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في هذا العدد:

مركز بحوث ودراسات دول حوض البحر الأحمر

RSBCRSC

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مجلة القُلـزم العلمية

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الآراء والأفكار التي تنشر في المجلة
تحمل وجهة نظر كاتبها ولا تعبر بالضرورة عن آراء المركز

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مركز بحوث ودراسات دول حوض البحر الأحمر
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موجهات النشر

تعريف المجلة:

مجلة (القُلزم) للدراسات العلمية مجلة علمية محُكمة تصدر عن مركز بحوث ودراسات دول حوض البحر الأحمر - السودان، بالشراكة مع أكاديمية المنهل للعلوم - السودان. تهتم المجلة بالبحوث والدراسات العلمية والمواضيع ذات الصلة بدول حوض البحر الأحمر.

موجهات المجلة:

1. يجب أن يتسم البحث بالجودة والأصالة، وألا يكون قد سبق نشره قبل ذلك.
2. على الباحث أن يقدم بحثه من نسختين. وأن يكون بخط (Traditional Arabic) بحجم 14 على أن تكون الجداول مرقمة وفي نهاية البحث وقبل المراجع على أن يشار إلى رقم الجدول بين قوسين دائريين .
3. يجب ترقيم جميع الصفحات تسلسلياً وبالأرقام العربية بما في ذلك الجداول والأشكال التي تلحق بالبحث.
4. المصادر والمراجع الحديثة يستخدم أسم المؤلف، اسم الكتاب، رقم الطبعة، مكان الطبع، تاريخ الطبع، رقم الصفحة.
5. المصادر الأجنبية يستخدم اسم العائلة (Hill, R).
6. يجب ألا يزيد البحث عن 30 صفحة، وبالإمكان كتابته باللغة العربية أو الإنجليزية.
7. يجب أن يكون هناك مستخلص لكل بحث باللغتين العربية والإنجليزية على ألا يزيد على 200 كلمة بالنسبة للغة الإنجليزية. أما بالنسبة للغة العربية فيجب أن يكون المستخلص وافياً للبحث بما في ذلك طريقة البحث والنتائج والاستنتاجات، مما يساعد القارئ العربي على استيعاب موضوع البحث وبما لا يزيد عن 300 كلمة.
8. لا تلزم هيئة تحرير المجلة بإعادة الأوراق التي لم يتم قبولها للنشر.
9. على الباحث إرفاق عنوانه كاملاً مع الورقة المقدمة (الاسم رباعي، مكان العمل، الهاتف، البريد الإلكتروني).

نأمل قراءة شروط النشر قبل الشروع في إعداد الورقة العلمية.

بسم الله الرحمن الرحيم

كلمة التحرير

الحمد لله رب العالمين، والصلاة والسلام على سيدنا محمد وعلى آله وصحبه أجمعين

وبعد:

القارئ الكريم,,,

السلام عليك ورحمة الله وبركاته.. نطل على حضراتكم من نافذة جديدة من نوافذ النشر العلمي وهي مجلة القلزم العلمية، ونحن في غاية السعادة والمجلة تصل عددها التاسع والثلاثون بفضل الله تعالى ومنته.

القارئ الكريم:

هذه المجلة تصدر بالشراكة مع أكاديمية المنهل للعلوم وهي إحدى الأكاديميات السودانية الفنية التي وضعت بصمات مميزة في مسيرة البحث العلمي، وهذا العدد هو التاسع والثلاثون في إطار هذه الشراكة العلمية التي تأتي في إطار استراتيجية مركز بحوث ودراسات دول حوض البحر الأحمر في تفعيل الحراك العلمي والبحث داخل السودان وخارجه.

القارئ الكريم:

هذا العدد يشتمل على عدد من البحوث والدراسات المهمة ذات البعد النظري والتطبيقي ولضمان نجاح واستمرارية هذه المجلة بإذن الله تعالى نأمل أن يرفدنا الباحثون بمزيد من اسهاماتهم العلمية المميزة مع خالص الشكر والتقدير للجميع..

أسرة التحرير

المحتويات

An overview of the assessment of earthquake events in Sudan

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Abstract:

This article deals with earthquakes in Sudan and the need to implement strategies to control shaking to reduce its impact in the country in the country. The review showed that almost every area of the country is at risk of some ground-shaking event. Earthquakes in Sudan are associated with the East African Rift System, Central African Rift System, Red Sea Rift System, Central Sudan Intraplate, Volcanic origin seismicity, and seismicity caused by Lake Nasir in southern Egypt. The severity and magnitude of these seismic events have resulted in devastating damage, including loss of life, collapse of buildings and civil structures, economic loss, psychological trauma, displacement of people, and great fear. The available data indicate that much of the damage was caused by earthquakes due to the collapse of buildings. Therefore, it is necessary to discuss objective, implementable, and sustainable measures to control the threat of seismic events in Sudan. The paper is expected to raise awareness of the emerging earthquakes in Sudan and draw the authorities' attention to the need for timely and practical mitigation strategies to avoid earthquake-related disasters.

Keywords: Seismicity, Rift systems, seismic hazard, Civil structures, Sudan

نظرة عامة على تقييم الأحداث الزلزالية في السودان

- **دفع الله صديق دفع الله وادي** - قسم الجيولوجيا الهندسية - كلية الجيولوجيا البترول والمعادن - جامعة بحري
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- **عبدالمطلب عبده عبدالله** - كلية علوم الأرض - جامعة البحر الأحمر

المستخلص:

تتناول هذه المقالة الزلازل في السودان، والحاجة إلى تنفيذ إستراتيجيات للسيطرة عليها، والحد من تأثيرها على البلاد. وقد أظهرت المراجعة، أن كل منطقة تقريبًا في البلاد، معرضة لخطر حدوث بعض أحداث الهزات الأرضية. ترتبط الزلازل في السودان بأنظمة الصدوع في شرق إفريقيا، وأنظمة الصدوع في وسط إفريقيا، وأنظمة الصدوع في البحر الأحمر، والزلازل الداخلية في وسط السودان، والزلازل ذات الأصل البركاني، والزلازل الناجمة عن بحيرة ناصر في جنوب مصر. وقد أدت شدة وحجم هذه الأحداث الزلزالية إلى أضرار مدمرة، بما في ذلك فقدان الأرواح، وانهيار المباني والمنشئات المدنية، والخسائر الاقتصادية، والصدمات النفسية، ونزوح الناس، والخوف الشديد. تشير البيانات المتاحة إلى أن الكثير من الأضرار كانت ناجمة عن الزلازل بسبب انهيار المباني. لذلك، من الضروري مناقشة التدابير الموضوعية

والقابلة للتنفيذ والمستدامة للسيطرة على خطر الأحداث الزلزالية في السودان. ومن المتوقع أن تعمل الورقة على زيادة الوعي بالزلازل الناشئة في السودان ولفت انتباه السلطات إلى الحاجة إلى استراتيجيات تخفيف عملية وفي الوقت المناسب لتجنب الكوارث المرتبطة بالزلازل.

الكلمات المفتاحية: الزلازل، أنظمة الصدع، الخطر الزلزالي، المنشئات المدنية، السودان

Introduction:

Earthquakes are one of the main disasters that have catastrophic consequences in today's world (Kanamori, 1978; Geller et al., 1997; Kanamori & Brodsky, 2004; Obara & Kato, 2016). Since the end of the twentieth century, more than 50 catastrophic earthquakes have occurred worldwide, claiming an estimated million lives (Guo, 2010; Alaneme & Okotete, 2018; 2022; Över et al., 2023; Kolivand et al., 2023; Jiang et al., 2023; Hussain et al., 2023) and affect millions of people every year (Ritchie & Rosado, 2022).

In 1992, the United Nations (UN) launched the Global Seismic Hazards Assessment Programme (GSHAP) project (Giardini, 1999; Kossobokov & Nekrasova, 2012) after recognizing that natural disasters were a significant cause of loss of life and development (Giardini, 1999). This project was designed from 1990 to 1999. The main objectives of the project were to raise global awareness and reduce the risks of natural disasters. The GSHAP was completed in 1999, and probabilistic seismic hazard assessment maps and digital analogs were published (Giardini et al., 1999; Shedlock et al., 2000; Kossobokov & Nekrasova, 2012). The project results are the most accurate maps of global seismic activity to date. Although the project was completed in 1999, the data collected are still accessible, including maps of the most active earthquake zones worldwide (Silva et al., 2014). Fig. 1 shows the seismic hazard map for Africa produced by the GSHAP.

Africa is relatively far from the margins of the plates and has fewer earthquake zones than other continents (Hartnady, 2002). Nevertheless, sporadic activities have occurred (Fairhead & Gridler, 1971; Wadi et al., 2021). These activities occur mainly in the northern part (Fig. 1), where the Arabian Plate collides with the Eurasian and African Plates (Poggi et al., 2020). The eastern part (Fig. 1) is home to one of the strongest African earthquakes (Foster & Jackson, 1998; Mulwa et al., 2014; Poggi et al., 2017).

Sudan and its surroundings have diverse geological and tectonic structures (Almond, 1986). The earthquake sources affecting most of the country are located in and around (1) the eastern part from the East African Rift System (EARS), (2) the central part from several rifts and volcanic, (3) the Red Sea coast near the Afro-Arabian border, and (4) Lake Nasir in the far north (Khattab, 1975; Ali & Whitely 1981; Flege, 1982; Browne & Fairhead, 1983; Bermingham et al., 1983; Browne et al., 1985; Clark & Browne, 1987). Earthquakes of varying intensities and magnitudes have occurred in all parts of the country mentioned above. Fairhead and Stuart (1982) reported that earthquakes have been recorded in Sudan and neighboring countries since 700 (BC). However, this instrument was used to record events that began in 2001 (Alhassan et al., 2007). The source in central Sudan has recently become more active (El Tahir & Midzi, 2019). In addition, there has been a marked increase in seismic activity in the Nile Basin and surrounding areas, which justifies an assessment of the seismic hazard of the country and the region (Clark & Browne, 1987; Abdalla et al., 2001; Ezzelarab et al., 2021).

This study aims to provide detailed insight into the reality of seismic activity in Sudan. It aims to raise awareness of Sudan's seismic activity in a language easily understood by everyone and to influence government engagement and policy regarding seismic hazards as geoscientists. A more comprehensive literature on seismicity in Sudan must be compiled to match the scope of the current study.

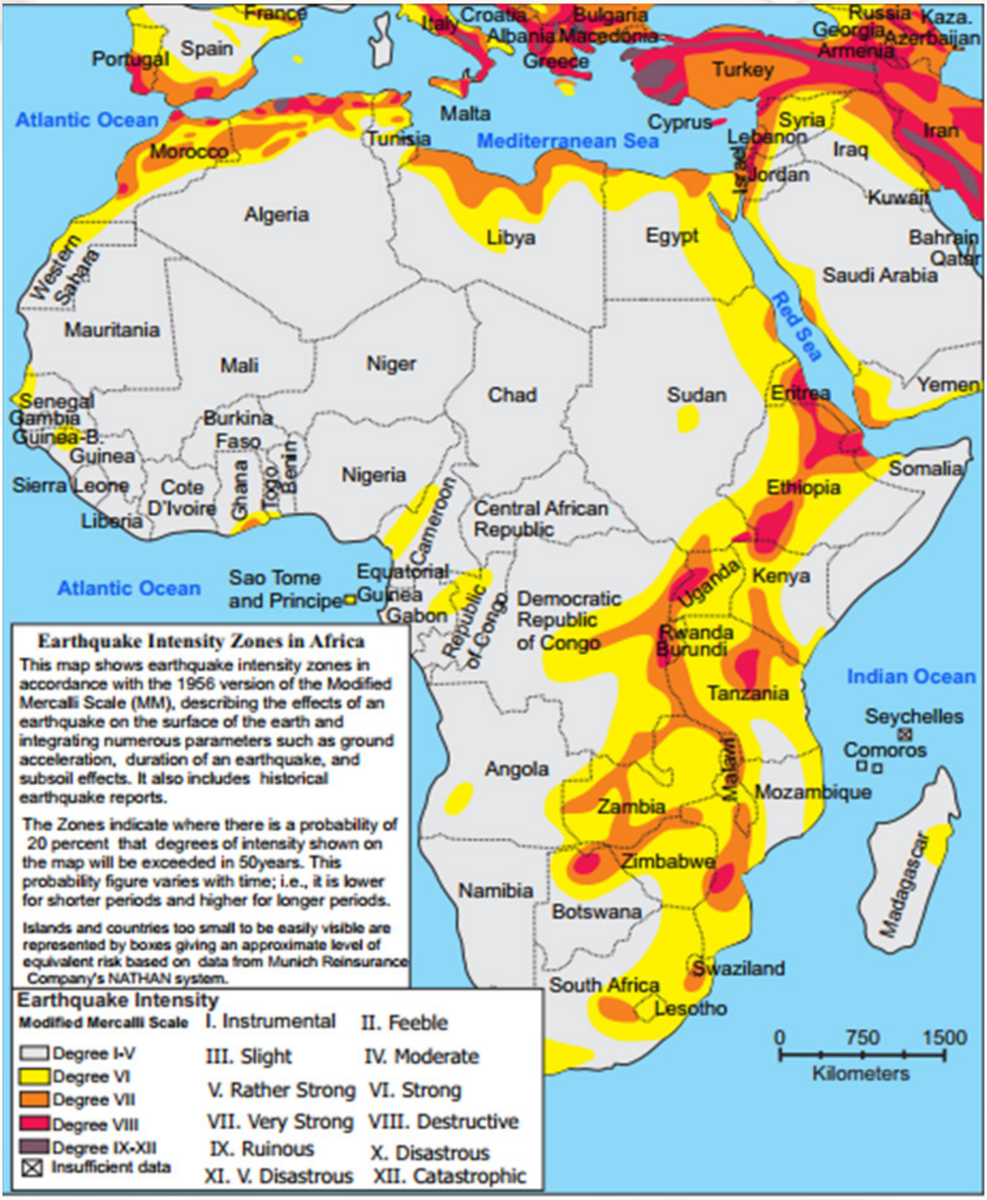

Fig. 1. Global seismic hazard map created by GSHAP after Giardini et al. (1999).

Terms and concepts:

In the earth sciences, various terms describe the nature and magnitude of earthquake effects. These terms make it easier for technical and non-technical experts to understand earthquakes. The two terms most commonly used in earthquake research are magnitude and intensity.

Earthquake magnitude has been proposed as the basis for geophysical and engineering analyses of earthquakes (Båth, 1981; Kanamori, 1983). It can be defined as a quantitative measure used to compare the strength of earthquakes worldwide, regardless of geological and geographical conditions (Borman, 2021). Therefore, earthquake magnitude is a logarithmic measure of the energy released by an earthquake (Hammed et al., 2016). Richter (1935) derived the earthquake magnitude scale from the maximum amplitude measured at various epicenter distances from the point of rupture in the Earth's crust. This scale is known as the Richter scale and is the first approach to assessing the magnitude of earthquakes (Boore, 1989).

The Richter magnitude also called the local magnitude ML, is, therefore, a numerical value that characterizes an earthquake and is independent of the location of the recording station (Rundle, 1989). Body wave magnitude (mB) is proposed to overcome local magnitude limitations. The magnitude of the body wave is calculated from the amplitude and period of the seismic body (Das et al., 2011). According to Kanamori (1983), the main advantage of mB is that it can be applied to both shallow and deep seismic events. Liu et al. (2007) pointed out that mB represents the magnitude of long-period body waves, and mb represents the magnitude of periodic body waves. Furthermore, shallow and distant earthquakes' surface wave magnitude (Ms) is derived (Di Giacomo & Storchak, 2022). Additionally, a relatively new scale, the moment magnitude (MW) scale, was introduced (Hanks & Canadian, 1979). This scale has the advantage that it can be used to measure more significant earthquakes (Baruah et al., 2012; Das et al., 2019).

Intensity is a term that describes the impact of an earthquake on the earth's surface (Dowrick, 1996; Grünthal & Musson, 2020). It is a qualitative measure of the actual shaking at a location during an earthquake (Hammed et al., 2016). Terms are shown in uppercase Roman letters. This scale was initially developed to extract observational data from seismic events. Masson et al. (2010) stated that the first detection scale was the Rossi-Forel scale, where he used 10 degrees to define the impact of an earthquake at a location. The intensity scale includes a range of specific severe reactions, such as moving furniture, damaging chimneys, and waking people up. There were several intensity scales according to the Rossi-Forel scale. After several revisions, the Mercalli scale (Eiby, 1996) became the modified Mercalli Intensity Scale (MMI), which now plays a vital role among geoscientists (Worden et al., 2012).

Table 1 provides a brief description of the 12 levels of the latest version of Mercalli strength. Additionally, other scales are used after the MMI scale in some parts of the world. They are the Medvedev-Sponheuer-Kalnik (MSK) scale (Hinzen & Oemisch, 2001) and the European Macroscopic Scale (EMS), a modified version for European buildings (Gruenthal, 1998; Musson et al., 2010).

The peak ground acceleration (PGA) equals the maximum ground acceleration at a particular location during an earthquake (Wald et al., 1999). The maximum ground acceleration corresponds to the maximum absolute acceleration amplitude recorded at an area during a particular earthquake (Douglas, 2003). Earthquake shaking generally occurs in all three directions (Çağnan et al., 2017). Therefore, PGA is often divided into horizontal and vertical components (Bozorgnia & Campbell, 2016).

Table 1 Modified Mercalli Intensity Scale (Eiby, 1966)

Level	Description
I	Not felt except by a very few under especially favorable conditions.
II	Felt only by a few persons at rest, especially on the upper floors of buildings. Delicately suspended objects may swing.
III	Felt quite noticeable by persons indoors, especially on the upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration is similar to the passing of a truck. Duration estimated
IV	Felt indoors by many and outdoors by few during the day. At night, some awakened. Dishes, windows, and doors are disturbed; walls make cracking sounds—a sensation like a heavy truck striking a building. Standing motor cars rocked noticeably.
V	Felt by nearly everyone; many awakened. Some dishes and windows were broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Damage is negligible in buildings of good design and construction, slight to moderate in well-built ordinary structures, and considerable damage in poorly built or badly designed structures; some chimneys were broken.
VIII	Damage is slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage is great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, and walls. Heavy furniture overturned.
IX	Damage is considerable in specially designed structures; well-designed frame structures are thrown out of plumb. Damage is significant in substantial buildings, with partial collapse and buildings shifted off foundations.
X	Some well-built wooden structures were destroyed; most masonry and frame structures were destroyed with foundations. Rail bent.
XI	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
XII	Damage total. Lines of sight and level are distorted. Objects are thrown into the air.

Geology of Sudan:

Sudan is one of the largest countries in the northeastern part of the African plate (Fig. 1, Fig. 2, and Fig. 3). It is generally underlain by Precambrian rocks, especially in the southwest, northeast, and center, which were roughly reactivated during the Neoproterozoic Pan-African tectono-thermal event (Ezzelarab et al., 2021).

Large parts of northern Sudan are covered by continental clastic sequences of mostly Mesozoic Nubian sandstones (Schlüter, 2008). Many geoscientists have described Sudan's geology (e.g., Reischman and Kröner (1994), Almond (1978), and Vail (1982, 1987). According to these scholars, the most important stratigraphic units of Sudan (Fig. 2) are (1) the basement complex, (2) Phanerozoic sediments, and (3) Cenozoic volcanic rocks.

The basement complex covers approximately 52% of Sudan, extending from the Archaean through the Early to Middle Proterozoic to the Pan-African (Schandelmeier & Darbyshire, 1984). Granitic and metamorphic rocks dominate the basement complex, which can be observed across all provinces of Sudan (Abdelsalam & Stern, 1993). These rocks have experienced regional metamorphism, ranging from greenschist to low amphibolite grade, and have undergone folding, shearing, and thrust faulting on a regional scale.

The Phanerozoic sediments encompass a wide range of ages from the early Palaeozoic, Mesozoic, and Cenozoic strata overlying the Precambrian rocks (Wycisk, 1991). Cenozoic volcanic activity extended from the Late Cretaceous to the Quaternary to the Paleogene (Almond et al., 1978).

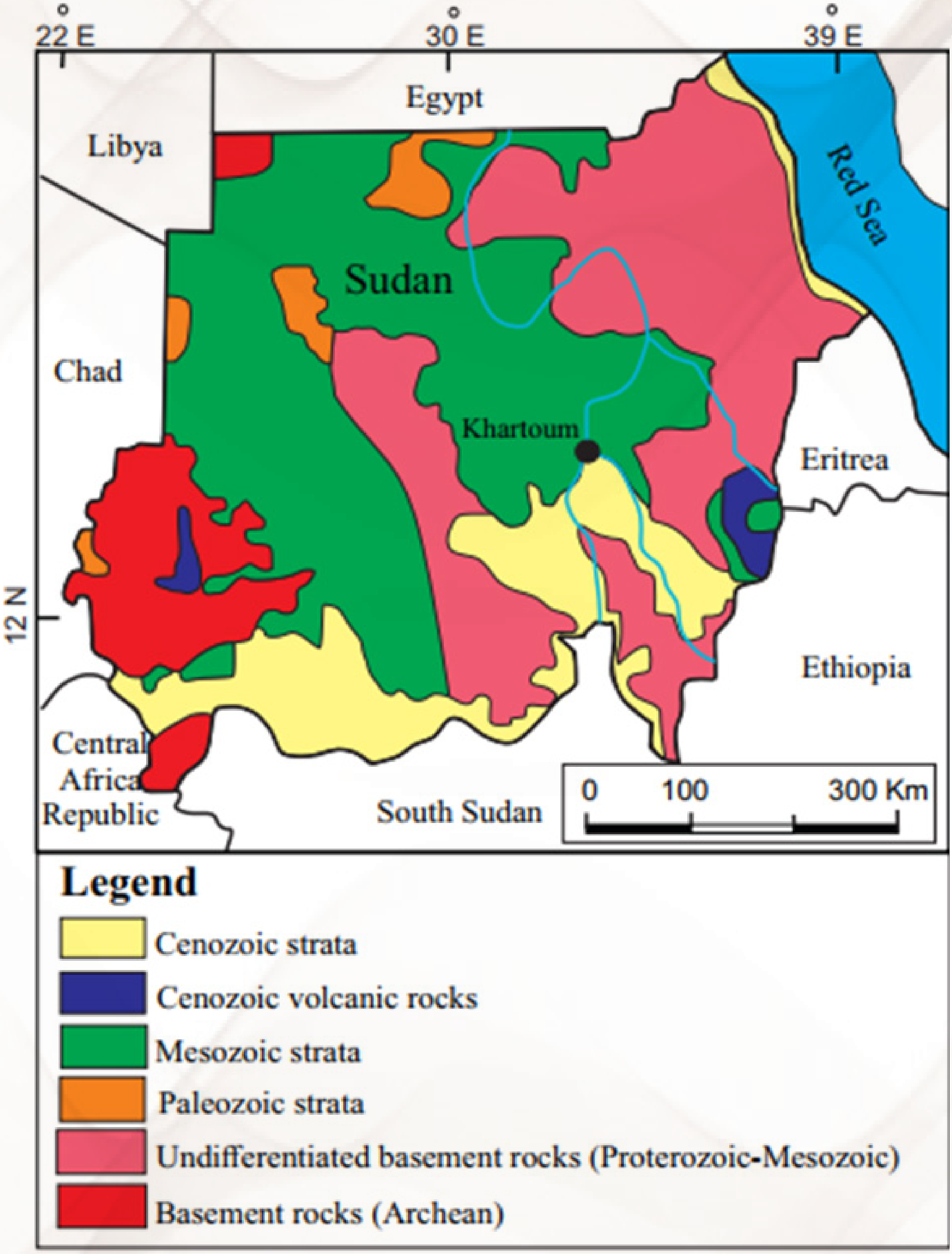

Fig. 2. Geological map of the study area, modified after GRAS (2004)

Tectonics features and earthquake history in Sudan:

Sudan is one of the countries considered to have low-to-moderate seismic activity (Mohamedzein et al., 2006). However, in the last 60 years, moderate to large earthquakes have occurred in various parts of the country (Clark & Sadig, 1967; Clark & Browne, 1985; Gaulon et al., 1992; Abdalla et al., 2001; Alhassan et al., 2007; El Tahir & Midzi, 2019). These earthquakes included May 20, 1990, with a magnitude of 7.4 Mw in the southern region (Giardini & Beranzoli, 1992; Gaulon et al., 1992), August 1, 1993, and November 15, 1993, in the northern part with magnitudes of 5.5 and 4.3 Mw respectively (Girdler & McConnell, 1994). In addition to these two areas, many parts of the country are considered active, especially the Red Sea area, which is constantly seismically shaken (Khan, 1975; Daggett et al., 1986; Youssef, 2015; Mitchell & Stewart, 2018). Fig. (3) provides Sudan's seismotectonics and seismicity (historical and current).

Sudan is located in the intraplate region of Northeast Africa. It is bounded by two active tectonic structures: the East African Rift System in the south and southeast and the Red Sea Rift Valley in the northeast. It is crossed by many rift systems (Clark & Browne, 1987). Some of these rifts are major rifts that span the African continent and beyond (Abdalla et al., 2001). Most faults associated with rifts have experienced several earthquakes of varying magnitudes (Ambraseys & Adams, 1986; Fairhead & Girdler, 1971). Fig. 3 shows the major rift system in Sudan and its surroundings.

The Afro-Arabian Rift System (AARS) runs from southeast to northeast and stretches over 6500 kilometers (Girdler, 1991). The East African Rift System (EARS) and the Red Sea Rift System (RSRS) are part of the Afro-Arabian Rift System (Fairhead & Stuart, 1982) and are considered to be very active (Browne & Fairhead, 1983; Browne et al., 1985; McKenzie et al., 1970). The East African rift systems (Fig. 3) consist of two branches: (1) a western branch that extends from the Mozambique coastal plain in the south to Lake Mobutu in the north (McKenzie et al., 1970; Ebinger, 1989; Girdler & McConnell, 1994) and (2) an eastern branch that runs from Tanzania in the south to the Ethiopian Afar Depression in the north (Chorowicz, 2005).

The Central African Rift System (CARS) extends from southwest to northeast across the African continent (Fig. 3) over a length of approximately 2000 km (Fairhead & Stuart, 1982; Bermingham et al., 1983; Fairhead, 1988; El Tahir et al., 2013). The CARS is part of the West African Rift System and extends from the Gulf of Guinea to the northeast of Sudan (Jorgensen & Bosworth, 1989; Ibrahim et al., 1996). The CARS are orthogonally connected to the Atbara, Blue Nile, White Nile, and South Sudan Rift Systems (Abdalla et al., 2001).

The South Sudan Rift System (SSRS), White Nile Rift System (WNRS), Blue Nile Rift System (BNRS), and Atbara River Rift System (ARRS) have similar tectonic features (Medani & Vail, 1974; Browne et al., 1985; Salama, 1997; Gani et al., 2009). The four rift systems run in a NW-SE direction and terminate in a line at the north-western end (Fig. 3). The SSRS extends in a northwest-southeast direction from western Sudan across southern Sudan and northern Kenya to the Indian Ocean (Bosworth, 1992). The SSRS overlaps with the CARS at its north-western end (King et al., 2013). According to Abdalla et al. (2001), the Bahr ElArab earthquake of February 26, 1947, was attributed to the SSRS. In contrast, the Jebel Dumbeir earthquake in 1966 and the Bara earthquake in 1974 were triggered by the WNRS (Qureshi & Sadig, 1967).

The intraplate zone in central Sudan shows scattered and low seismic activity (Fairhead, 1988; Schandelmeier et al., 1990). The volcanically induced seismicity of Jebel Marra and Lake Nassir (Fig. 3) also shows low seismic activity; its effects are limited to the Darfur region in the west and Khartoum (Bermingham et al., 1983).

Although geoscientists have paid little attention to the study of seismicity in Sudan, some studies have described earthquake events in the country. Qureshi and Sadig (1967) and Clark and Browne (1987) studied earthquakes and related faults in central Sudan, including a series of earthquakes that began on October 9, 1966, and continued until April 1967. They hypothesized that these seismic events were associated with the western branch of East Africa and the Red Sea Rift System (EARS).

The study conducted by Ambraseys and Adams (1986) revealed that the majority of Sudan's activities are situated near the East African Rift System (EARS). Nevertheless, the northeastern area of Sudan is susceptible to earthquakes originating from the Red Sea, and there have been instances of earthquakes in the central intraplate region that could potentially result in damage.

Two significant earthquakes occurred in southern Sudan in May and July 1990. The primary earthquake, which occurred on May 20th of that year, was one of the most substantial events ever recorded in Africa and had a magnitude of 7.4 on the MS scale (Girdler & McConnell, 1994). Its focal mechanism revealed a left-lateral strike-slip fault oriented parallel to the Aswa fault zone (Gaulon et al., 1992). This fault zone is a critical Proterozoic tectonic feature (Baker & Wohlenberg, 1971).

Abdalla et al. (2001) created a probabilistic seismic hazard map for the region depending on the number of seismic zones. Their results showed that the maximum peak ground acceleration (PGA) occurs in the Red Sea region, where the PGA reached 607 cm/sec2 for 250 years, whereas other regions have a relatively low PGA. Table 2 summarizes the eight regions of Sudan and their surroundings for different periods.

According to El-Nadi et al. (2005), most local events occurring near Khartoum were linked to faults believed to have been responsible for the Khartoum earthquakes in August 1993. Similarly, Mohamedzein et al. (2006) discovered that the active rifts and faults in central Sudan can potentially cause damaging earthquakes in the generally low-hazard area of Khartoum, the capital of Sudan.

El Tahir and Midzi (2019) utilized seismic data from various sources, including the Eastern and Southern Africa Catalogue, International Seismology Centre (ISC), and National Oceanic and Atmospheric Administration (NOAA), to create regional hazard maps for different return periods and exceedance probabilities. Specifically, they produced maps with 50-year, 100-year, and 10% exceedance probability return periods. Their analysis revealed a high seismic hazard in South Sudan, whereas other parts exhibited slightly lower values.

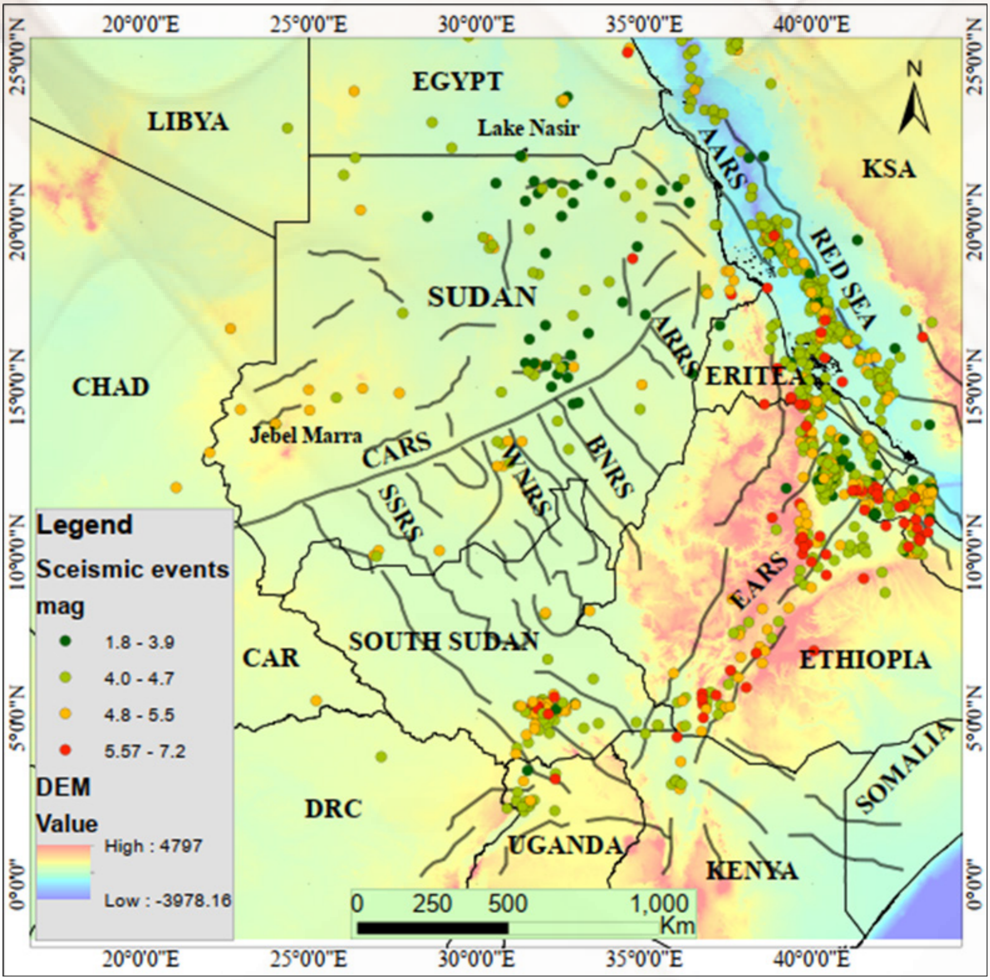

Fig. 3. Seismotectonics and seismicity (historical and current) of Sudan and its surroundings, data from Sudan Seismic Network (SSN), United States Geological Survey (USGS), Abdalla, et al. 2001, Giardini et al. (1999), Ezzelarab et al., 2021)

Table 2 Seismic source region of Sudan and its vicinity (Abdalla et al., 2001)

Source region No.	Source Name	Source Boundaries Coordinates	Maximum Instrumental Earthquake
I	Northern Sudan	(20.1 E, 19.3 N), (36.2 E, 16.0 N) (30.7 E, 23.5 N), (36.2 E, 20.4 N)	5.8
II	Central Sudan	(29.6 E, 13.0 N), (33.9 E, 10.7 N) (32.0 E, 17.0 N), (36.1 E, 15.0 N)	6.4
III	Southwestern Sudan	(26.3 E, 09.4 N), (32.7 E, 06.6 N) (27.2 E, 10.9 N), (10.7 E, 08.9 N)	6.8
IV	Southern Sudan	(30.9 E, 03.6 N), (33.5 E, 03.6 N) (31.7 E, 06.5 N), (34.4 E, 06.5 N)	7.2
V	Equatorial Uganda	(28.8 E, 00.0 N), (33.5 E, 00.0 N) (08.9 E, 03.1 N), (33.5 E, 03.1 N)	7.5
VI	Central Ethiopia	(34.0 E, 02.0 N), (36.5 E, 00.0 N) (38.0 E, 13.3 N), (40.7 E, 10.7 N)	7.7
VII	Afar and the Gulf of Aden	(36.2 E, 16.0 N), (42.5 E, 09.0 N) (40.7 E, 18.7 N), (44.9 E, 13.8 N)	7.5
VIII	Red Sea	(37.4 E, 18.7 N), (40.0 E, 18.7 N). (37.4 E, 22.4 N), (40.0 E, 20.0 N)	7.2

Sudan Seismic Network:

The Sudan Seismic Network (SSN) was established in 2001 by the Sudan Geological Survey (GRAS) to monitor seismic activity in Sudan and abroad (Alhassan et al., 2007). SSN is located in Khartoum state and consists of three long-term stations. These stations are distributed around Silatiat (SLAT), Melkhyat (MRKH), and Jebel Auliya (JAWL) in Khartoum (capital) and are 32 km, 23 km, and 42 km from Khartoum's central station, respectively. Recently, new stations were added to the network to cover a wider country area. The stations are (1) Arkawwit (ARKT) in the east, (2) Muhammad Qool

(MQOL), (3) Kasala (KSLA) in the east, (4) Marawi (MRWI), and (5) Abu Hamad (HMAD) in the north, (6) Jabalia (JBLN) in the south, and (7) Al-Obeid (OBID) in the west. SSN is currently a full member of the International Seismological Center (ISC) and regularly sends data to the ISC. Figure 4 shows the distribution of SSN stations.

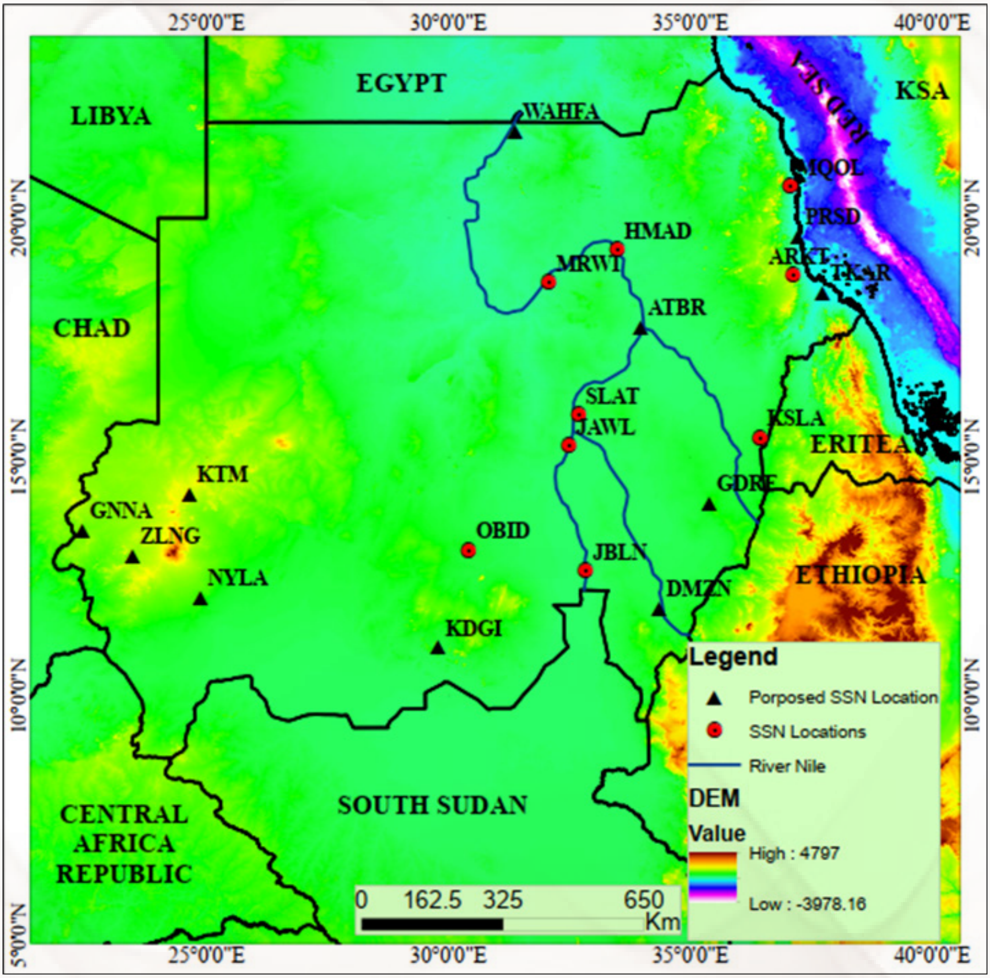

Fig. 4 Distribution of the locations of the SSN stations and the stations proposed in this work

Results and discussion:

Sudan's seismicity map shows that many regions of the country, particularly around the Red Sea and Central African Rift Valley (CARS), are vulnerable to seismic activity of varying magnitudes. These seismic activities can cause severe property damage, reduce quality of life, and even lead to economic instability in some affected areas. Magnitude information can be subjective because it comes from residents of the area where the event occurred. However, it does indicate the extent of damage and impact for each event.

Reports indicate that the intensity of earthquakes in Sudan varies between I and VIII, which means that earthquakes in northeast Africa have minimal or no impact to slight damage to well-constructed buildings (e.g., Sadig 1967; Sykes, 1970; Browne et al., 1985; Shudofsky, 1985; Ambreseys & Adams, 1986; Clark & Browne, 1987; Gaulon et al.,1992; Mohamedzein et al., 2006; Alhassan et al., 2007; El et al., 2019; Ezzalarab et al., 2021). However, the damage has not been very severe, and there is a need to develop earthquake mitigation methods as Sudan is known to be affected by intra-plate earthquakes, which increase the frequency of earthquake occurrence.

Earthquakes in Sudan are associated with the following features: (1) East African Rift System, (2) Central African Rift System, (3) Red Sea Rift System, (4) Central Sudan Intraplate, (5) Volcanic origin seismicity and (6) seismicity caused by Lake Nasir in southern Egypt.

The central and Red Sea coasts are the country's most seismically active regions. Seismic activity can cause significant structural damage to large buildings and critical systems. As Sudan does not have seismic codes, it is highly recommended that such codes be introduced and that engineers be provided with seismic construction guidelines and regulations.

The tectonic and seismic conditions of the African countries in Table 3 are similar to Sudan's. The Sudanese government still needs to introduce an earthquake risk reduction strategy through norms or regulations.

Table 3 Seismic Code and Standards in African Countries that are prone to seismic activities (Modified after Alaneme and Okotete 2018)

S/N	Country	Code/Standard	Seismic Code?
1	Egypt	Egyptian Code 201 2008-draft (ECP201, 2008-draft) (Serror et al., 2010).	Yes
2	Algeria	RPA99/Version 2003 (CGS, 2003) (Zermout et al., 2008).	Yes
3	Cameroon	None	No
4	Democratic Republic of Congo	None Exists	No
5	Ethiopia	Ethiopia Building Code Standard (EBCS) (1995). Volume 8 Seismic (Lubkowski et al., 2014).	Yes
6	Sudan	None	No
7	South Sudan	None	No
8	Uganda	US 319:2003, Ugandan Ministry of Lands, Housing and Urban (Zajac & Davies, 2015).	Yes
9	Rwanda	Building Regulations Manual (2009) from the Rwanda Ministry of Infrastructure (MININFRA) (Lubkowski et al., 2014).	Yes
10	Burundi	Not Known	No
11	Kenya	Kenyan Code (1973) (Worku 2014).	Yes
12	Tanzania	Not known.	No
13	Malawi	Various Malawi Standards include building materials and construction practices (Lubkowski et al., 2014).	No
14	Djibouti	Not known	No
15	Mozambique	A version of the Portuguese Code from the colonial era (Bommer, 2010).	No
16	South Africa	The South African Code – SANS 10160–4:2011 (Roth & Gebremeskel, 2017).	No
17	Ghana	The Ghanaian Code – 1990 (Worku, 2014)	Yes
18	Nigeria	Nigeria National Building Code (NBC, 2006) (Ogunbiyi, 2014).	No

Many studies have highlighted the ineffectiveness of earthquake regulations in Africa for various reasons (Alaneme & Okotete 2018). The ineffectiveness of African norms is believed to be due to the lack of legal instruments to enforce existing norms (Kinde et al., 2011; Worku, 2014). Moreover, the adoption of narrower-scope codes is limited to government institutions such as schools, hospitals, and other public institutions (Bendimerad, 2004; Meslem et al., 2012). Similarly, it has been noted that existing regulations in African countries do not include specific seismic requirements (Worku, 2013), which certainly affects the response of civil structures to ground movements (Kassegne, 2014).

Conclusion:

This paper focuses on Sudan's often underestimated seismic activity and highlights the need to apply shaking mitigation strategies. This article shows that virtually all regions of Sudan are at risk from some seismic event, whose size and intensity can result in widespread damage. The review emphasizes the need for proactive measures in Sudan to mitigate earthquake risks, particularly in regions with seismic activity. It also suggests new measures to reduce earthquakes and seismic hazards.

Recommendations:

The current Sudan Seismic Network (SSN) should be expanded to cover a wider area transformed by the rift valley. Potential locations or cities for additional SSN stations are Atbara (ATBR), Wadi Halfa (WAHFA), Gedarif (GDRF), Tokar (TKAR), Port Sudan (PRSD), El Damazin (DMZN), Kadugli (KDGI)), Nyala (NYLA), Kutum (KTM), Zaringei (ZLNG), and EL-Geneina (GNNA). Figure 4 shows the location of the proposed new station.

Sudan's architects, civil engineers, geoscientists, and the government should implement effective seismic regulations in response to the increasing vulnerability to earthquakes in many parts of the country.

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Declaration of Competing Interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability:

All data used during the study are available from the corresponding author by request.

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