorded in the study region were queried for the hypocentral parameters on the Internet at isc.ac.uk, and the ISC Bulletin was searched for the event catalogue. The event catalogue was queried for the past 45 years, starting from 1978 up to the year 2024, at the following geographic coordinates: longitude 19.00˚E to 7.00˚E, and the latitude was probed at latitude 27.00˚N to 40.00˚N. These events were plotted on the image map to illustrate and decipher the region's hypocentral distributions using Mirone software; see **Figure 1**. However, the Focal Mechanism Solutions (FMSs) or the Fault Plane Solutions (FPSs) were queried at the Global Centroid Moment Tensor website: https://www.globalcmt.org/CMTsearch.html using similar geographic coordinates corresponding to the region of study. A total of fifty-four FMS data were obtained, corresponding to different seismotectonic domains of the region, identified by the Global Centroid Moment Tensor Project as: Morocco, Azores-Cape St. Vincent, Strait of Gibraltar, Algeria, and Northern Algeria. Fifteen additional FMS datasets were obtained from the literature on Morocco's High Middle Atlas junction zone (**Table 1**). The corresponding strike, dip, and rake of each of the FMS data were plotted to generate their respective beach balls using Rake software [27] (**Figure 2**).

The stress tensor inversion was carried out using the Michael algorithm and Coulomb software. [28] implies that a focal mechanism solution represents two possible fault planes and slips. Thus, to invert fault plane solutions for the stress field, emphasis must be given either to: 1) knowing which plane is the fault plane a priori, 2 having an algorithm that does not need to know, or 3) having an algorithm that is capable of correctly distinguishing the fault planes from the auxiliary planes [29].

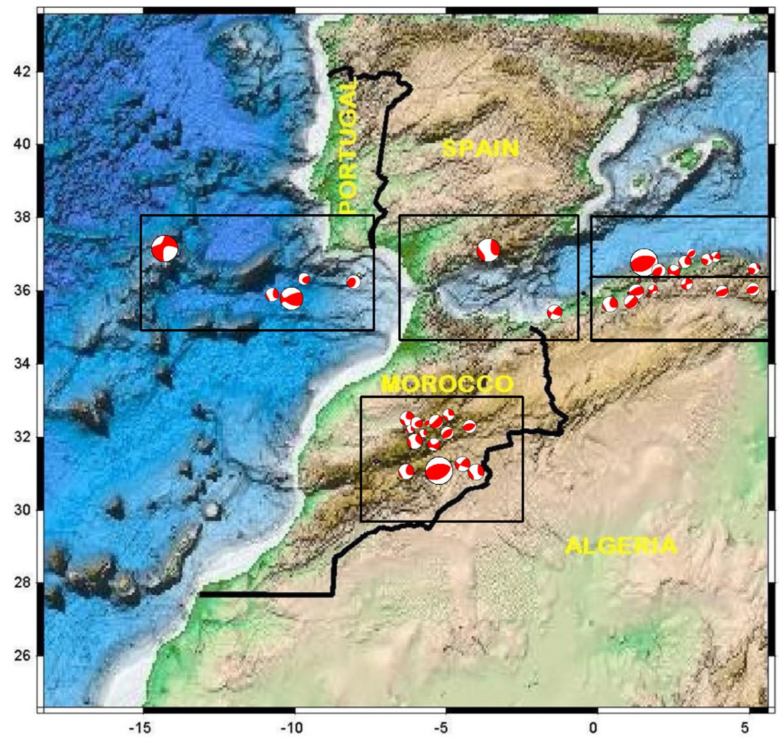

Figure 2. Zone-wise positioning of the beach balls in their respective seismotectonic domains.

Table 1. Distributions of the Focal Mechanism Solutions (FMSs) within the study zone.

Zone	Number of Events	Depth (km)			Magnitude (Mw)		
		Min	Max	Avge	Min	Max	Avge
Morocco	15	5.2	16	10.6	3.3	5.2	4.25
Azores-Cape St. Vincent	5	15	44.9	29.95	5	6	5.5
Strait of Gibraltar	8	12	16.5	14.25	4.9	6.3	5.6
Algeria	17	10	15.	12.5	5	7.1	6.05
Northern Algeria	9	12	15.1	13.55	4.8	6.8	5.8

Otherwise, known as the Gauss method, it works on the concept of the best-fit stress tensor. First, the compatibility measure takes into account both: 1) the angular misfit between the resolved shear stress and the actual direction of movement on the fault plane, and 2) the ratio between the normal and shear stress on the fault plane (**Figure 3**).

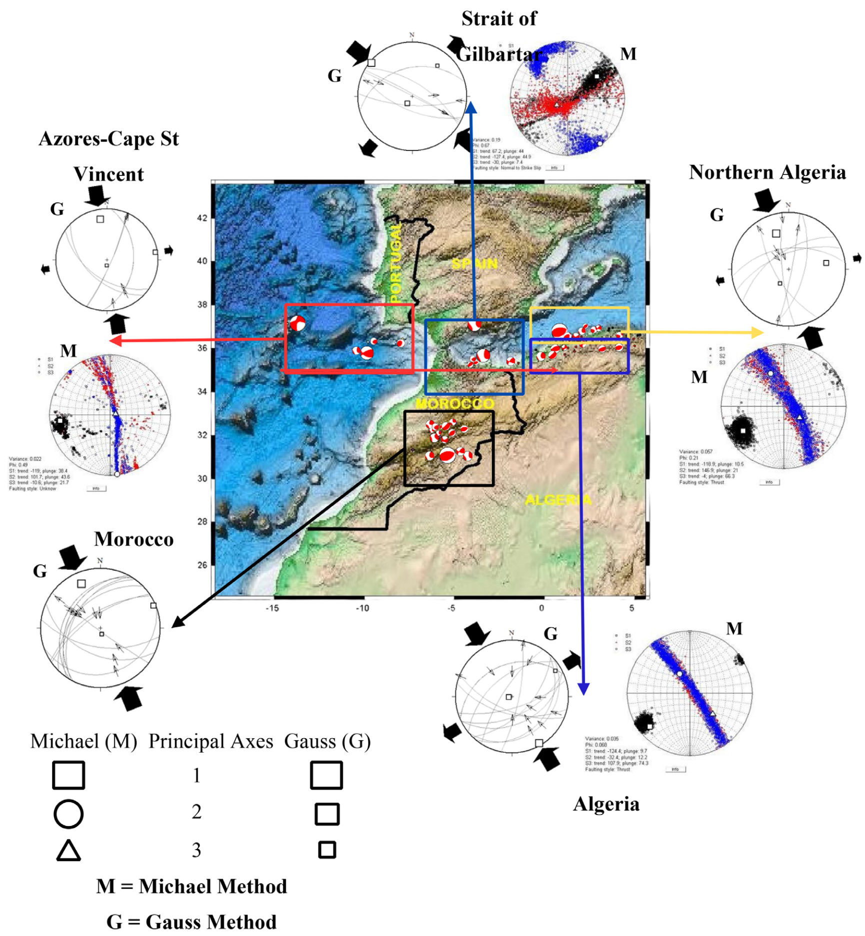

Figure 3. Results of the stress tensor inversion for the various seismotectonic domains of the investigated region.

5. Result

The hypocenter data of the region, spanning some forty-five years, reveal the epicentral distributions of the study region, having a focal depth of shallow (0 - 33 km) indicated in red; intermediate depth (33 - 70 km) indicated in green, and deeper depth (70 - 150 km) indicated with blue coloration. They depict seismicity clustering through the High Middle Atlas of the mountains of Morocco up to the Strait of Gibraltar, Iberian Sea, Spain, Portugal, and the Gulf of Cadiz and Cape Saint Vincent (see **Figure 1**). [30] utilized both Michael and Gauss techniques for examining the tectonic stress regimes in the Gulf of Guinea. In this study, we examine the nature of the stress regimes characterized by the Nubia-Eurasia plates (study region), employing the Michael algorithm and the Gauss method. We observed that the region is not homogeneous but rather characterized by varying tectonic domains: The Strait of Gibraltar is characterized by strike-slip regimes. The results of the stress tensor inversion for each of the investigated seismotectonic domains are shown in **Table 2**. The principal stresses and obtained orientations from Michael and Gauss methods are illustrated in **Figure 3**. The Strait of Gibraltar comprised the stress tensor inversion of 8 focal mechanism solutions, which shows that the principal compression axis $\sigma 1$ is along the NW-SE direction. The Michael method revealed azimuthal, plunge, and φ measurement of this zone, for principal compression axis ($\sigma 1$) as follows: 67.20, 44.0, and φ = 0.67. Compression axis ($\sigma 1$) measurement, using the Gauss method, is as follows: azimuthal value of 309.0, plunge of 2.0, and φ = 0.55 respectively, while the recessive extensional axis $\sigma 3$ is along the NE-SW direction. The Northern Algeria region is characterized by purely oblique thrust FMS of 9 events that were utilized in the stress tensor inversion analysis.

Michael method, for the principal compression axis $\sigma 1$ axial direction NN-W/SS-E, shows an azimuthal value of −118.9, a plunge value of 10.5, and φ 0.21; Gauss method shows the azimuth, the plunge, and the φ values as follows: 341, 23.0, and 0.58, respectively. The recessive extensional axis is along the W-E direction. The Algeria region utilized 17 FMS (s) of earthquake events for the stress tensor inversion; the zone is characterized by strike-slip regimes with the dominant principal compression axis ($\sigma 1$) along the N-W/S-E direction. Michael method analysis for the $\sigma 1$ regime revealed an azimuthal value of −124.4, a plunge of 9.7, and φ of 0.07; Gauss technique shows the azimuthal value of 150, plunge of 2.0, and the phi of 0.54. The recessive extensional axis is along N-EE/S-WW. The Morocco region is characterized by purely thrust regimes and utilized 15 FMS(s) data for the stress tensor inversion study. The main principal compression axis is along NN-W/SS-E. The Gauss method shows the azimuth of 337.0, plunge of 13.0, and phi of 0.47, respectively. The Azores-Cape St. Vincent zone is mainly thrust oblique and characterized by strike-slip tectonic stress regimes with the dominant principal compression axis along the N-S direction. Michael method revealed the azimuthal value of −119.0, plunge is 38.4, and φ of 0.49, while the Gauss measurement revealed the azimuthal value of 351.0, 13.0, and 0.59, for the plunge and φ, respectively. The above results have been synthesized in **Figure 4** to include the velocity vector of the African plate movement with respect to Eurasia.

Table 2. Result of the stress tensor inversion for the five subzones of the Nubia-Eurasia region.

Zone	Method	($\sigma 1$)		($\sigma 2$)		($\sigma 3$)		φ	φ Avg	Variance	Std. Dev
		Azim (0)	Pln (0)	Azim (0)	Pln (0)	Azim (0)	Pln (0)				
Morocco	Michael	-	-	-	-	-	-		0.47	-	-
	Gauss	337.0	13.0	67.0	2.0	166.0	77.0	0.47		-	-
Strait of Gibrater	Michael	67.2	44,0	127.4	44.9	−30.0	7.4	0.67	0.61	0.19	0.2969
	Gauss	309.0	2.0	213.0	72.0	40.0	18.0	0.55			
Azores-Cape St. Vincent	Michael	−119.0	38.4	101.7	43.6	−10.6	21.7	0.49	0.54	0.022	0.36628
	Gauss	351.0	13.0	81.0	2.0	180.0	77.0	0.59			
Algeria	Michael	124.4	9.7	−32.4	12.2	107.9	74.3	0.068	0.304	0.035	0.1902
	Gauss	150.0	2.0	258.0	84.0	60.0	6.0	0.54			
Northern Algeria	Michael	118.9	10.5	146.9	21.0	−4.0	66.3	0.21	0.395	0.057	0.23900
	Gauss	341.0	23.0	81.0	22.0	210.0	57.0	0.58			

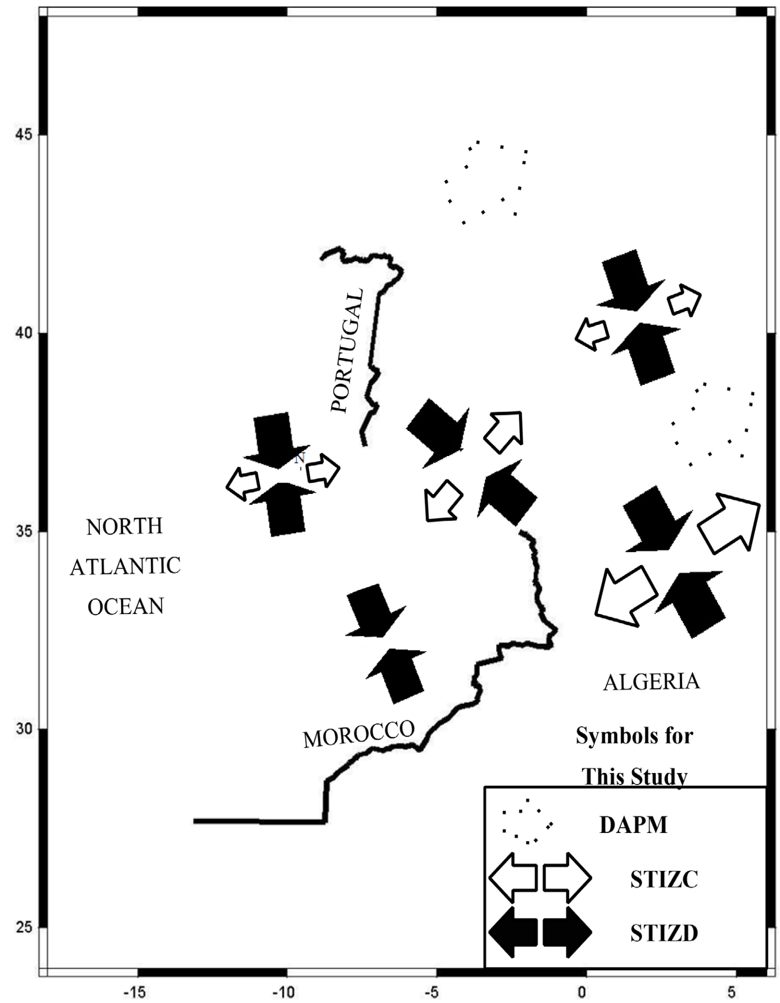

Figure 4. A map depicting the synthesized stress tensor inversion results and the velocity vector of the African plate with respect to the Eurasian plate. Pairs of convergent arrows denoted by STIZD stand for the compressive stress regime and the divergent arrow denoted by STIZC stands for extensional stress regimes. The large, dotted arrow mark on the top right corner of the figure indicates the velocity vector of the African plate.

6. Discussion

The study of the tectonic stress regime is highly essential for seismic hazard assessment investigation, and it is one of the key components of earthquake prediction studies. This study has been effectively carried out utilizing the FMS data set acquired from the Global Centroid Moment Tensor (GCMT) data catalogue, on the GCMT website: https://www.globalcmt.org/CMTsearch.html. The acquired data were limited, 39 FMS, distributed through four seismotectonic domains: the Strait of Gibraltar, Northern Algeria, Algeria, and Azores-Cape St. Vincent. There was no data available for the Morocco seismotectonic zone. Hence, we searched through the literature and we were fortunate to discover the article written by [23], from which we extracted the 15 FMS data belonging to the High Middle Atlas junction of Morocco. These FMS data contained only the first nodal plane, and without the second nodal plane, the Michael algorithm could not work. Therefore, we were able to run only the Gauss Algorithm for the Morocco region.

The investigated region is geologically complex. The Ocean Drilling Program (ODP) indicates an immature volcanic arc crust in the eastern Alboran Sea, which was suggested to have formed between 11 and 8 Myr ago [31] [32]. The Alboran seafloor is complex, consisting of ridges, seamounts, faults, and deep basins. The ODP Leg 161 revealed that the West Alboran Basin basement consists of metamorphic rocks of continental origin instead of oceanic rocks. Contrarily, the ODP drilling along the East Alboran Basin revealed calc-alkaline to alkaline rocks [31] [32]. In view of the foregoing, we advocate for an active seismic reflection geophysical survey to complement the passive seismological technique, in order to image the buried passive fault lines from where the built-up stress within the region could be ruptured to unleash terrible and devastating earthquake events on the adjoining region.

7. Conclusions

The seismicity of the investigated region (Nubia-Eurasia plate) depicts seismicity clustering through the High Middle Atlas of the mountains of Morocco up to the Strait of Gibraltar, Iberian Sea, Spain, Portugal, and the Gulf of Cadiz and Cape Saint Vincent (see **Figure 1**). The region is seismically active and it is within and in the adjoining regions of the convergence zones of the Africa and Eurasia plate boundaries. Historically, devastating earthquake occurrences have been recorded within the investigated region on multiple occasions, accompanied by loss of lives and destruction of several properties.

We have carried out the stress tensor inversion for the five different seismotectonic domains that comprise the investigated region: Northern Algeria, Algeria, Morocco, Azores-Cape St. Vincent, Morocco and Strait of Gibraltar. The investigated zones are characterized by varying tectonic stress regimes: Northern Algeria, Algeria, Azores-Cape St. Vincent, and the Strait of Gibraltar are characterized by strike-slip tectonic stress regimes, while Morocco is purely characterized by compression (convergence) stress regimes. However, the seismotectonic domains that are characterized by the strike-slip tectonic stress regimes are dominated by the principal compression axis $\sigma 1$, an indication of thrust oblique FMS data.

Since the tectonic stress regimes of the investigated region are dominated by the principal compression axis, which is virtually oriented North-South, along the direction of the convergence movement of the Nubia and Eurasia plates, there is an increase in seismicity rates and active tectonism in the region. Currently, the principal compression axial orientations of all the seismotectonic domains within the region of study are towards N-S or along the convergence movement of the Nubia-Eurasia plates; thus, the seismicity of the region shall remain active, with higher possibilities of occurrence of devastating earthquake events in the near future. These observations, thus far, emphasize the need for integrated earthquake seismicity monitoring, seismic hazard precursory and preparedness studies to mitigate future seismic hazard in the region.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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