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Structural Elements and Seismic Activity in Jordan and Its Levant Surroundings

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Abstract

Earthquakes are among the most severe natural hazards that affect different regions of the globe. Generally, earthquakes take place on geologic weakness zones of the earth, especially faults. In Jordan and the Levant countries, active faults are abundant, especially, the Dead Sea Transform Fault and its offspring faults resulting in the formation of the Jordan Rift Valley. The Dead Sea Transform Fault is the main active tectonic feature in the region that builds the tectonic boundary between the Arabian and African plates. The recent earthquake of 2023 in Türkiye and Syria, which left behind tens of thousands of casualties and enormous damage, scared the inhabitants in Jordan who were afraid that such earthquakes might hit in Jordan. This paper discusses the main geologic structures in Jordan and its immediate surroundings, along which earthquakes have taken place in the past, and how the genetics of the geologic structures relate to the earthquakes and their magnitudes. The study concludes that the fractured tectonics and tensional faulting of Jordan characterized by short fault extensions including the Dead Sea Transform Fault, which, on its eastern side, is divided into several east-west striking blocks, seem to accommodate tectonic movements on a block size, and that does not allow for the accumulation of tectonic stresses to produce large earthquakes. Earthquakes during the last century indicate that only along the Jordan Rift Valley earthquakes of intermediate magnitudes have taken place, but along all other fault zones, only very mild earthquakes have taken place and are expected, in the future to release tectonic pressures in the same mild form.

Keywords

Earthquakes, Major Structures, Extensional Faulting, Dead Sea Transform Fault, Jordan

1. Introduction

Jordan is located in a seismically active region and the Dead Sea Transform (DST) fault system makes it susceptible to earthquakes. In contrast, Jordan does not experience large earthquakes as frequently as other regions such as Japan, Iran or Türkiye. Nevertheless, seismic activity does occur periodically (Arab Weather, 2023; Haddad et al., 2020; Jreisat &Yazjeen, 2013; Salamon, 2009). The most significant recent earthquake in Jordan occurred in 1927, which had approximately a magnitude of M 6.2 and caused some damage and casualties in central Jordan and mainly in northern Palestine. Furthermore, the 1995 Gulf of Aqaba earthquake, which occurred on 22 Nov. 1995, with a magnitude of M 7.2 resulted in minor destructions in Aqaba City (Al-Tarazi & Korjenkov, 2007; Haddad, 2020; Al-Tarazi, 2000; Jreisat & Yazjeen, 2013, Husein et al., 1995). Since 1927, only low-magnitude earthquakes have taken place in Jordan, with no major damages, also because of better quality constructions.

Many studies have been conducted on earthquakes in Jordan and the Levant (Haddad et al., 2020; Jreisat & Yazjeen, 2013; Salamon, 2009; Al-Tarazi, 2000; Husein et al., 1995; Abou Karaki, 1987; among others) and some studies related the earthquakes to active geologic structure, especially to the Jordan Rift Valley structure (Jreisat & Yazjeen, 2013; Al-Tarazi & Sandvol, 2007; Ambraseys, 2006).

Many previous studies have also addressed the nature of the faults and weakness zones along which movements and earthquakes have taken place in the past (Jreisat & Yazjeen, 2013). This study tries to correlate faults and weakness zone types and movements along them, with earthquake activities in order to clarify the probabilities of large earthquakes that can take place along these structures.

The study concentrates on the correlation of earthquakes, which have occurred during the last ten decades in Jordan with the major geologic structural elements. The correlation will indicate the potential of large earthquakes, which might hit the area. The background of the study is based on the facts that the geologic structures in Jordan are extensional and their lengths are short, which do not allow stresses to accumulate. In addition, the Dead Sea Transform Fault, which is also an extensional structure, is divided on its eastern side into several E-W blocks, where strong earthquakes can hardly be expected.

2. Analysis and Discussion of the Structural Framework and Seismicity

2.1. Structural Elements in Jordan and Surrounding Areas

The base underlying sedimentary, volcanic and metamorphic rocks in Jordan consists of a rigid granitic basement that crops out in southern Jordan. It dips in a northeasterly direction and extends further south and west into Saudi Arabia and Egypt across the Red Sea. In a northerly and easterly direction, sedimentary rocks cover the granitic basement, which is encountered at depths of 3 - 6 km in north Jordan and at greater depths further north and east in Syria and Iraq (**Figure 1**) (Modified after Pollastro et al., 1999; Bender, 1968; Quennell, 1959).

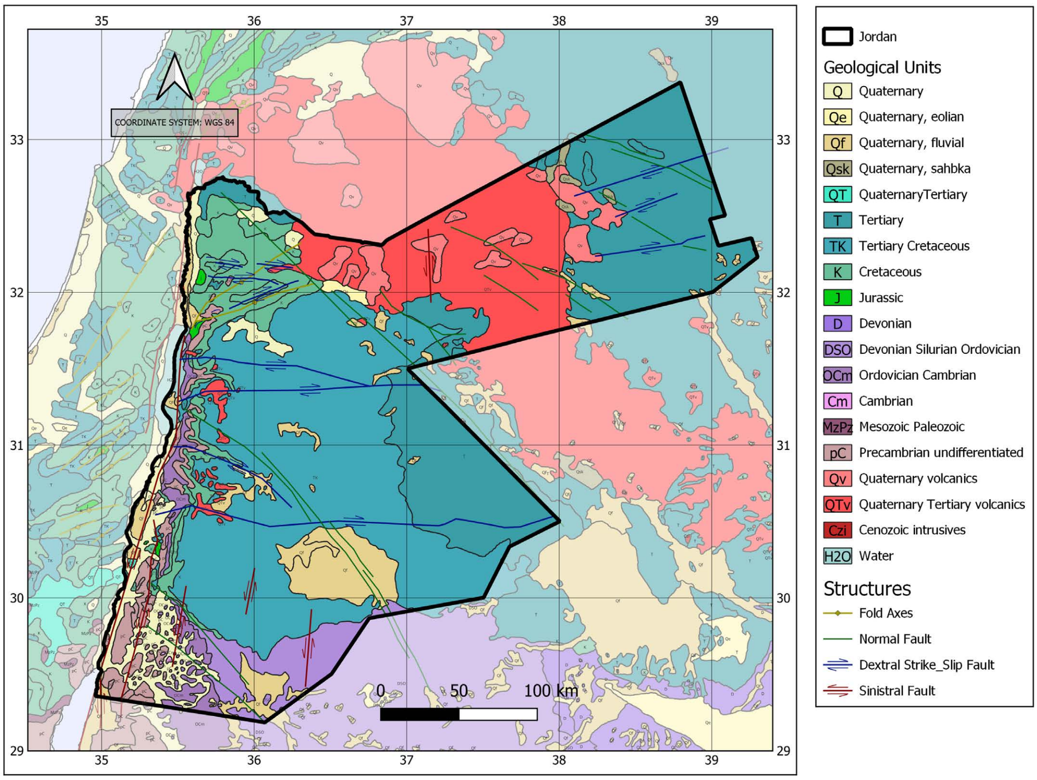

Figure 1. A simplified geological map of Jordan and its neighboring regions reveals the Arabian Shield in the extreme southwest of Jordan, notably in the Aqaba Mountains, extending into Saudi Arabia and Sinai, Egypt. Sedimentary rocks cover the majority of Jordan's area. The most comprehensive stratigraphic sequence, spanning from the Precambrian to the Quaternary, is evident in the west of Jordan, particularly along the Dead Sea Transform Fault and its associated uplift processes. Additionally, volcanic plains are significant, spreading across north-central Jordan and extending from Syria, through Jordan, and into Saudi Arabia (Modified after Pollastro et al., 1999; Bender, 1968; Quennell, 1959).

The structures in this granitic basement, where it crops out in the Aqaba Mountains, along Wadi Araba, and in the underground of the country as investigated by geological and geophysical studies (Bender, 1968) can be summarized as follows:

- Very strongly present: NW-NNW trending horst and graben structures separated by faults such as Ras en Naqab uplifted structure, Jafr Depression, Karak-Fayha Graben, Bayer-Kilwa Swell, Sirhan Depression, Rutba Uplift, volcanic necks in Jabal Druz area and dykes and faults in Aqaba and Wadi Araba granitic basement (**Figure 2** and **Figure 3**).
- Strongly present: N-S ± 10^0: Jordan Valley Fault, Quweira Fault, Jafr Paleozoic Basin, Safra Swell, Qatrana-Quneitra Swell and dykes in Aqaba and Wadi Araba granitic basement.
- Weakly present in Paleozoic time, but strongly reactivated after Neogene time: ±E-W faults: Salawan, El-Hasa, Karak, Swaqa, Shihan, Zarqa Ma'in, Suweima-Hallabat, and Zarqa River among others (**Figure 3**).

The major blocks trending NW-SE to ± N-S, which form graben and horst structures are untenable to stay without breaking perpendicular to their trends to form the above-mentioned ±E-W faults.

All the above-mentioned structures are extensional structures, along most of them magmatic dykes, volcanic eruptions, and fault and joint fillings were deposited (Bender, 1968; Quennell, 1959) indicating their tensional origin. Dykes in the granitic basement do not penetrate the overlying younger sediments indicating that the faults and weakness zones along which they ascended are older than the overlying sediments, and that they had affected the granitic basement rocks only (Bender, 1968). In addition, the increasing thickness of sediments in the depressions of Sirhan, Jafr and others indicates the preexistence and continuous down wrapping of these depressions.

The structural elements, categorized according to their trends, form in the underground of Jordan a big number of individual, from each other, separated granitic basement blocks and therefore, any reactivated or new stress field, which affect the granitic basemen and its overlying rock series, can only manifest itself in relative vertical or horizontal movements along these ancient structural surfaces.

Major, extended compressional structures are not known from Jordan and smaller ones are restricted to some minor local folding mostly accompanying normal flexures trending ±E-W.

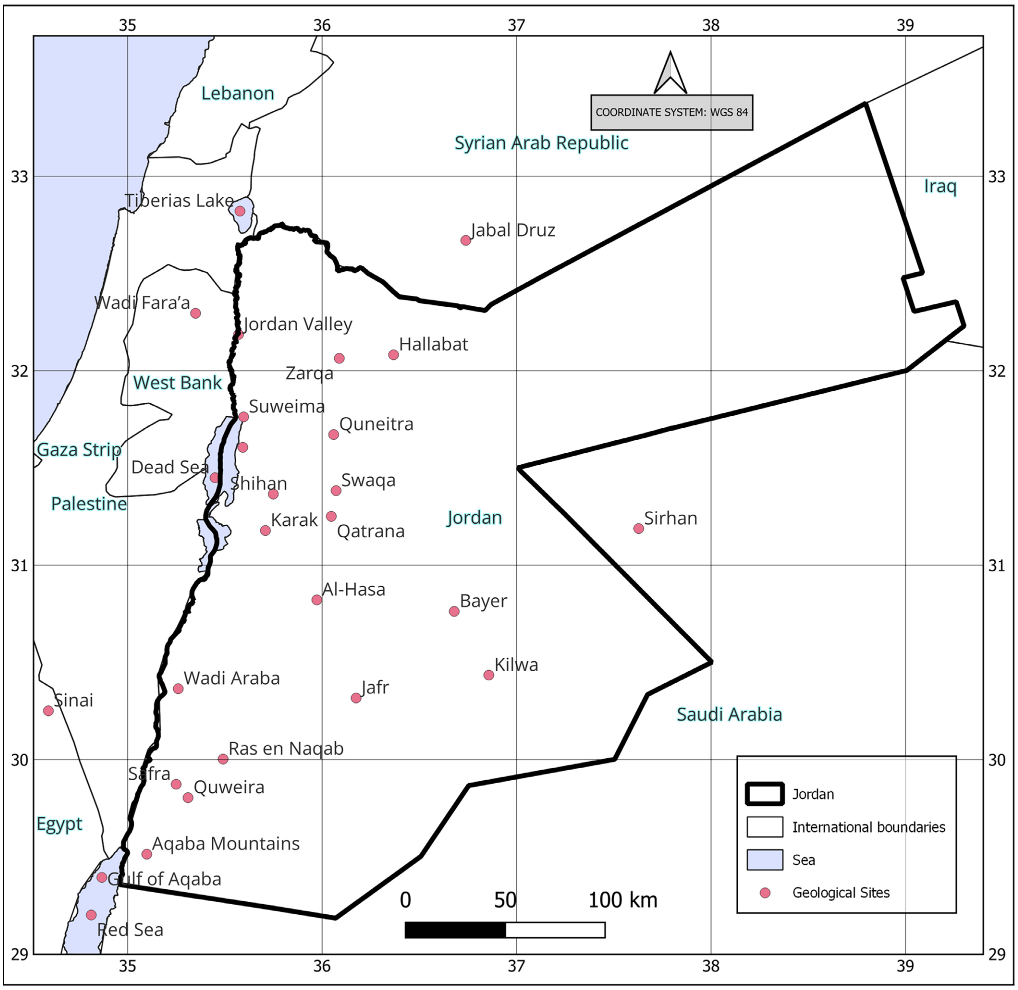

Figure 2. A geographic map illustrating key locations relevant to this study.

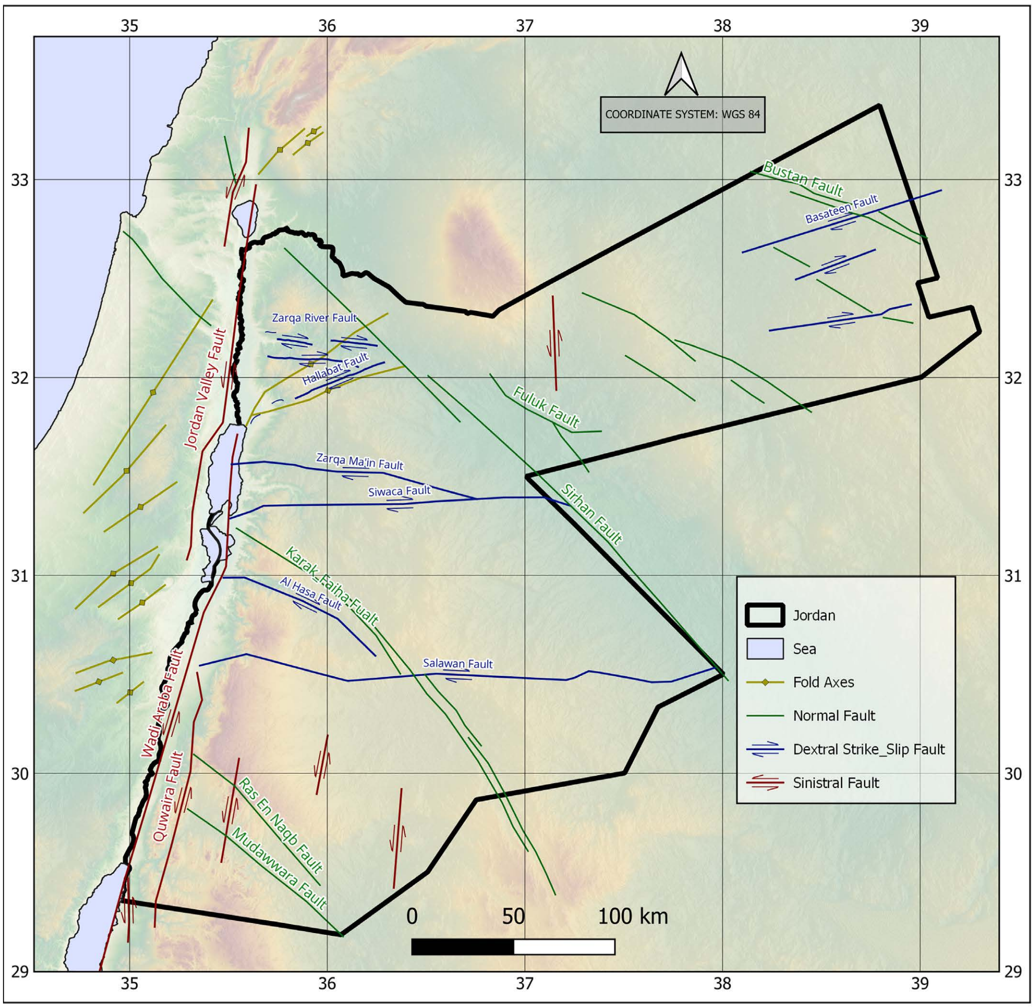

Figure 3. Major geologic structures on Jordan (modified after Powell et al., 2015; Diabat, 2012; Diabat & Masri, 2002; Bender, 1968).

Horizontal-peak stylolites trending 130˚ - 140˚ are mapped in Jordan, mostly affecting Upper Cretaceous and Early Tertiary rocks indicating at a stress field acting in that direction. In addition, Pliocene and some Pleistocene rocks show horizontal stylolites trending 170˚ (Salameh & Zacher, 1982). These stylolites indicate at an Early Tertiary stress field acting in the trend direction of these stylolites, at times when the sediments were still semi-lithified. It seems that after the formation of the stylolites the stress field changed direction from ±N-S to become NW-SE; during late Tertiary early Quaternary time, producing no major folding structures in Jordan. Slickensides as a result of strike slip movements are known in Jordan. They are mostly sinistral, striking N ± 10˚ reflecting a stress field trending ±N-S. Strong dextral strike slip faulting movements are observed along ±E-W striking faults indicating at a stress field acting in a NW-SE direction. The fact that these slickensides are found affecting Tertiary and Upper Cretaceous rocks indicates that the reaction of rock series in Jordan to new stress fields takes place along pre-existing discontinuity surfaces, especially faults.

The collision of the Arabian Plate with the Anatolian and Iranian Plates (Eurasian Plate) further NNW, N, NE and E of Jordan has produced compressional structures in the Palestinian Block and the Palmyra Mountain Chain in Syria, where the sediment cover of the granitic basement is thick (>3 km).

The collision seems to have produced stress fields in Jordan, which have only reactivated older structures along the, from each other separated old granitic basement blocks of pre-collision eras with very limited frictional contacts to each other. These blocks reacted by tilting and vertical movements relative to each other producing flexures, dextral strike slips, and undulations in the incompetent Mesozoic, Tertiary and Quaternary sediments compared to the competent granitic basement.

Slickensides caused by strike slip movements are very common in Jordan. They are sinistral, striking N ± 10˚ reflecting a stress field trending ±N-S. In addition, strongly represented are dextral strike slip movements along the ±E-W striking faults and joints indicating at a stress field acting in a NW-SE direction. The fact that these slickensides are found affecting Tertiary and Upper Cretaceous rocks indicates that the reaction of rock series in Jordan to new stress fields took place along pre-existing discontinuity surfaces, especially faults.

The almost total absence of compressional structures in Jordan in Paleozoic and Mesozoic times indicates that Jordan had not been affected by major stress fields during these geologic eras to leave behind their effects.

Recorded earthquake occurrences in Jordan have been concentrated along the JRV, playground of the DST fault and its offspring structures near the Rift Valley. This situation deserves special attention to explain the mechanisms and stress fields producing the earthquakes and to clarify the possibilities of occurrences of devastating earthquakes from a geological point of view.

From a structural point of view and considering the original structures of the granitic basement, the DST fault cannot be a straight line, but a zigzag line in coincidence with the lineaments in the granitic basement. East-west dextral strike slip movements along the eastern side of the JRF took and are taking place along the many ± E-W trending weakness zoned, which originated in the granitic basement, and which are portrayed in the overlying sedimentary rocks. That can be seen on the examples of the many ±E-W trending faults in Jordan such as: Salawan, Al-Hasa, Karak-Fayha, Shihan, Zarqa Ma'in, Suweima-Hallabat, and Zarqa among others (**Figure 3**).

For that reason, strike-slip movements along the DST take place along extensional structures and not along compressional ones and hence their low magnitude earthquakes. Only when blocks move past each other due to strike slip movements, the sinuosity of the Rift Valley fault pattern produces collision along bends in the S-shaped block boundaries. Such blocks are only short in their lengths and their frictional resistance to movements is low due to the extensional nature of the DST and the E-W faults.

2.2. Seismicity

Available data sources on earthquakes in Jordan such as the International Seismological Center bulletins (ISC and the Jordan Seismological Observatory (JSO) bulletins (1983-2012) were compiled by Jreisat and Yazjeen (2013) to illustrate the distribution and magnitudes of earthquakes along the DST and its surrounding areas. The available data from the International Seismological Centre, spanning 1918-2023 (ISC, 2023), indicate that the southern part of the area, specifically the Gulf of Aqaba, is the most affected region by earthquakes, both in terms of magnitude and frequency (**Figure 4**). The epicenter of the 1995 earthquake of a magnitude of 7.2 lies in the Gulf of Aqaba, at around 100 km south of Aqaba City (Jreisat & Yazjeen, 2013). According to these authors, the Gulf of Aqaba presents the most active tectonic zone near Jordan, and after 1996, it seems that the region could be entering a cycle of reduced seismic activity in terms of the number of major earthquake events. Data produced throughout the last 20 years of monitoring show moderate seismic activity in Jordan.

During the last 100 years, only in 1927, an earthquake of M 6.2 (with the epicenter along Wadi Fara'a on the Palestinian part of Sinai Plate struck the region. This event left some damage in Jordan and Palestine.

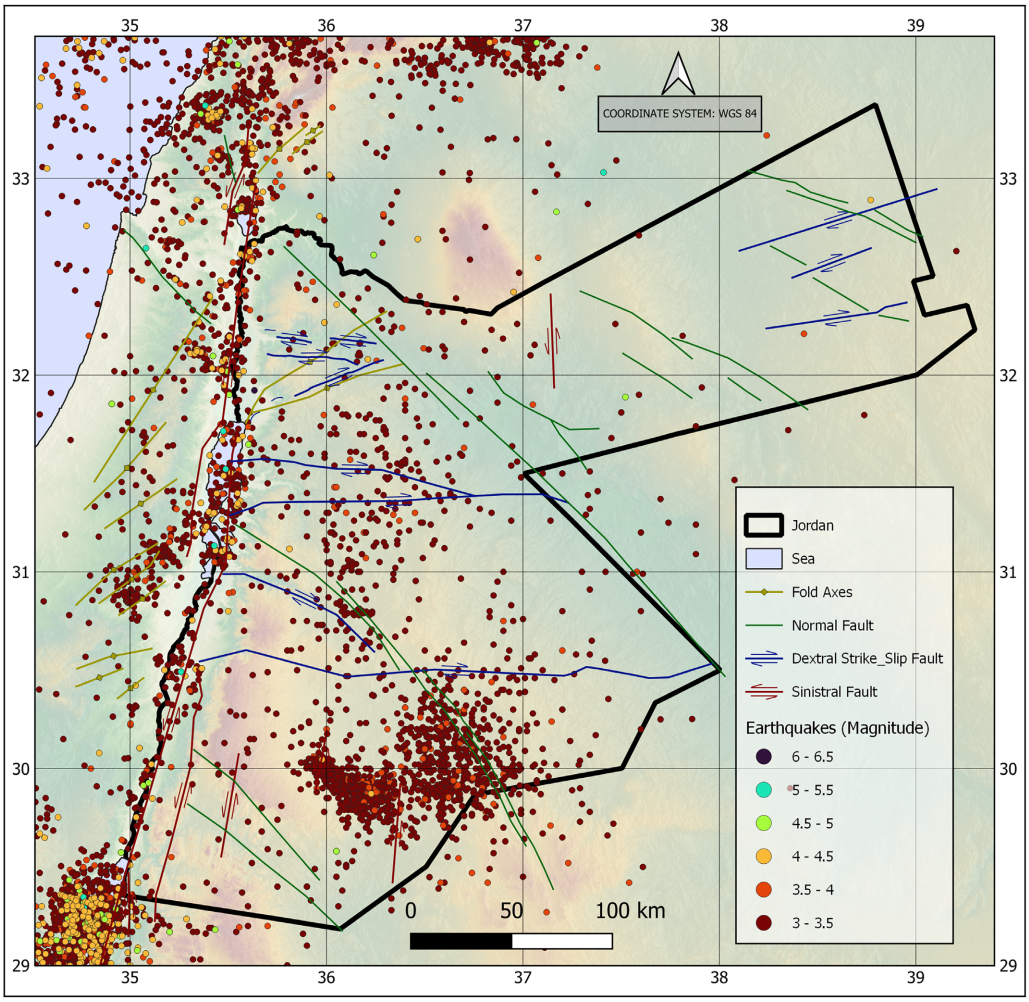

Figure 4. Locations of all magnitudes earthquakes > 3, which took place in Jordan from 1918 to 2023 showing that they concentrated along the Jordan Rift Valley (Modified after ISC, 2023).

Jreisat and Yazjeen (2013) calculated the seismic behavior of the Gulf of Aqaba at a maximum expected local magnitude of M˛6.4, in Wadi Araba at M 5.1 and in the Dead Sea M 5.9.

Figure 5 shows the locations of earthquakes of M > 4, which have struck the area during the last 100 years. The figure also shows that earthquakes of M > 5.5 have not struck in Jordan during these 100 years. That is, as elaborated above, the result of extensional type of the faulting system and short lengths of faults, which do not allow tectonic stress to accumulate and release to produce strong earthquakes.

Figure 6 shows the peak ground acceleration distribution in Jordan, which indicates that the potential acceleration is less than 0.75 m/s^2. This means that the area has moderate exposure to earthquakes M 5.0 - 5.5 and very low exposure to M 5.5 - 6 (Johnson et al., 2023).

3. Findings and Discussion

The DST fault is an active seismic boundary between the Arabian and African

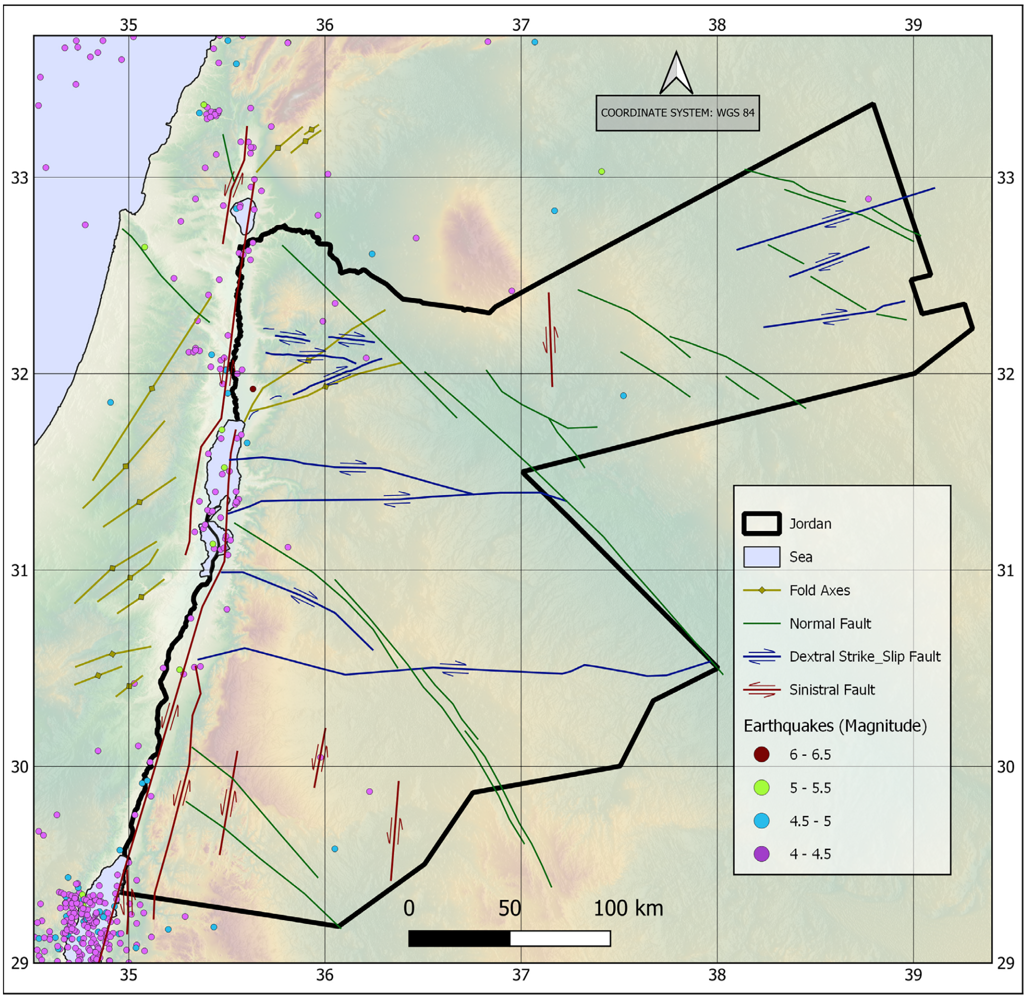

Figure 5. Locations of earthquakes of M > 4, which took place in Jordan from 1918 to 2023 showing the small number of such earthquakes, and that no earthquake of M > 5.5 has hit during the last 100 years. (Modified after ISC, 2023).

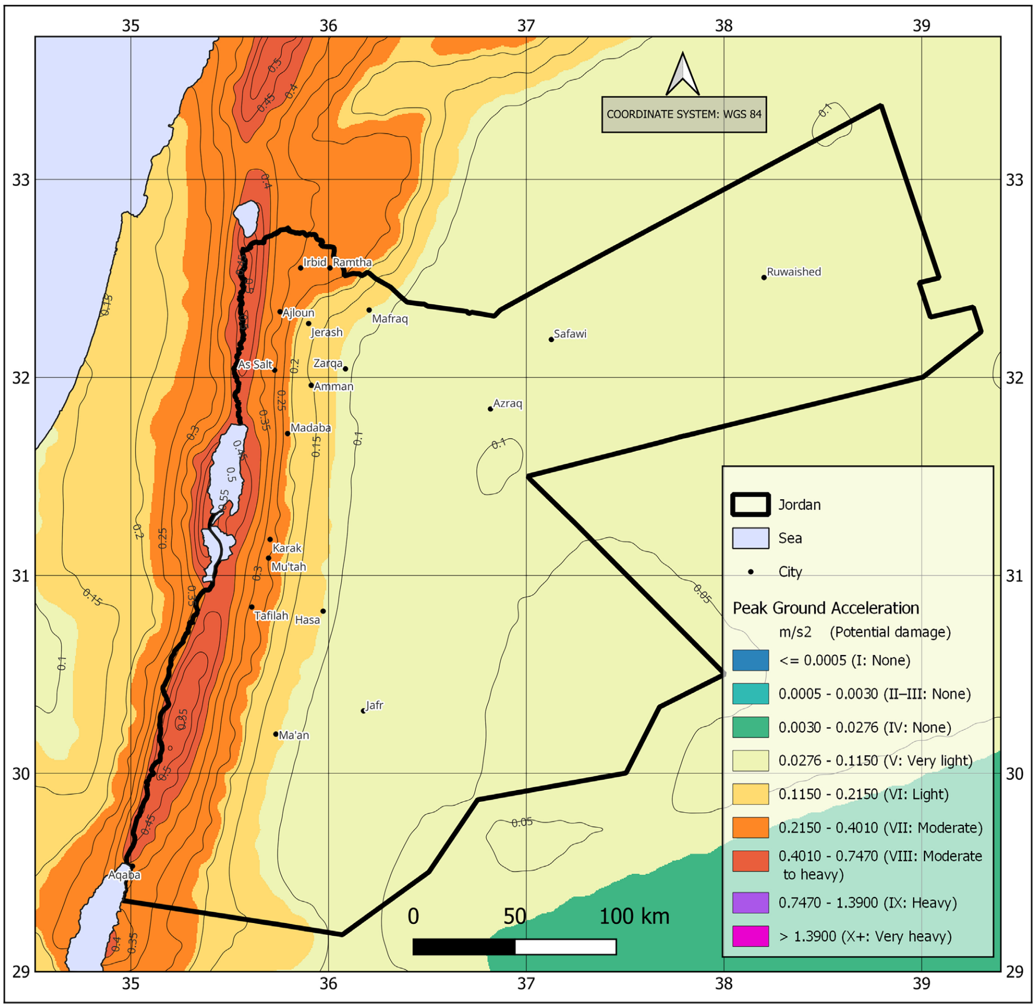

Figure 6. The peak ground acceleration distribution in Jordan (Modified after Johnson et al., 2023).

Plates intersected by many ±E-W dextral faults on its eastern side. The gradual anti-clockwise rotation of the stress field from ±N-S acting during Paleozoic times to ±NW-SE since Neogene time has reactivated movements along the structural lineaments created by the Paleozoic ±N-S stress field.

The shallow sedimentary cover of the Granitic Basement underlying Jordan reacted to the since Neogene prevailing ±NW-SE stress field by rotational movements of the granitic blocks against each other producing extensional features along which volcanic eruptions took place. Worth mentioning here is that compressional structures in Jordan are very rare and are restricted to minor folding and some ridges along the DST. Along the short tensional structures in Jordan, tectonic stress cannot accumulate to produce major earthquakes of M > 6. The DST fault in Jordan is also a tensional fault (Pull-apart) and its eastern shoulder mountains are severed by deep-seated E-W to SE-NW striking faults in the granitic basement. This constellation allows block-wise movements of the short blocks of N-S extensions of a few tens of kilometers, which can only result in earthquakes of small magnitudes, generally less than 5.

The updated seismo-tectonic map for Jordan and surrounding areas show that the most active segments in the studied period are the Gulf of Aqaba. Whereas, the Dead Sea basin, the Jordan River plain, Wadi Araba and Tiberias Lake areas showed much lower activity.

In southeast Jordan, low magnitude earthquakes accompanied the extension of Karak-Fayha Graben structure, but the magnitudes of earthquakes there are low as can be expected along tensional faults, as evidenced by the basaltic dikes and volcanic necks along this graben structure.

The seismic activity of faults, outside the DST, is much less than that of the DST. As **Figure 5** and **Figure 6** show where earthquakes of more than 5.0 magnitude have during the last 100 years not taken place.

4. Conclusion

The compiled and updated earthquake map for the study area for the period 1918-2023, and the updated seismotectonic map for the DST and other faults in Jordan and its surrounding areas show, the Dead Sea basin, the Jordan River area, Wadi Araba and Tiberias Lake areas have much lower seismic activities than the area south of Aqaba along the Gulf of Aqaba. The fracture tectonics and tensional faulting of Jordan characterized by short fault extensions including the Jordan Rift Fault, which is bordered on its eastern side by several separated E-S striking blocks, seem not to allow tectonic stress fields to accumulate. The structural geologic constellation seems to accommodate tectonic movements on a block size, which does not allow the accumulation of stress to produce large earthquakes. Earthquakes during the last 100 years indicate that only along the Jordan Rift Valley earthquakes of intermediate magnitude M ± 5 M can take place, but along all other fault zones, very mild earthquakes have taken place and are expected to take place.

The analyses of the types of geologic structural elements in Jordan mainly composed of tensional elements and seismic activities during the last 100 years do not indicate a sudden major release of tectonic stresses leading to major earthquakes of M > 5.5. That is what present geologic research allows interpreting, nonetheless, nature has its own ways.

Conflicts of Interest

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

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