

Article

Analyzing Recent Tectonic Activity Along the Karak Wadi Al Fayha Fault System Using Seismic, Earthquake, and Remote Sensing Data

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Abstract: The Karak Wadi Al Fayha Fault (KWF) is a major NW-trending intraplate wrench fault system extending over 325 km from Western Karak in Jordan to Wadi Al Fayha in Saudi Arabia. Structurally linked to the Precambrian Najd Fault System, the KWF has been previously mapped using field observations, gravity, magnetic, and reflection seismic methods. However, these approaches lacked the vertical resolution necessary to characterize its shallow structure, leaving its influence on recent deposits and surface topography poorly understood. This study employs reflection seismic sections integrated with a Digital Elevation Model to refine terrain analysis and enhance fault mechanism solutions for determining the regional stress field pattern. Our results provide compelling evidence of the KWF's upward propagation into the surface, as demonstrated by deformation of the uppermost Cretaceous and Cenozoic successions, distinct geomorphic features in the Digital Elevation Model, alignment of earthquake epicenters along the fault, and active landslides associated with its movement. We suggest that the reactivation of the KWF has been influenced by changing stress fields from the Late Cretaceous (Turonian) to the present. The Northwestern Arabian plate has undergone multiple tectonic stress transitions, including WNW–ESE compression associated with the Syrian Arc Fold-Belt system (Turonian–Plio–Pleistocene) and subsequent NNE–SSW extension linked to Red Sea rifting (Neogene–present). The analysis of fault mechanism solutions suggests that the latest fault movements result from the continued activity of the Irbid Rift event (Eocene) and the Dead Sea Transform Fault since the Miocene.

Keywords: Arabian plate; tectonic evolution; seismo-stratigraphy; Karak Wadi Al Fayha Fault; Dead Sea Transform Fault; landslide



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1. Introduction

Tectonic activity has played a critical role in shaping Earth's surface, driving the formation of mountains, basins, and other major landforms. Neotectonics or active faults, which examine recent tectonic activity from the Holocene epoch to the present (past 11,000 years), focus on ongoing crustal movements (e.g., [1–4]). Evidence of neotectonic processes includes sediment accumulation in basins, earthquake activity, the burial or exposure of rocks, and the geomorphological evolution of landscapes [5]. Most earthquakes, however, result from the reactivation of inherited fault systems, which serve as the path of least resistance for strain relief. This study of active faults combines multiple disciplines, including

geomorphology, seismology, plate tectonics, geodesy, and remote sensing, playing a crucial role in assessing geological hazard risks.

The Karak Wadi Al Fayha Fault (KWF) is an NW-trending intraplate tectonic structure that was identified by Bender [6], Stern and Johnson [7], and Al Hseinat et al. [8] (Figures 1 and 2). It extends over 325 km from Western Karak in Jordan to Wadi Al Fayha in Saudi Arabia [9–12] and plays a significant geological role, particularly in the densely populated Karak region. Recent seismic activity, including minor earthquakes and landslides, indicates ongoing neotectonic movement along the fault.

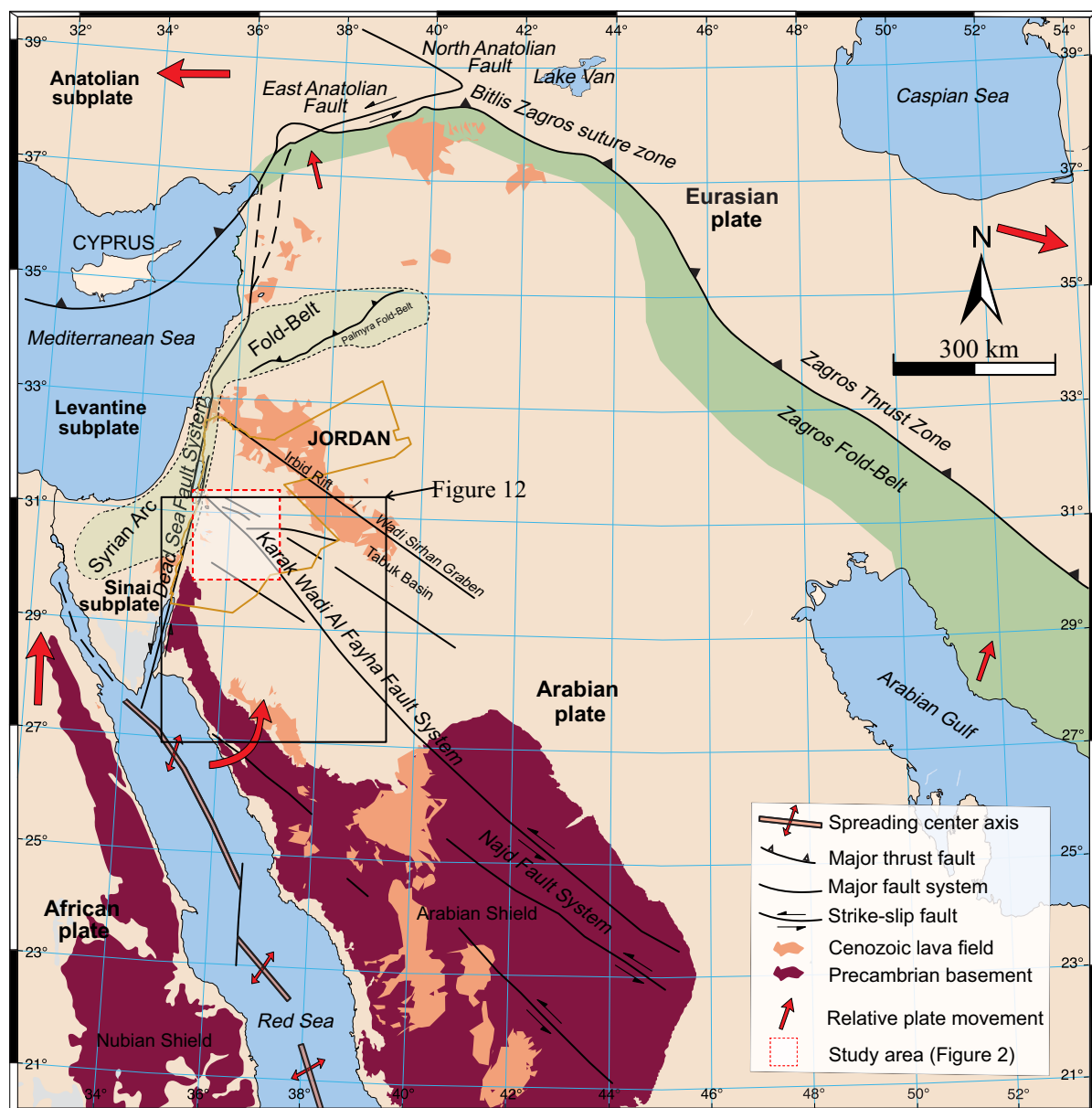


Figure 1. A regional tectonic map of the Middle East (based on [7]) presents the location of Jordan and the major tectonic structures within (modified from [8]).

In response, Karak Municipality has evacuated residents from several cracked houses, highlighting the fault's impact on infrastructure and public safety. Previous geological and geophysical studies have mapped the KWF zone using field observations, gravity, magnetic, and reflection seismic methods [6,8,11,13,14]. However, these methods lacked the vertical resolution necessary to characterize the fault's shallow structure, limiting our understanding of its influence on recent deposits and surface topography. The under-

compacted nature of near-surface deposits and low signal-to-noise ratios in seismic profiles have further hindered the identification of shallow fault boundaries. Notably, no prior study has applied the focal mechanism solution (FMS) technique to analyze faulting processes along the KWF.

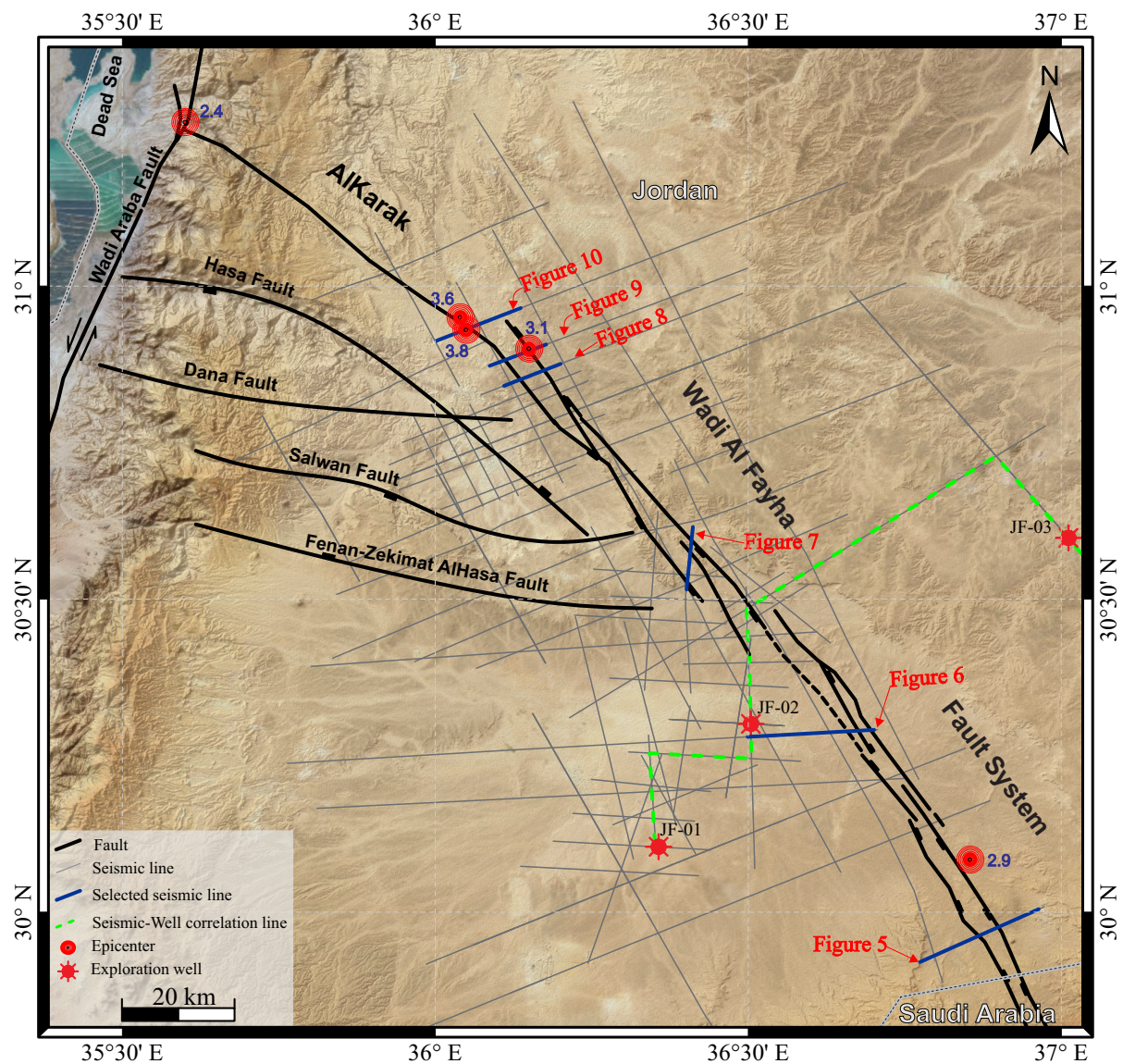


Figure 2. A Google Earth map depicts the study area, located east of the Dead Sea Transform System (refer to Figure 1 for location). The map displays the distribution of earthquake epicenters, seismic lines, and exploration wells. The locations and extents of major fault systems are adapted from Al Hseinat et al. [8], while earthquake epicenter data are provided by the Jordanian Seismological Observatory. Exploration wells are labeled as follows: JF-01 (Al-Jafr-01), JF-02 (Al-Jafr-02), and JF-03 (Al-Jafr-03).

To address these limitations, this research combines high-resolution seismic imaging with a Digital Elevation Model (DEM) to improve terrain interpretation—an approach widely utilized in geological and seismic studies (e.g., [15–18]). Furthermore, Focal Mechanism Solutions (FMS) for selected earthquakes were examined to characterize the prevailing stress field. This technique helps identify fault orientations and the direction of slip, offering critical insights into the regional tectonic stress regime [19].

This study examines the structural evolution and deformation patterns of the KWF, with a focus on its connection to regional tectonic systems. The fault’s kinematics and reacti-

vation history are analyzed in the context of shear stresses associated with the Precambrian Najd Fault System and subsequent tectonic events. Examining these processes is essential for understanding the fault's role in regional geotectonics and evaluating its potential seismic hazards. Despite its importance, the deformation patterns of the KWF have not been thoroughly examined at this scale, underscoring the need for further investigation.

2. Regional Geological Background

The Precambrian basement underlying Jordan represents the northernmost portion of the Arabian–Nubian Shield, which formed before <600 million years ago [20]. This basement is most prominently exposed in the southern and southeastern parts of the country and is primarily composed of igneous and metamorphic rocks [13,21–24]. Over time, particularly since the mid-Precambrian, the area has experienced significant uplift and erosion, resulting in the partial removal of the original basement rock. This erosional history is evidenced by the presence of the Precambrian unconformity in Southern Jordan [23,25]. During the later stages of the Precambrian, the Arabian plate became integrated with neighboring tectonic entities along the African plate's northeastern boundary within Gondwana. This tectonic convergence led to crustal stretching and the formation of the Najd Fault System—a network of major left-lateral strike-slip faults active between 620 and 540 Ma [19,20,26,27]. The earliest phases of this fault system's activity align with the deposition of the Saramuj Formation, which was later intruded by igneous dikes [24,28] (Figure 3).

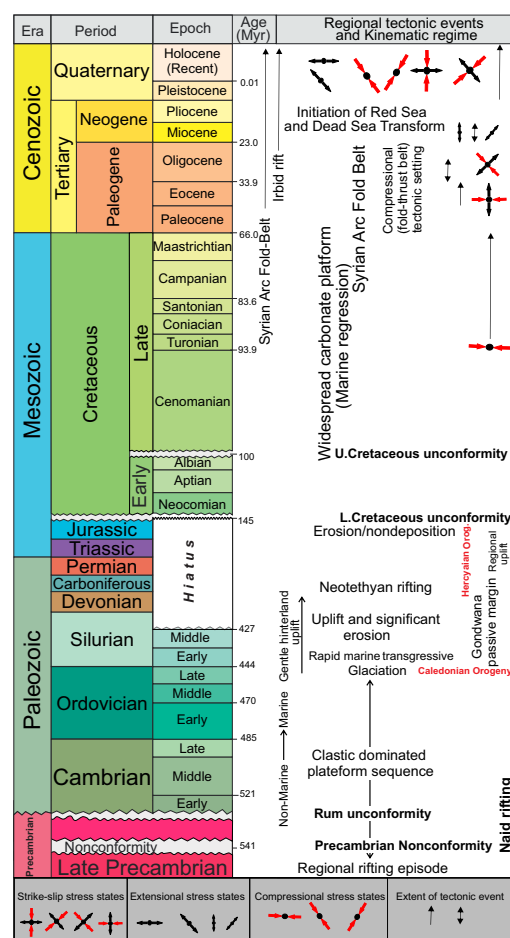


Figure 3. The geological column representing the study area outlines the principal lithologies, stratigraphic groups, formations, and their respective ages based on interpretations adapted from previous works [8,20,27,28].

As the Early Cambrian began, Jordan and adjacent regions lay along the continental margin of the Afro-Arabian plate, with sedimentation taking place above the Rum Unconformity [20,29]. Subsequent geological periods, such as the Ashgillian glaciation during the Ordovician–Silurian, caused major erosional events in Southern Jordan and Northern Saudi Arabia [30]. These glacial impacts are recorded in the subsurface of Central Jordan, where the Silurian Glacial Unconformity distinctly separates the Upper Ordovician strata from those of the Silurian (Figure 3) [8]. Ice loading and unloading during this time are also thought to have reactivated older geological structures. Between the Middle Silurian and Early Cretaceous, significant uplift affected the Arabian plate, forming highland areas in Central and Southern Jordan. These areas were later subject to extensive erosion, coinciding with European tectonic events like the Caledonian and Hercynian orogenies [8,20,31,32].

In the Late Turonian, the closure of the Meso-Tethys Ocean and the collision between the Afro-Arabian and Eurasian plates caused horizontal compression along the Levant margin [33,34]. This initiated two paleo-stress phases: first, a WNW-ESE compressional regime during the Turonian that produced the Syrian Arc Fold-Belt (Figure 3) [35–38], and second, a NNE–SSW extensional regime that began in the Neogene and persists today. The latter is linked to Red Sea rifting and sinistral motion along the Dead Sea Transform Fault (DSTF) [39].

Near the DSTF, stress orientations vary, becoming sub-parallel or sub-perpendicular to the fault's trace [40]. Eyal [38] proposed that these variations stem from the interaction between the Syrian Arc and Dead Sea stress regimes.

During the Late Eocene, the Afar mantle plume uplifted Northeastern Africa, gradually extending its impact into the Levant. This contributed to the development of low-relief landscapes in Jordan, Israel, and Egypt [41–47]. The combined influence of this plume, the Red Sea rifting, and volcanic activity beneath the lithosphere significantly altered the tectonic character of the region, resulting in the formation of structures like the Irbid Rift and the DSTF.

The N–S extension of the Irbid Rift intersected early development phases of the DSTF during the Early Miocene, and both features continue to shape Jordan's tectonic landscape today [48,49]. Recent data confirm ongoing N–S extension and localized E–W compression near the DSTF, with older faults adjusting to the evolving stress regime since the Late Cretaceous [39,49–51]. While the DSTF accommodates relative motion between the Arabian and African–Sinai plates, it responds to rather than drives the region's deformation [52]. This study integrates reflection seismic, seismological data, and remote sensing techniques to assess the activity of the KWF and its interactions with the prevailing stress field.

3. Data and Methods

3.1. 2D Reflection Seismic Ad Well Data

In collaboration with the Ministry of Energy and Mineral Resources of Jordan and the University of Jordan, a total of 71 two-dimensional seismic lines were acquired across the study region, spanning an area of ~18,150 km² (Figure 2). The combined length of these profiles reaches 3200 km, with line spacing ranging from 2 to 4 km. Data acquisition was carried out using vibroseis sources operating in the 8–70 Hz frequency range, with signals generated every 100 m. The geophone array consisted of SM-4 10 Hz, LRS 1011, and GEO-10 Hz sensors, connected via land streamers of varying lengths—96 m (48 channels), 200 m (96 channels), and 250 m (120 channels)—with a geophone interval of 2 m. The maximum recording time for each shot was 2.55 s.

3.1.1. Seismic Data Processing and Quality Control

Following the acquisition, the seismic data underwent a series of processing steps to produce time-migrated seismic sections (see Table 1). The processed profiles were then imported into the IHS™ KINGDOM software (v.2018.0) for interpretation and quality assurance, which included addressing mis-ties. These mis-ties—caused by inconsistencies between intersecting seismic lines or between seismic and well datasets—were evaluated through wiggle trace alignment, time correlation, and amplitude matching, following the approach of Bishop and Nunns [53]. Corrections were applied to ensure a coherent time–depth conversion. Additional processing involved refining horizon picks and standardizing amplitude and phase characteristics across the seismic dataset. Any anomalies that could interfere with accurate interpretation were detected and corrected accordingly.

Table 1. Seismic data processing sequence flow.

Pre-processing	Demultiplex Trace muting (top mute) Trace amplitude recovery (exponent 4 dB/s from 0.0 to 2.5 s) Automatic gain control Band pass filter F-K filter
Pre-staking processes	Deconvolution (Designature: minimum phase input assumed) Scaling (offset: 201–3750 m) Time: 0–1000 ms) Velocity Analysis (surface referenced) Normal Moveout Correction Datum statics (Datum 650 and 800 m (ASL) Replacement Velocity 2200 m/s) Common depth point/ straight (fold 30 and 40)
Post-staking processes	Time-Variant Filter: time (s) → bandwidth (Hz) 0.0–0.6 8–40 1.0 8–45 2.0 8–35 Spiking Predictive Deconvolution F-K Migration Post-migration processes –Trace mixing, Automatic gain control

3.1.2. Seismic-Well Correlation

The processed seismic sections were correlated with three exploration wells: Al-Jafr-01 (JF-01) [54], Al-Jafr-02 (JF-02) [55], and Al-Jafr-03 (JF-03) [56], drilled in the Al-Jafr region as part of Jordan’s oil and gas exploration efforts (Figure 2). Figure 4 presents the stratigraphic correlations based on available well data. Multiple seismic lines intersect well locations, allowing for a direct correlation between well lithologies and seismic reflectors (Figure 2).

3.2. Digital Elevation Model (DEM)

High-resolution multispectral data are crucial for digital image processing, enhancing geological lineament extraction [57–60]. Satellite imagery is widely used to identify geological lineaments, which often indicate subsurface features like fault zones [61–64]. Analytical hill-shading techniques simulate topography using artificial light from specific angles, making features perpendicular to the light more visible [65–68]. Multi-illumination methods applied to ALOS/PALSAR hill-shaded images enhance lineaments by using alternative lighting directions. Mark [69] suggested combining relief images from multiple azimuths, while Jenny [70] developed a four-angle method for better relief quality. The ALOS/PALSAR DEM, with a 12.5 m resolution, was developed by the University of Alaska Fairbanks and is freely available. The DEM, acquired on October 4th, 2009, was mosaicked, clipped, and used to generate multi-directional hill-shaded images in ArcGIS 10.8.2.

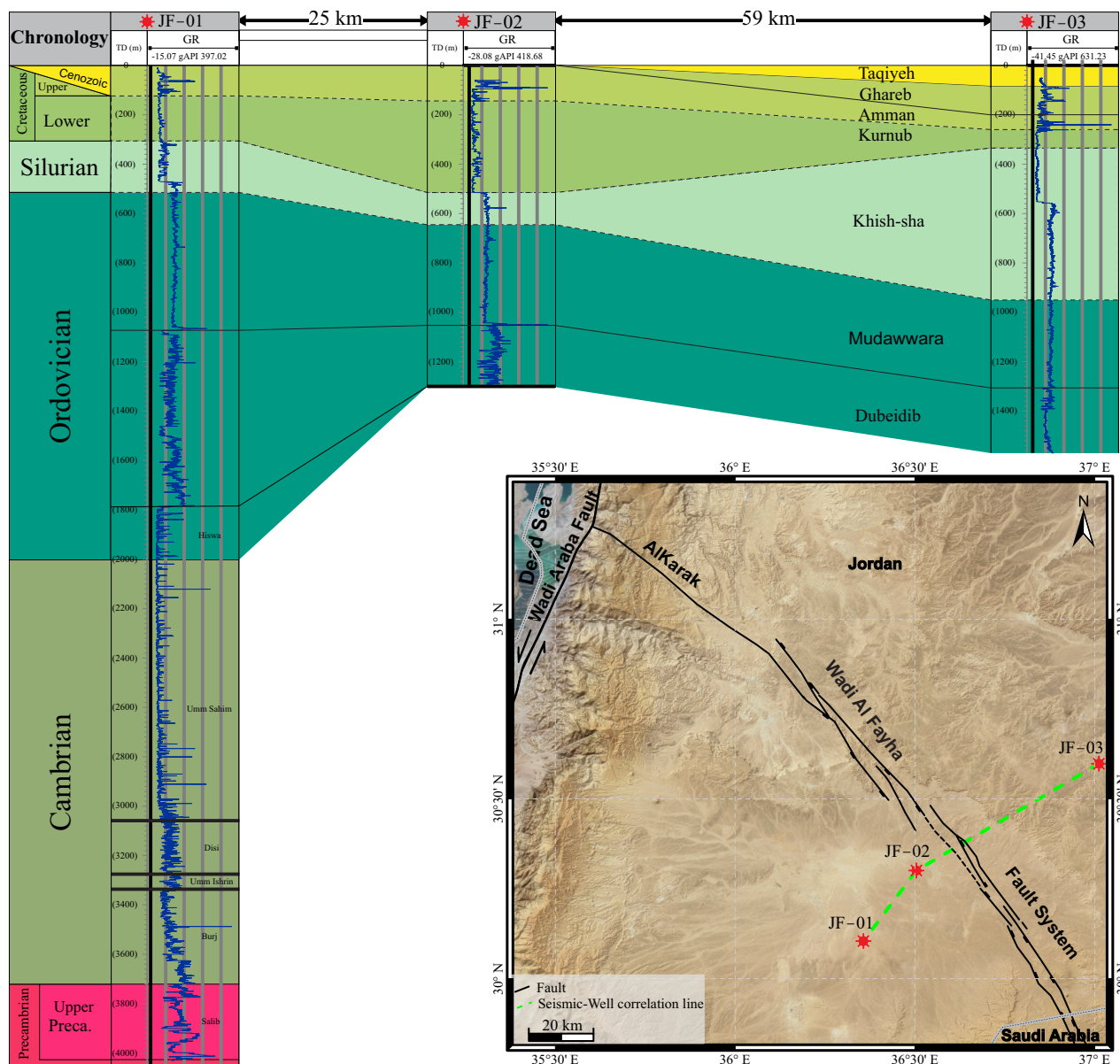


Figure 4. Well-to-well correlation highlighting lithological boundaries across the study area. JF-01: Al-Jafr-01, JF-02: Al-Jafr-02, and JF-03: Al-Jafr-03 exploration wells. The dotted green seismic lines indicate the correlation.

3.3. Fault Mechanism Solution (FMS)

FMS is essential for understanding the movement along faults during seismic events and is commonly employed to analyze regional stress tensor patterns (e.g., [71,72]). Different styles of faulting—such as normal, strike-slip, and thrust mechanisms—serve as key indicators of tectonic stress conditions and help identify the orientation of the maximum horizontal compressive stress (SHmax). This analytical approach assumes that the focal mechanism's kinematic axes—namely the pressure (P), null (B), and tension (T) axes—are statistically aligned with the principal stress directions (σ_1 , σ_2 , and σ_3). Nevertheless, the specific fault plane that ruptures during an earthquake is inherently associated with these kinematic orientations. Consequently, the SHmax direction deduced from FMS is shaped not only by the stress regime but also by the orientation and characteristics of the reactivated fault and the area's existing structural configuration.

This study analyzed 5 earthquake events that occurred between 1983 and 2024, with local magnitudes (M_L) ranging from 2.9 to 3.8. These events were selected based on stringent

criteria, including high-quality waveform recordings, a well-distributed seismic station network with good azimuthal coverage, and clear P-wave first-motion polarity data. Although numerous earthquakes were recorded during this timeframe, only those meeting these rigorous standards were chosen to ensure the reliability of the FMS. The seismic waveform data were processed using the “SEISAN 12” earthquake analysis software (v.2021) [73–75], applying a systematic analytical approach to determine FMS. The earthquakes included in the analysis were relatively shallow, with focal depths ranging from ~ 7 km to 20 km below the Earth’s surface [76].

4. Results

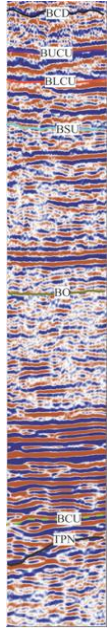
4.1. Stratigraphic Framework

The seismic stratigraphic framework in this study expands on previous interpretations by incorporating well data from JF-01, JF-02, and JF-03 (see Figure 2), building upon the foundation established by Al Hseinat et al. [8].

4.2. Key Seismic Horizons and Units

Table 2 summarizes the significant seismic horizons identified in this study. Well-log data indicate a prolonged depositional hiatus spanning the Middle Silurian to Lower Cretaceous, suggesting extensive erosion and non-deposition. This stratigraphic gap aligns with regional tectonic uplift and exposure events Figure 4 (e.g., [31]).

Table 2. Key seismic horizons interpreted across the study area.

Key horizon	Description	Reflection
Base Cenozoic Deposits (BCD)	Identified in localized seismic sections and corroborated by JF-03 well data.	
Base Lower Cretaceous Unconformity (BLCU) and Base Upper Cretaceous Unconformity (BUCU)	These major unconformities delineate the shift from Paleozoic to Mesozoic sedimentation.	
Base Silurian Unconformity (BSU)	Indicates a regional erosional surface truncating underlying Ordovician units.	
Base Ordovician (BO)	Represents the transition to Ordovician sandstone deposition.	
Base Cambrian Unconformity (BCU)	Separates the Precambrian Saramuj Formation from the Cambrian sandstone deposit.	
Top Precambrian Nonconformity (TPN)	Marks the interface between the crystalline basement and the overlying sedimentary sequences.	

4.3. Seismic Characteristics of Key Reflectors

The TPN horizon, the deepest and most continuous reflector, exhibits low- to medium-amplitude, irregular seismic responses (Figures 5–7). It defines the acoustic basement, below which no reflections are observed. The overlying upper Precambrian Saramuj Formation presents a distinct seismic signature, truncated at the top by the BCU (Seismic sections).

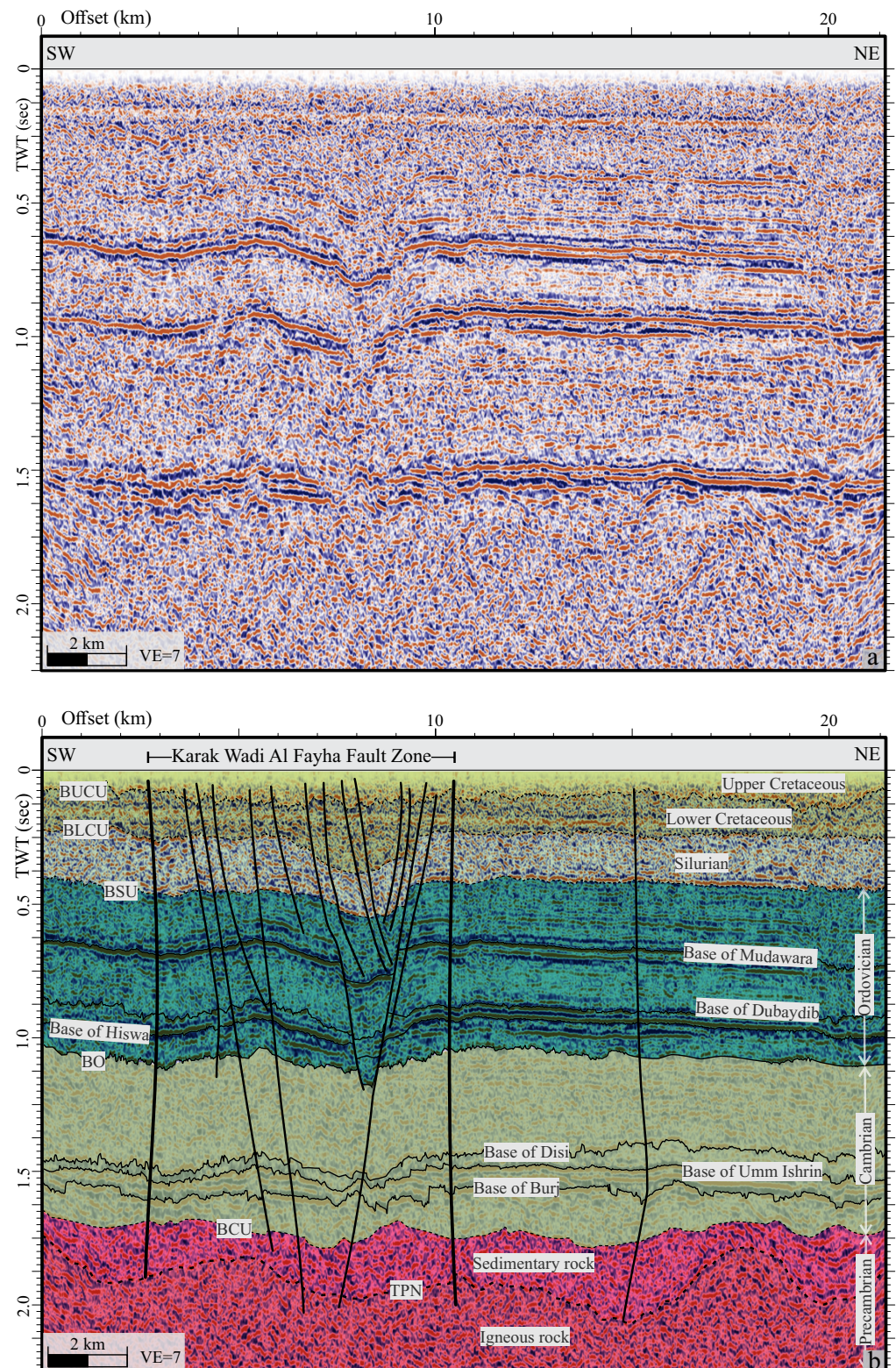


Figure 5. (a) An uninterpreted SW-NE seismic section (for location, see Figure 2). (b) Interpreted section in the southeastern corner of the study area. The seismic section illustrates the stratigraphy from Precambrian to recent times. The KWF cuts the strata from the Precambrian into the uppermost Cretaceous. Some segments propagate, penetrating the surface. The fault shows a system of normal faults that form a negative flower structure deformation pattern.

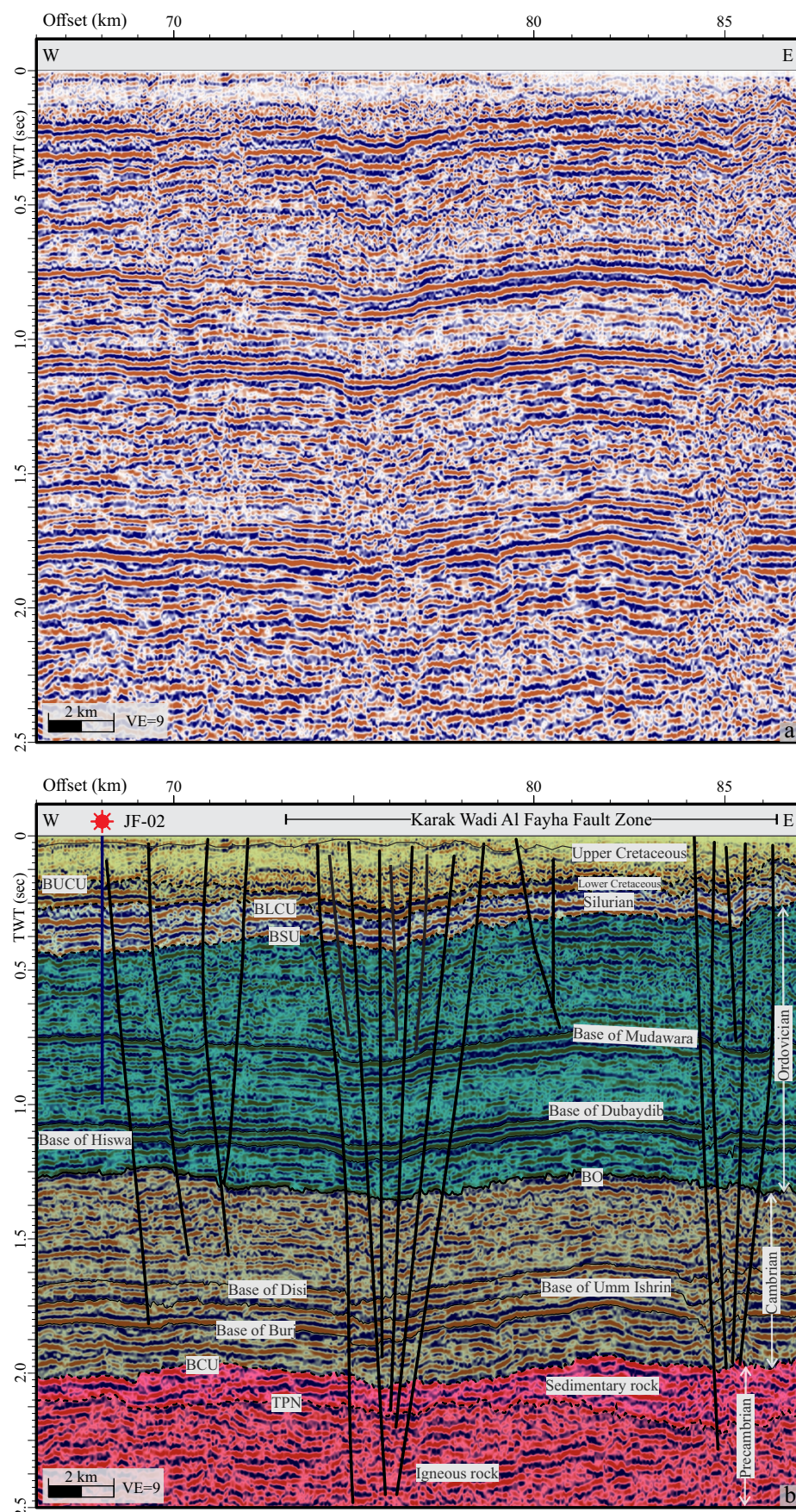


Figure 6. (a) An uninterpreted W-E seismic section (for location, see Figure 2). (b) Interpreted section in the southeastern part of the study area. This section exhibits the stratigraphy from Precambrian to recent times.

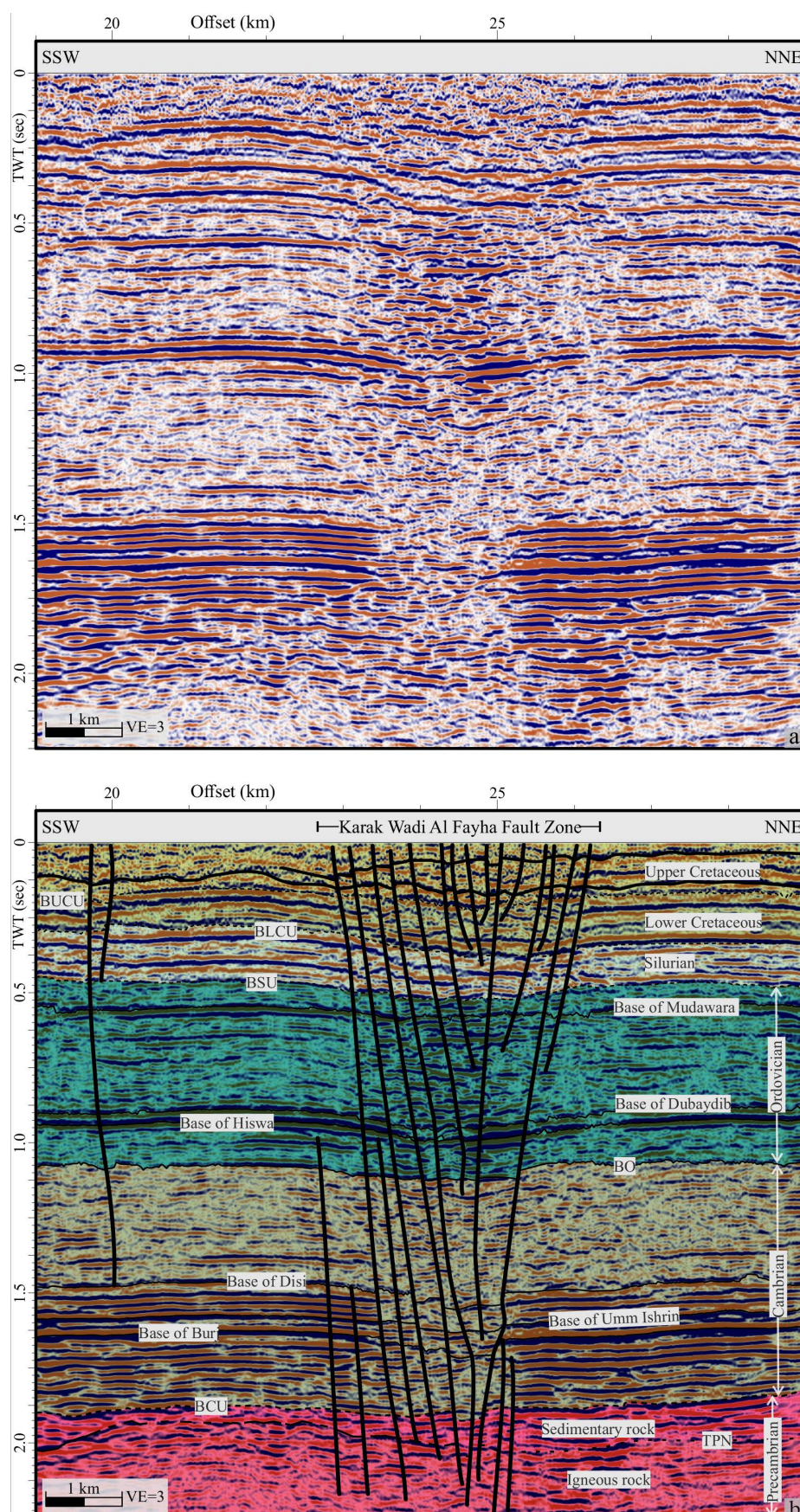


Figure 7. (a) An uninterpreted NNE–SSW seismic section (for location, see Figure 2). (b) Interpreted section in the middle part of the study area. This section also shows the stratigraphy from Precambrian to recent times.

The BCU reflector is a prominent angular unconformity, displaying a wavy and irregular geometry in the southeast but becoming more uniform to the northwest (Figure 6). This horizon marks the base of the Cambrian Saleb Formation. It aligns with the ‘Rum Unconformity’ identified in Southern Jordan by Powell et al. [29]. Cambrian sedimentary layers attain a maximum thickness of ~2 km, gradually thinning to around 810 m toward the northeast [8]. Key internal seismic reflectors within this sequence align with the bases of the Burj, Umm Ishrin, and Disi formations and are identifiable across the majority of the seismic profiles (Figures 5–7).

The Ordovician unit lies above the BO horizon and is capped by the BSU, an irregular and wavy unconformity (Figures 5–10). Internal reflectors within this sequence correspond to the Base of Hiswa, Base of Dubaydib, and Base of Mudawwara Formations, which are distinguishable in most seismic profiles. The Silurian unit, confined between the BSU and BLCU, comprises a well-stratified succession with parallel to sub-parallel, strong-amplitude reflections. The BSU is associated with the Silurian Glacial Unconformity, as documented by Al Hseinat et al. [8].

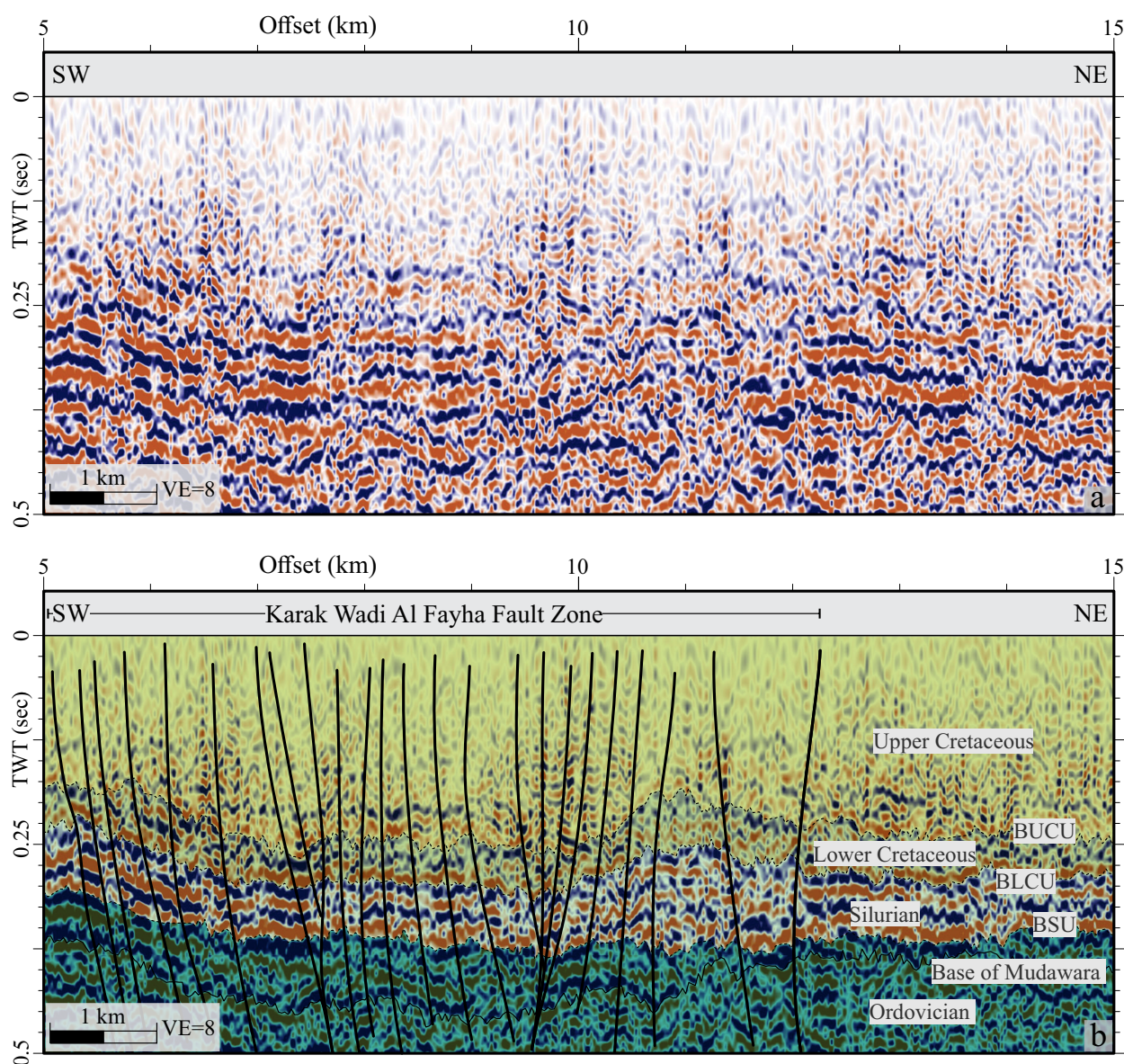


Figure 8. (a) An uninterpreted SW-NE seismic section (for location, see Figure 2). (b) Interpreted section illustrating stratigraphy from the Ordovician to recent deposits. The section highlights the significant deformation of Upper Cretaceous and Cenozoic deposits within the KWF zone.

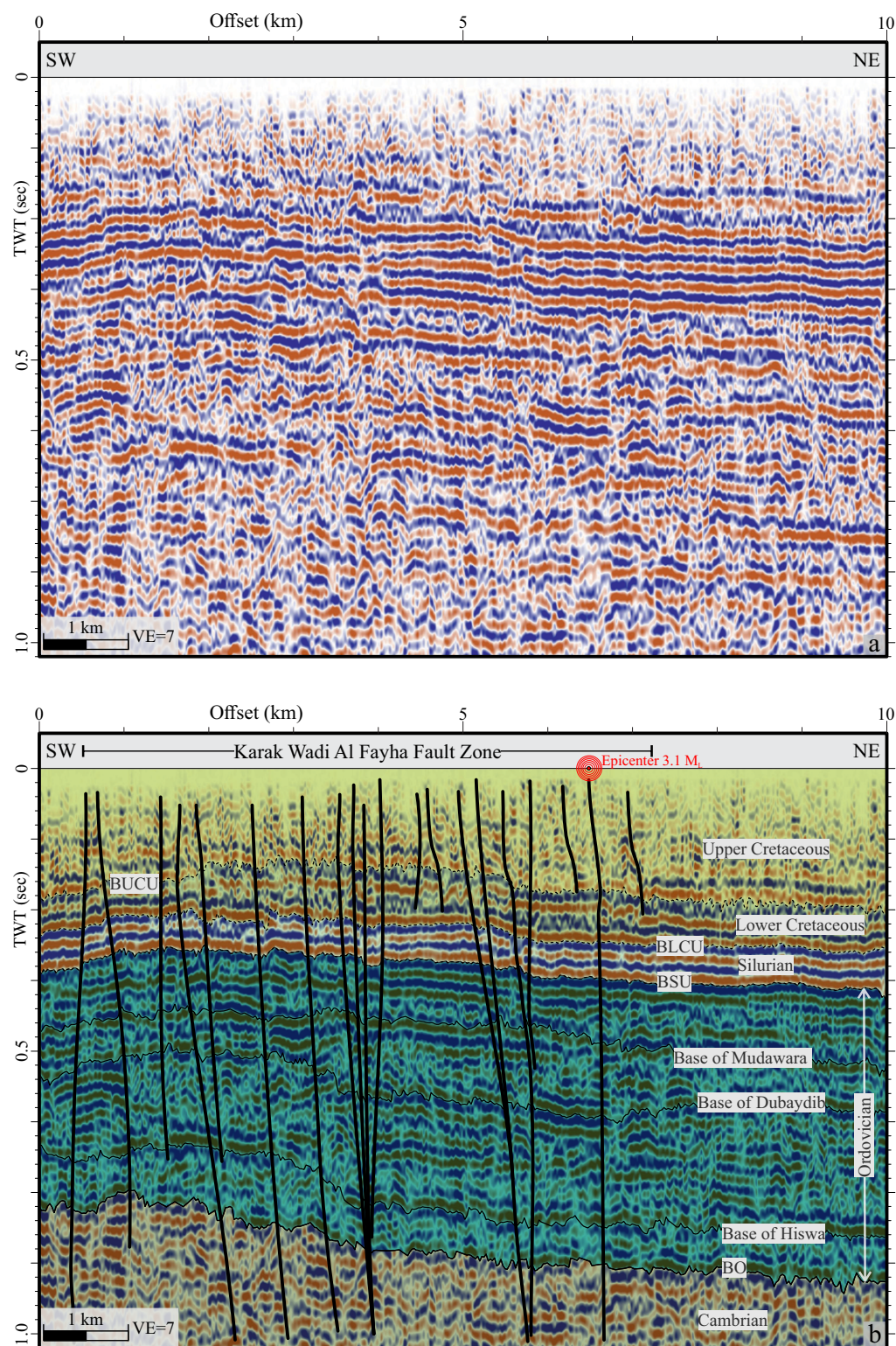


Figure 9. (a) An uninterpreted SW-NE seismic section (for location, see Figure 2). (b) Interpreted section illustrating stratigraphy from the Ordovician to recent deposits. The section highlights the significant deformation of Upper Cretaceous and Cenozoic deposits within the KWF zone. The epicenter of an earthquake was located at 7 km offset.

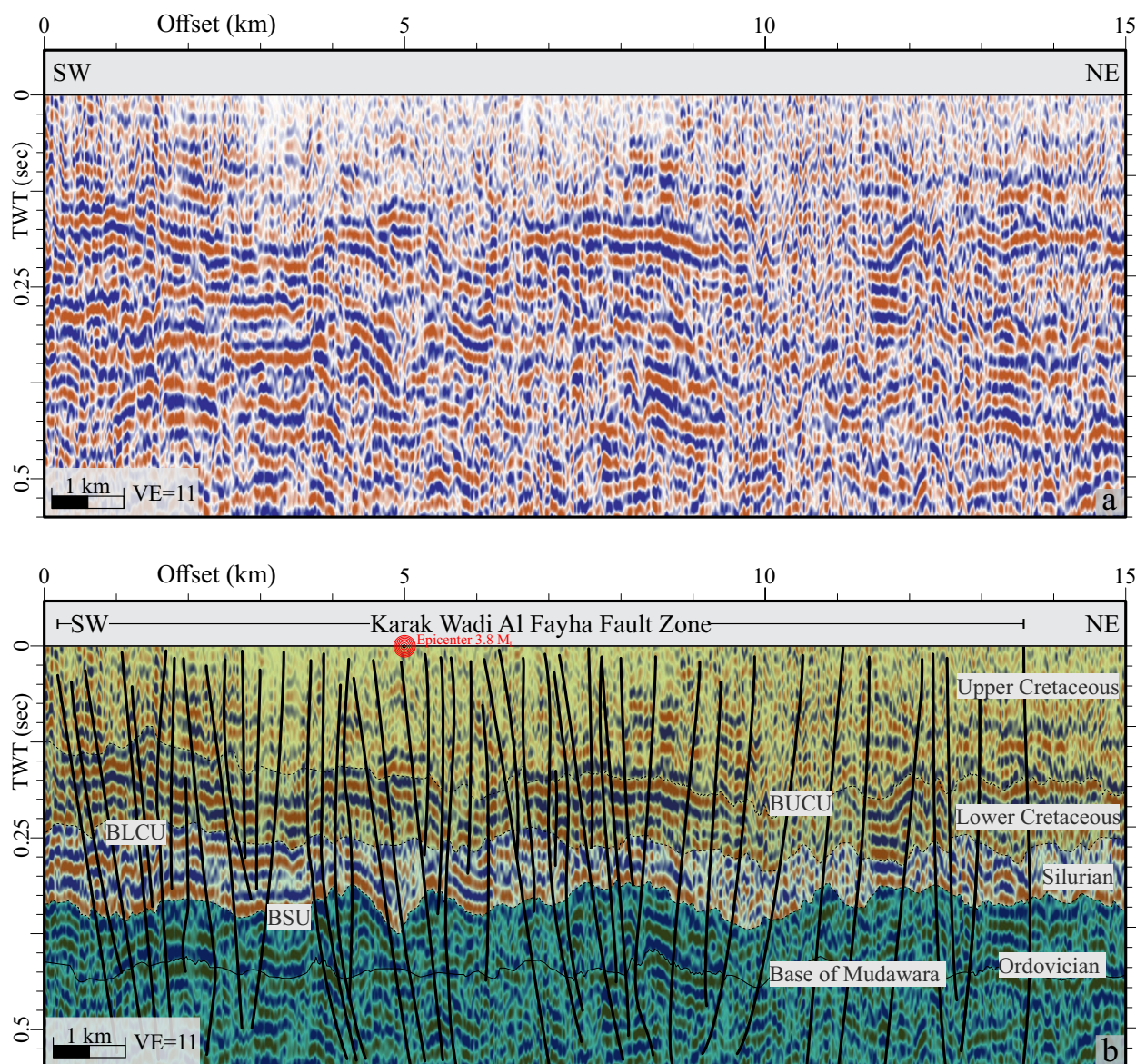


Figure 10. (a) An uninterpreted SW-NE seismic section (for location, see Figure 2). (b) Interpreted section illustrating stratigraphy from the Ordovician to recent deposits. The section highlights the significant deformation of Upper Cretaceous and Cenozoic deposits within the KWF zone. The epicenter of an earthquake was located at 5 km offset.

The Lower Cretaceous sequence consists of a relatively thin but uniform unit traceable across the entire study area. The BLCU and BUCU horizons define its base and top, respectively (Figures 5–10). Correlation with well-log data suggests the BLCU corresponds to the base of the Kurnub Sandstone Formation (Early Cretaceous). This boundary is characterized by a continuous but irregular/wavy reflector, demarcating the contact between the Silurian and Lower Cretaceous strata. The unconformity represents a significant period of uplift and erosion from the Middle Silurian to the Early Cretaceous (Figure 3) [31].

The Upper Cretaceous deposits exhibit irregular yet continuous reflection patterns. Determining the top boundary of this unit (Figures 5–10) and its transition to the overlying BCD deposits is challenging across much of the study area. Where observable, these deposits display a distinct but wavy, continuous reflector (Figures 6, 9 and 10).

4.4. Subsurface Characteristic of the KWF

4.4.1. Seismo-Tectonic Characteristic

The seismic profiles in Figure 2 cross the KWF extension through the study area, though no profiles are available in the northwest corner. However, several essential seismic sections (Figures 5–10) are interpreted to characterize the subsurface structure of the KWF. Figures 5–7 provide an overall view, displaying the deformed rock layers from Precambrian igneous formations to the uppermost Cretaceous deposits, while Figures 8–10 focus on sedimentary layers ranging from the Cambrian period to recent deposits.

Figure 5 illustrates a structurally complex fault zone in the southeastern portion of the study area, featuring two sub-parallel primary normal faults along with several smaller internal fault segments. These major faults, separated by ~7 km, cut across the full stratigraphic column—from Precambrian to uppermost Cretaceous—demonstrating features of growth strata. The internal faults form a horst-like geometry, suggesting the presence of a negative flower structure. In the section between 7 km and 10 km, the stratigraphic layers spanning from the Cambrian to the uppermost Cretaceous define a graben system.

Toward the northwest, the structure narrows from ~5 km in Figure 6 to 3.5 km in Figure 7, with densely clustered normal faults. These faults significantly impact the entire rock sequence, from Precambrian formations to uppermost Cretaceous deposits, with several extending into recent deposits and reaching surface levels.

Further to the northwest, the upper sections of the seismic profiles reveal highly deformed Cretaceous and Cenozoic successions (Figures 8–10), with KWF segments extending to the surface. Seismic sections in Figures 9 and 10 show earthquake epicenters at offsets of 6.5 km and 5 km, corresponding to magnitudes of 3.1 M_L and 3.8 M_L , respectively.

Near the DSTF in this study's northwest corner, there are several earthquake epicenters (Figure 11). Four earthquakes, with magnitudes ranging from 3.1 M_L to 3.8 M_L , align with the surface trace of the KWF.

Figure 11 provides compelling evidence of active landslides in Karak City. Over the past decade, Karak Municipality has been forced to evacuate multiple homes due to severe structural damage caused by these landslides. Notably, eight earthquake epicenters are situated within this active landslide zone, underscoring the strong correlation between seismic activity and ongoing ground instability.

4.4.2. DEM and FMS Results

The multi-illumination hill-shaded images in Figure 12a–c were created by integrating multiple light azimuths, effectively enhancing the visualization of surface relief features oriented in different directions. This technique reveals a distinct pattern of both positive and negative elements. As indicated by the white arrows in Figure 12b,c, the negative relief features primarily correspond to the surface expression of the KWF in Earth's topography. Conversely, the positive relief elements represent elevated landforms, such as topographic ridges and scarps.

The FMS analysis shown in Figure 12d identifies both strike-slip and oblique-slip faulting. FMS (moment tensors) provide two possible fault motion scenarios, represented by two nodal planes (e.g., [77]), which are essential for accurately interpreting fault behavior during seismic events. To ensure consistency with regional paleo stress analysis, we selected the nodal planes that best align with these findings. Consequently, seismic activity has been classified into two areas based on earthquake distribution, key tectonic structures (DSTF and KWF), and faulting characteristics. Three seismic events along the KWF segments exhibit normal faulting, with nodal planes oriented in the NNE–SSW and NW–SSE directions. In

contrast, analysis of two earthquakes at the DSTF–KWF intersection reveals a transtensional mechanism, with nodal planes oriented in the NW–SE and NE–SW directions.

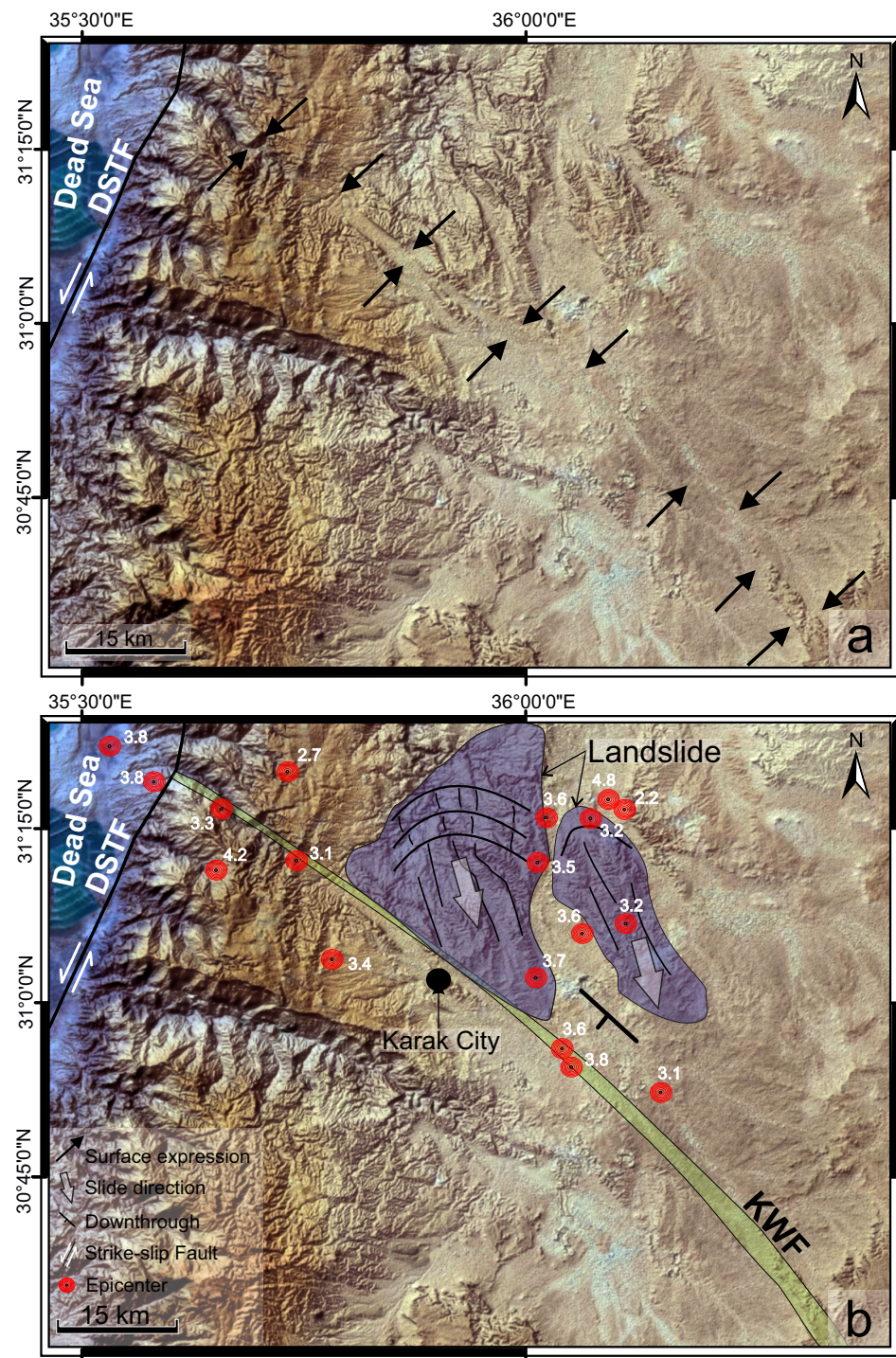


Figure 11. Satellite image showing the northwestern part of the study area (for location, see Figure 2). (a) Highlights the surface expression of the KWF in a highly complex region close to the DSTF. (b) Displays the KWF buffer zone, earthquake epicenters, and the site of the landslides impacting Karak City. Black arrows indicate KWF surface expression. DSTF: Dead Sea Transform Fault, KWF: Karak Wadi Al Fayha Fault.

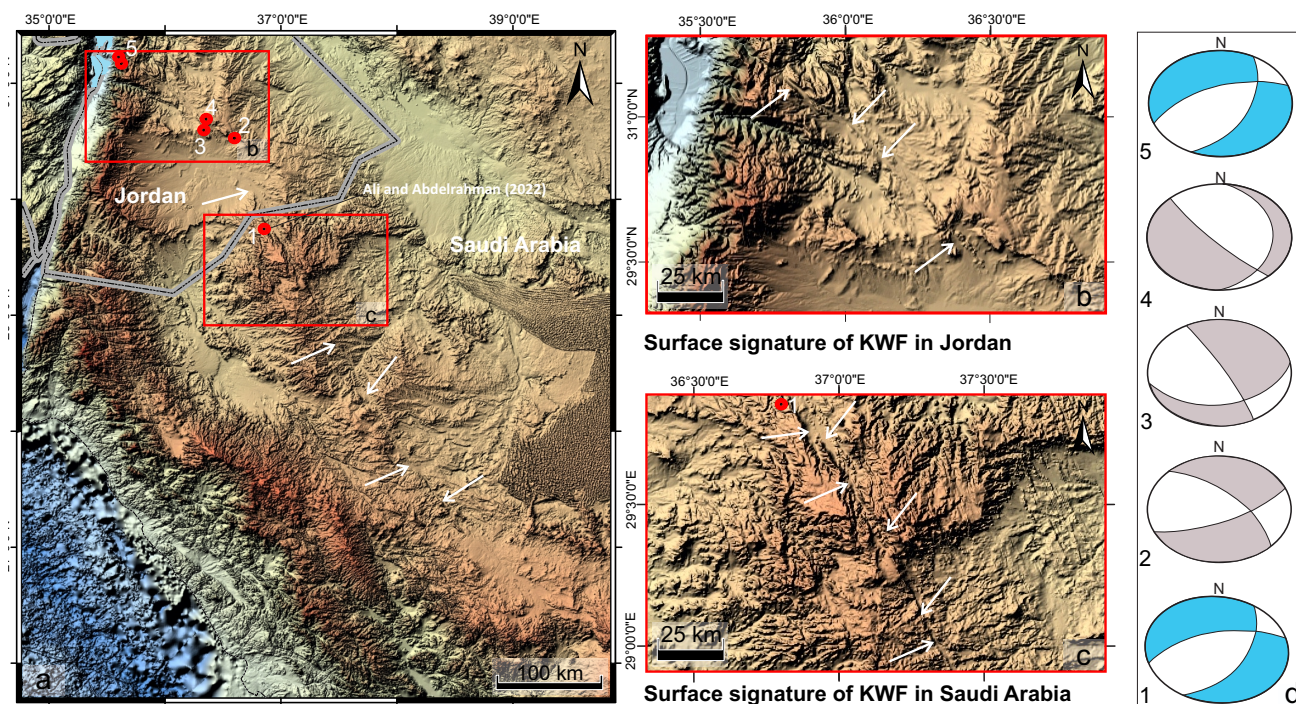


Figure 12. (a) Multi-illumination hill-shaded image of the Arabian plate created by integrating multiple light azimuths (for location, see Figure 1). It reveals a distinct pattern of both positive and negative surface elements. (b) Negative relief of the KWF in Jordan (marked by white arrows). (c) Negative relief of the KWF in Saudi Arabia (marked by white arrows). (d) Fault mechanisms of selected earthquakes along the KWF. Events 1 and 5 show left-lateral strike-slip mechanisms associated with normal faulting (transensional mechanisms). Events 2–4 show a normal mechanism. KWF: Karak Wadi Al Fayha Fault.

5. Discussion

5.1. Seismo-Stratigraphic Evolution

The stratigraphic evolution of the Central Jordan Region, from Precambrian deposits onward, has been extensively analyzed by Al Hseinat et al. [8]. However, with the available seismic dataset, their interpretation can be extended to include the study area. Accordingly, the stratigraphic evolutionary history from the Precambrian igneous rocks to the most recent deposits can be summarized as follows:

The TPN horizon represents a nonconformity surface that separates the Precambrian basement from the overlying upper Precambrian deposits (Figures 5–7). This geological boundary is well recognized in Southern Jordan and near the Jordan–Saudi border [23,25,29].

Well-log data suggest the presence of Saramuj Formation deposits above the TPN, indicating extensive Precambrian rifting and erosion before the Early Cambrian. Seismic analysis reveals that these deposits are truncated by the BCU horizon, representing an angular unconformity comparable to the Rum Unconformity in Southern Jordan [29]. On a broader scale, subsidence linked to the Najd Fault System led to the transgression of the Tethys Ocean into the Eastern Arabian Plate during the earliest Cambrian, with this extension continuing into the late Early Cambrian, ultimately influencing the plate's western margin [20,26].

The thickest Cambrian and Ordovician deposits in the study area can be attributed to Jordan's position along the marginal shelf of the African–Arabian plate during the Early Cambrian [27]. Additionally, the gradual subsidence facilitated the accumulation of sediments from the south, maintaining sea-level stability [20,27]. This extended period of shelf conditions persisted until later orogenic events, leading to the substantial thickness of these deposits, as also observed by Al Hseinat et al. [8].

The truncation of uppermost Ordovician reflections against the BSU horizon serves as a key indicator of the Silurian–Ordovician boundary (Figure 6). This interpretation aligns with the work of Al Hseinat et al. [8], who provided a detailed subsurface mapping of this boundary. Seismic profiles reveal a notable absence of sedimentary deposits between the Middle Silurian and the lowermost Cretaceous (Figures 5–7), suggesting an extended period of uplift and/or non-deposition. This stratigraphic gap has been previously recognized by Ruban et al. [31], Gvirtzman and Weissbrod [78], and Al-Jallal [79]. According to Ruban et al. [31], this period corresponds to the separation of the Hun Superterrane (Middle Silurian–Devonian), with early Cimmerian subduction dynamics exerting a more direct influence on the region's tectonic history.

In the aftermath of this major event, the Early Cretaceous saw the extensive deposition of Kurnub Sandstone, which was transported eastward across the Arabian plate [20]. The overlying Upper Cretaceous strata suggest a shallow marine environment characterized by carbonate platforms, chert, and phosphate deposits [80]. The BUCU horizon is identified as an erosional unconformity, reflecting a period of marine regression (seismic lines). Seismo-stratigraphic interpretation of the uppermost layers was challenging due to the low signal-to-noise ratio in the seismic data, making the precise delineation of the base and top of the Cenozoic sediments difficult. However, the BCD horizon was observable in certain seismic sections (Figure 7).

5.2. Seismo-Tectonic Evolution of the KWF

Drawing on the findings from this study, along with insights from previous research, this discussion examines the initiation and reactivation history of the KWF, spanning from the late Precambrian to the present.

Seismic sections spanning the study area from southeast to northwest reveal considerable deformation in post-Precambrian deposits, marked by numerous normal faults that shape a horst–graben system. The subsurface structure of the KWF is segmented, displaying en échelon fault patterns with stepover offsets (Figures 5–7). This segmentation forms short fault segments that interconnect adjacent en échelon structures, resulting in a continuous fault zone. Additionally, the presence of flower-like structures indicates a notable strike-slip component.

Calculations of vertical displacement along major fault segments indicate that the most significant movement occurred during the Precambrian era. Additionally, seismic interpretations (Figures 8–10) suggest that these fault segments have propagated upward through the Upper Cretaceous deposits, extending to the surface or near-surface. The following discussion explores regional tectonics, with a particular focus on recent tectonic forces that may have contributed to the reactivation of the KWF.

5.3. Late Precambrian–Latest Cretaceous Tectonics

During the late Precambrian, the convergence of the Arabian plate with adjacent tectonic units along the northeastern boundary of the African plate within Gondwana led to crustal extension and initiated the formation of the Najd Fault System [19,20,26]. Within this tectonic framework, the origin of the KWF is interpreted (Figure 13a). This interpretation is consistent with observations by Al Hseinat et al. [8], who identified transtensional stress signatures in the region during this era. These insights also align with Stein's [19] work, which linked late Precambrian rifting and strike-slip faulting in Northern Afro-Arabia to the development of the Najd system in both time and geography. Regionally, NW–SE-oriented wrench fault systems observed across the Arabian plate have often been associated with the broader Najd Fault System by various researchers (e.g., [26,81–83]).

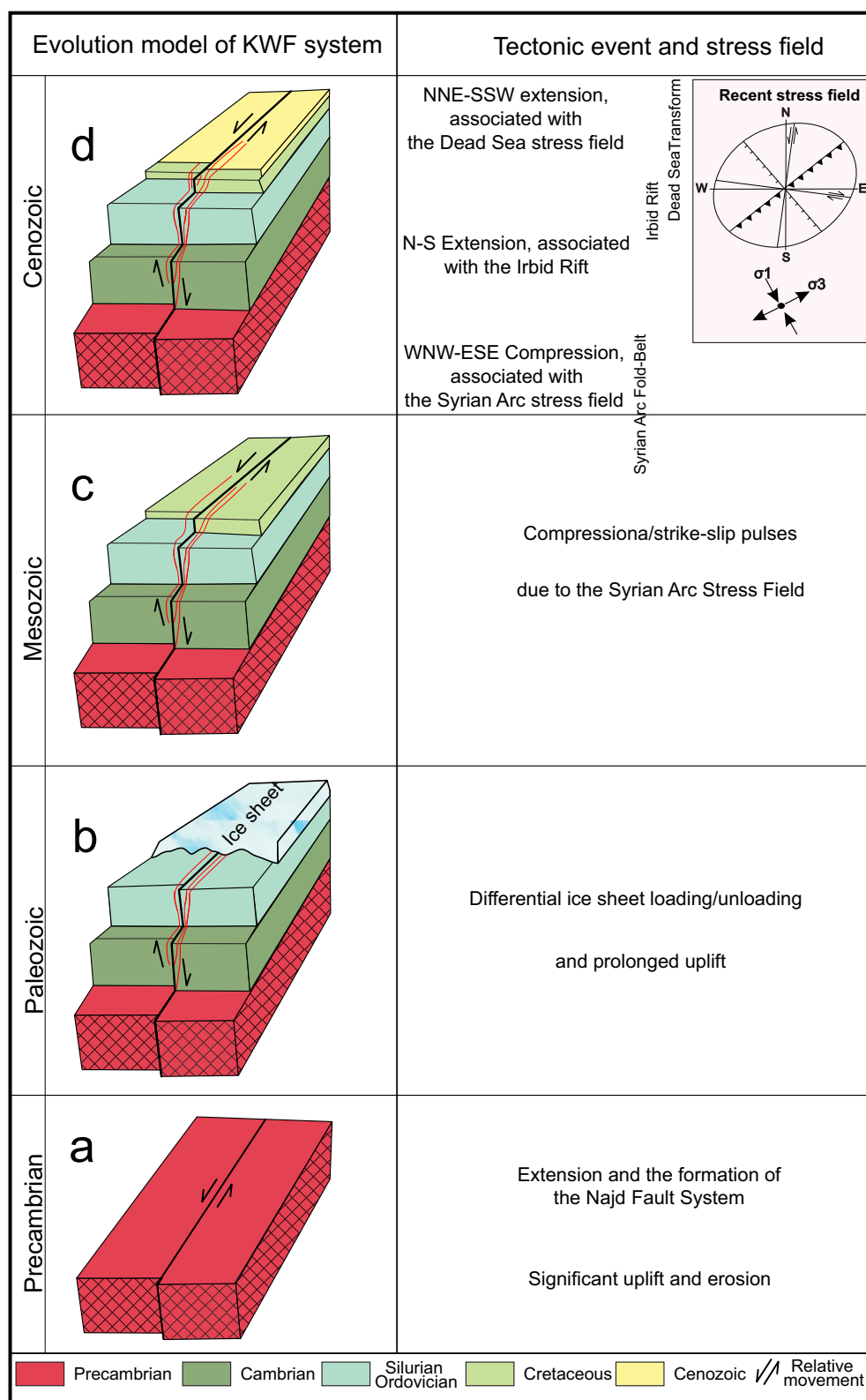


Figure 13. A conceptual 2D model (not to scale) illustrating the evolutionary stages of the KWF from the Precambrian to the present. (a) Development of the initial basement fault system associated with the Najd Fault System. (b) Reactivation during the Paleozoic, likely influenced by differential loading and unloading due to glacial dynamics, combined with long-term uplift (adapted from Al Hseinat et al. [8]). (c) Renewed activity from the Late Cretaceous to Late Eocene, driven by compressional and strike-slip tectonic events. (d) Continued reactivation from the Latest Cretaceous to the present in response to evolving regional stress regimes.

To avoid redundancy, the subsequent tectonic evolution from the late Precambrian to the latest Cretaceous is briefly outlined here, based on the model proposed by Al Hseinat et al. [8]. This includes (i) reactivation of Paleozoic faults linked to variable ice sheet dynamics and prolonged uplift (Figure 13b); (ii) intense faulting driven by compressional and strike-slip tectonics from the Late Cretaceous through the Late Eocene, which also contributed to the development of the Syrian Arc Fold-Belt (Figure 13c); and (iii) ongoing fault activity associated with the DSTF since the Miocene (Figure 13d).

5.4. Recent Tectonic Activity Along the KWF

Field investigations along the northwestern extension of the KWF reveal complex deformation patterns within the exposed Upper Cretaceous strata, most notably marked by the presence of two active landslides (Figure 14). These observations are consistent with the results of Al Hseinat et al. [8], who documented southeast-dipping sedimentary layers oriented toward Karak city—an indicator of displacement associated with fault movement. The link between fault orientation and slope instability is well-established; landslides tend to occur more readily when the slope direction is parallel to the fault strike [84]. Active faults often foster conditions favorable for landslides by reshaping the landscape, creating steep terrain, and weakening the structural integrity of rocks. Earthquakes, frequently generated by these faults, act as common triggers for such slope failures. This connection underscores the importance of assessing active fault zones as potential landslide hazards, particularly in seismically active areas.



Figure 14. Photographs of landslides triggered by recent fault activity in the northwestern extension of the KWF. Red arrows indicate landslide expression.

Collectively, these findings provide compelling evidence of ongoing fault activity and its direct influence on surface deformation, reinforcing the tectonic significance of the KWF in shaping the regional landscape.

Additionally, DEM analysis identifies a prominent NW–SE-trending lineament, marking the surface expression of the KWF (Figure 12a–c). This structural feature, combined with earthquake records indicating several seismic events over the past century (Figure 2), suggests ongoing fault activity. However, a comprehensive review of seismic data from 1907 to 2025 indicates that the KWF exhibits relatively low seismic activity. Despite this, fault displacement does not always generate detectable seismic waves, as movement can occur through fault creep. This process, which can be continuous or episodic, has been extensively well-known in previous studies (e.g., [85–88]).

Furthermore, several studies, including Aldersons et al. [89], Abou Elenean et al. [90], Hofstetter et al. [91,92], and Wetzler et al. [93], have consistently shown that earthquakes in this region typically originate at depths shallower than 30 km, within the lower portion of the upper crust. This well-established pattern highlights the predominance of shallow seismicity in the area, lending further support to the observations and conclusions presented in this study.

The preceding discussion raises an important question: What might be the potential underlying cause of the recent tectonic activity?

Since the Turonian, the northwestern segment of the Arabian Plate has been shaped by three primary paleo-stress regimes (e.g., [35–38]). These include (1) a WNW–ESE compressional regime attributed to the Syrian Arc stress field, which contributed to the formation of the Syrian Arc Fold-Belt (Figure 1); (2) a N–S extensional phase linked to the development of the Irbid Rift, active from the Oligocene (~25–17 Ma) and remains ongoing (Figure 3) [39,44]; and (3) a NNE–SSW extensional regime associated with the Red Sea rifting and left-lateral displacement along the DSTF, reflecting the influence of the Dead Sea stress field from the Late Miocene onward [39,94]. The Syrian Arc stress field has exerted widespread tectonic control throughout the Levant, impacting areas such as Northern Sinai, Israel, Palestine, Jordan, Lebanon, and Syria (e.g., [38,95,96]). The N–S extension associated with the Irbid Rift is also consistent with tectonic activity along the Wadi Sirhan Graben, which experienced renewed movement during the Oligocene and remains tectonically active [50]. This extensional regime has promoted the development of normal faults in Jordan, oriented orthogonal to the σ_3 axis [8].

The identification of a flower-structure pattern in the seismic profiles supports the presence of a strike-slip faulting component, likely active during the Late Cretaceous or afterward (see Figures 5 and 6). Tectonic activity during the Early Miocene is associated with major regional events such as the Bitlis–Zagros collision, the initiation of Red Sea rifting, and the evolution of the DSTF (Figure 3) (e.g., [40,97,98]). Around 20 million years ago, the DSTF intersected the Irbid Rift, leading to the deformation of both the Arabian and Sinai subplates, primarily along a north–south trend (e.g., [99–101]). This N–S extensional regime continues today near the DSTF, accompanied by localized zones of E–W compression [39]. Importantly, faults generated during earlier tectonic events can become reactivated, regardless of their original orientation relative to newer stress fields (e.g., [102]).

The westernmost portion of the KWF lies within a geologically complex region marked by the convergence of several fault systems [103]. In this zone, tectonic deformation may also be influenced by activity along DSTF, making the interpretation of fault dynamics more challenging. FMS near the junction of the DSTF and KWF indicates a transtensional regime, with nodal planes trending northward and in a northwest–southeast orientation. These patterns are consistent with left-lateral strike-slip faulting, which aligns with the main

traces of the DSTF. Transtensional environments typically develop at releasing bends along strike-slip faults or within oblique rift systems [104]. Such settings are often associated with lithospheric thinning and are capable of forming deep sediment-filled depressions, including pull-apart basins.

The subsurface characteristics of the KWF reveal normal faults within a half-graben system that exhibit flower-like structures, suggesting a combination of strike-slip and normal fault components. This interpretation is further reinforced by FMS analysis, which confirms a normal fault mechanism along the KWF and transtensional features at its intersection with the DSTF, reflecting the ongoing activity of both the Irbid Rift and DSTF. On a regional scale, these findings are consistent with those of Ali and Abdelrahman [105] (Figure 12; event No. 1), who identified a dominant transtensional component along the Najd Fault System in Saudi Arabia.

Thus, the rejuvenation of the pre-existing KWF has been driven by shifts in the regional stress field from the Eocene to the present. These findings have potential implications for seismic hazard assessments, particularly in terms of site response, fault behavior, or regional hazard models, especially in regions such as Karak City, which could benefit from further investigation in future work.

6. Conclusions

- The KWF is a prominent NW-trending intraplate fault system extending from Western Karak in Jordan to Wadi Al Fayha in Saudi Arabia. This study integrates reflection seismic profiles with high-resolution DEM analysis to better understand the fault's structural configuration and its influence on surface morphology. FMS from selected earthquakes were also evaluated to infer the prevailing stress regimes affecting the fault system;
- Seismic interpretation reveals that the KWF is a deeply rooted structure that originated as part of the Precambrian Najd Fault System. It displays a staircase fault geometry, with displacements extending from the Precambrian basement through to the uppermost Cretaceous strata. Additional fault segments disrupt formations from the Middle Cambrian to the Late Cretaceous, producing a negative flower structure and localized half-graben systems. In some areas, these faults appear to propagate toward the surface, possibly affecting younger deposits;
- Topographic analysis using multi-illumination hill-shaded DEMs shows a continuous surface expression of the KWF across both Jordan and Saudi Arabia. Field observations document slope instability, particularly in the northwestern sector, where landslides have caused infrastructure damage and led to precautionary evacuations by the Karak Municipality. While such observations may suggest recent deformation, further investigation is needed to confirm ongoing tectonic activity;
- The tectonic evolution of the KWF reflects a long and complex history. It originated during Precambrian extensional events linked to the Najd Fault System. Paleozoic fault reactivation was likely influenced by glacial loading and unloading processes, along with prolonged regional uplift. During the Mesozoic, especially from the Late Cretaceous to Late Eocene, compressional and strike-slip tectonics associated with the Syrian Arc deformation further reactivated the fault. In more recent geological time, changes in the regional stress field—beginning with the Eocene development of the Irbid Rift and continuing with the Miocene evolution of the DSTF—may have contributed to additional fault reactivation and transtensional deformation;
- Overall, this study offers new insights into the structural evolution of the KWF, emphasizing its role within the broader tectonic framework of the region. While indications of recent fault-related deformation exist, further detailed geochronological and geodetic

studies are necessary to assess the current level of activity and its implications for seismic hazard assessment.

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Abbreviations

Abbreviation	Definition
DEM	Digital Elevation Model
DSTF	Dead Sea Transform Fault
FMS	Fault Mechanism Solution
KWF	Karak Wadi Al Fayha Fault

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