



# Tectono-geomorphic development of an active transtensional depression: a case study of Mountain Tuwaiq Plateau, south Riyadh City, Saudi Arabia

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Accepted: 12 October 2020 / Published online: 10 November 2020  
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## Abstract

Central Arabian Mountain Tuwaiq Plateau, south Riyadh City underwent geologic work, including calibrated, filtered, geo-referenced and ortho-rectified synthetic aperture radar (SAR) imageries of the ERS-1/2 and ENVISAT satellites. The Jurassic Mountain Tuwaiq Plateau shows cuestas with flatiron geomorphology dipping gently, which is eroded by an eastward dendritic drainage pattern atop Mountain Tuwaiq, which pours southward running into the Wadi Hanifah valley. The E-W Druma, Nisah, Awsat, Bu'ayja, Rufa'a and Mugarah grabens of Central Arabia are superposed on the plateau's geologic and geomorphic features and appear to be part of the Sahaba strike-slip fault. The graben system has turned the N-S Mesozoic beds into escarpments, with them dipping inwardly towards the north and south and forming a multiple horst and graben. The overlying Cretaceous rocks were transtensionally deformed, and they crop out next to the Jurassic sequence. The transtensional system has also thrown the upper Cretaceous and Paleogene rocks down atop the lower Cretaceous rocks. The overall drainage pattern is an eastward running centripetal pattern that is overprinted by a longitudinal parallel system. Moreover, the Wadi Hanifah valley was displaced by Wadi Laha sinistral fault. The Central Arabian graben system of Mountain Tuwaiq Plateau may fit in the transtensional horsetail splay tectonic landform and damage zone area of the Wadi Sahaba transform fault at the termination mechanism. This intra-plate setting and continental interior may relate to the collision of Arabian and Eurasian plates, in which the transform fault represents Mountain Zagros' thrust belt westward escape structures in the Arabian hinterland area.

**Keywords** Wadi Hanifah · Wadi Nisah · Mountain Tuwaiq · Tectonic geomorphology · SAR radar · Transtensional depression

## Introduction

Tectonic geomorphology includes the study of landform assemblages, landscape evolution and tectonic development in areas and regions affected by fault-related tectonic activity (Roy and Purohit 2018). Utilising a synthetic aperture radar

(SAR) for such studies is probably suitable for arid settings, where seasonal changes in vegetation and moisture are minimal (Burbank and Anderson 2012). SAR amplitude image-ries have been used in arid and semi-arid areas in a variety of fields. Singhroy and Saint-John (1999) conducted geological mapping, and Wade et al. (2001) monitored hydrological events and performed structural mapping via amplitude image-ries. Brivio et al. (2002) monitored flooding in the Piedmont region of Italy in November 1994. Mercier et al. (2004) detected and characterised oil spills in marine settings. In the course of geological exploration in arid zones, Baghdadi et al. (2005) demonstrated that band L or C SAR imagery has greater potential for mapping than advanced spaceborne thermal emission and radiometer (ASTER) optical images, especially for linear structures, such as dikes, and circular structures. Hachemi et al. (2009, 2010) detected landscape changes in the sub-Carpathian region of Buzau in

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Romania, Hachemi and Thomas (2013) detected Barkhan field mobility and Hachemi et al. (2014, 2015) mapped the evolution of coastal features and extensions of cities.

In Saudi Arabia, shuttle radar images have been used to detect several geological features (Al-Hinai et al. 1997), eolian sand covers (Dabbagh et al. 1997) and faults under the Quaternary sands of the Dahna Desert (Weijermars 1998). In the field of cartography, Alsalman (2010) showed the usefulness of the interpretation of Synthetic Aperture Radar SAR imagery from the Radarsat-1 satellite in mapping applications in Riyadh. Another study was conducted by Abdelkareem et al. (2020a) on the integration of multi-spectral and radar images for geological, geomorphic and structural study in the Al Qunfudhah region, south western Saudi Arabia. An additional study by Abdelkareem et al. (2020b) employed optical and radar images for the identification and monitoring of active/inactive landforms in the driest desert of Saudi Arabia.

The urban area in the southern region of Riyadh City is witnessing accelerating infrastructure development, such as the Qiddiya amusement park along the Mount Tuwaiq escarpment, which is located in the study area. Thus, the present study aims to determine the geological structures and related tectonic elements that caused the E-W superposition of the active transtensional graben system that divides the N-S trending Tuwaiq Mountain series between south Riyadh and Al Kharj cities. This study sheds light on the geomorphic changes of Mountain Tuwaiq that occurred after the development of the Nisah segment, which is associated with the regional strike-slip fault system in west Al Kharj City. Furthermore, a new model for the tectono-geomorphic development of the Mesozoic and Cenozoic rocks in the study area is introduced.

## Geological background

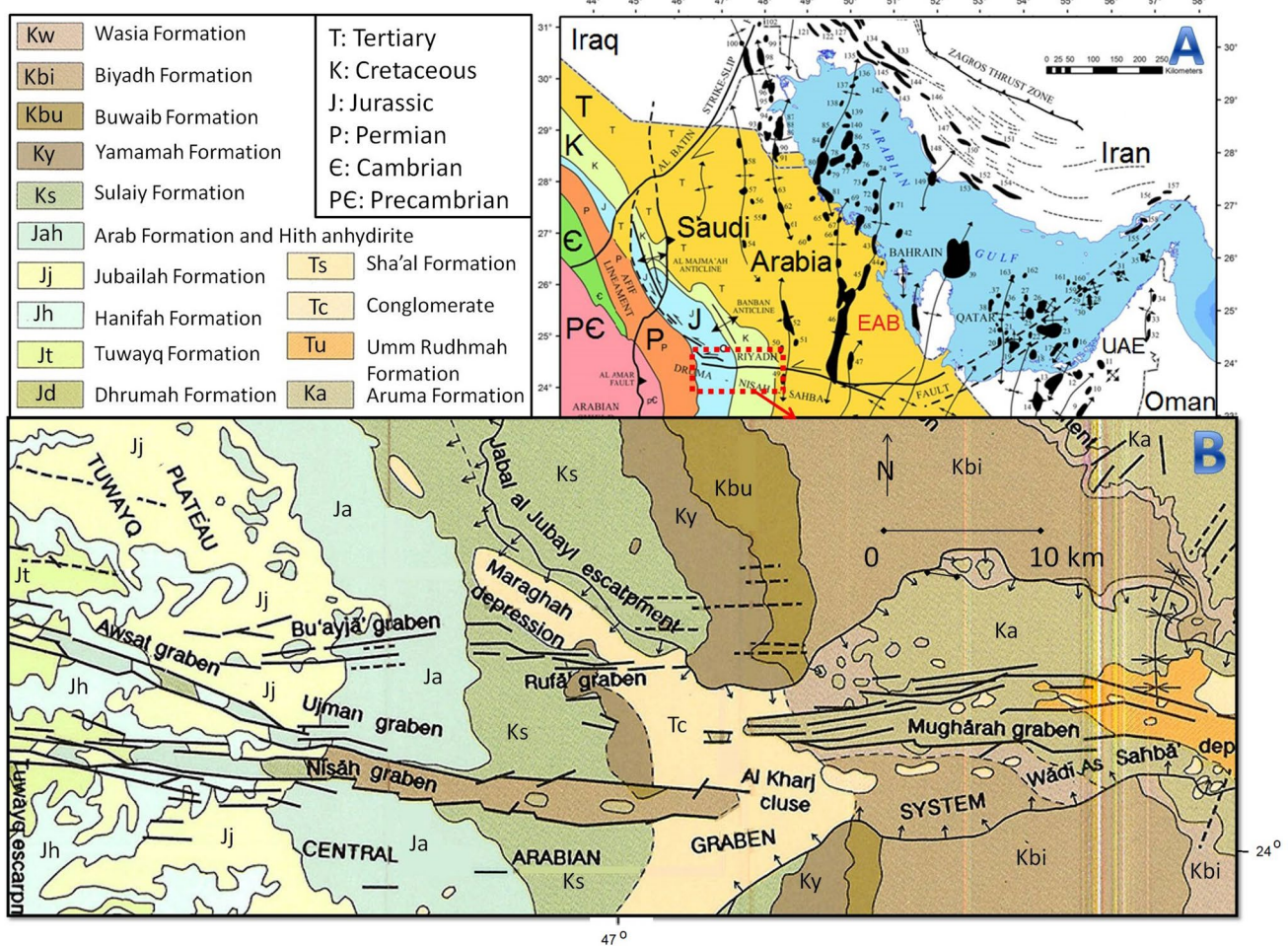
Mountain Tuwaiq Plateau's landscape is generally a N-S trending mountain series in Central Arabia. The geological framework of the study area is characterised by Mesozoic and Paleogene rocks (Fig. 1), which generally crop out as a north–south curved belt that is known as the Central Arabian arch at a regional level (Al Hinai et al. 1997). The geologic context of the Mesozoic to lower Cenozoic rocks is part of the Interior Homocline that bounds the Arabian Shield to the west (Powers et al. 1966). The Central Arch (curved Interior Homocline belt) was cross-cut by the Central Arabian transtensional system (Fig. 1B, Fig. 2). The rock units of the study area are characterised by a variety of sedimentary rocks, but they are mostly limestone interbedded with evaporites, sandstone and siltstone (Fig. 1). The middle Jurassic Mountain Tuwaiq Plateau shows cuestas with flatiron geomorphology that dip gently and have been eroded by the

eastward dendritic drainage pattern atop Mountain Tuwaiq, which pours into the southward running Wadi Hanifah valley (Fig. 3). Between latitudes 24° and 25° North and longitudes 46° and 48° East (Fig. 1), the South Riyadh plateau underwent geologic and geomorphologic modification as a result of an about 100 by 200 km depression that contains six large E-W features. From northwest to southeast, they are the Druma graben, Wadi Laha fault and valley, Bu'ayja graben and valley, Wadi Awsat (middle) graben, Wadi Nisah graben and Maraghah graben (Figs. 1B, 4).

The Wadi Nisah graben, one of the important structural elements of the study area, is oriented east–west towards the city of Al-Kharj (40 km southeast of Ar Riyadh city) and is about 90 km long and 2–3.7 km wide (Fig. 4). The normal faults down thrown displacement of the graben are estimated to be between 100 and 500 m (Powers et al. 1966; Vaslet et al. 1991; Weijermars 1998). Most of the graben is covered with alluvial deposits. The Wadi Awsat graben is also about 90 km long (Fig. 4), cutting in limestone rocks and the graben retreat has been estimated to be between 50 and 300 m long (Powers et al. 1966). The Wadi Awsat valley is thought to be a tributary of Wadi Nisah as it obliquely trends with the Nisah graben (Fig. 4). To the northeast of the Awsat graben, Bu'ayja graben is an isolated 10 km long graben that is almost parallel to the Nisah graben. Above the Bu'ayja graben, the Wadi Laha strike-slip fault is exposed, and it seems to be connected to the Druma graben (Fig. 4). The sedimentary cover of the study area is thick, with it being widely distributed in the central part of the Arabia and ranging in age from Jurassic to Quaternary (Fig. 2). The Cretaceous rocks were transtensionally deformed and crop out next to the Jurassic sequence. The transtensional system has also thrown the upper Cretaceous and Paleogene rocks down on top of the lower Cretaceous rocks.

The tectonic features of the study area are part of the Central Arabian transtensional system, which has an overall left-lateral displacement (e.g., Bamoussa et al. 2017). The transtensional fault zone gets narrower, indicating the southern boundary of the East Arabian Block (EAB), and is of Pliocene–Pleistocene age further to the east, where it reaches the Zagros mountain belt (Weijermars 1998; Bamoussa et al. 2017). The EAB and other large-scale features, such as the Al Majma'ah strike-slip fault and Jinadriyah and Jabal Al Jubail anticlines (Fig. 1A) in the Central Arabian Plate, represent the fore-arc part of the late Alpine-Himalayan orogeny that took place since Eocene and was probably active during the Quaternary Period (Bamoussa et al. 2017).

This tectonic event was followed by karstification and collapse features development during the pluvial times of the Pleistocene epoch in the Arabian Plate (e.g., Bamoussa 2018). Due to the Pleistocene pluvial conditions, two types of karsts were developed, namely the dinaric and interstratal features karsts (e.g., Memesh et al. 2008; Bamoussa



**Fig. 1** Location of the study area within geologic and tectonic framework. **A** Shows the East Arabian Block (EAB) and major deep-seated anticlines and oil and gas fields, modified after Bamoussa et al. (2017).

**B** Shows detailed geologic map of the study area and the graben system, after Vaslet et al. (1991)

2018). Carbonates and evaporite bearing Mesozoic rocks were affected by breccia pipes, packed karsts breccia and collapse geomorphology along the Interior Homocline for more than 500 km from north of Riyadh to south Al Kharj. They are mostly affecting the carbonate of the Lower Cretaceous Sulaiy Formation and underlying Upper Jurassic Arab Formation (Nagm et al. 2018; Bamoussa 2019). The two rock units (Sulaiy and Arab fms) underwent karstification and collapse features after the dissolution of the evaporite-bearing Hith Formation that originally occurred below Sulaiy and above Arab fms. (Memesh et al. 2008, 2017). Two stages of depression developments affected the Lower Cretaceous Sulaiy Formation, with tectonic development coming first and forming the accommodation of Quaternary deposits, which was followed by geomorphic development during karstification that widened the accommodation space for the Quaternary deposits (Bamoussa 2018). Further erosional factors, such as surface water and

winds, cause more collapses to the sides of the depressional areas of the cliffs and margins (Al Ghamdi 2007). It is worth noting that the urban area of Ar Riyadh city is mainly underlain by Arab with overlying Sulaiy formations, which underwent the abovementioned tectonic and geomorphologic history.

The tectono-geomorphic changes control Wadi Hanifah, which runs diagonally from northwest to southeast, passes through south Ar Riyadh city and eventually pours into and merges with Wadi As Sahaba, which is east of Al Kharj city. It forms an overall subparallel to subdendritic drainage pattern with its west to east flowing tributaries, Wadi Namar and Wadi Laban, which are in the northern proximal area north of Riyadh city (Fig. 3). Moreover, when the Wadi Hanifah valley reaches the Al-Ha'ir village in southeast Riyadh, it connects with Wadi Laha east of the village. Wadi Awsat, which is to the south of Wadi Laha is considered as a tributary of the Nisaha valley.

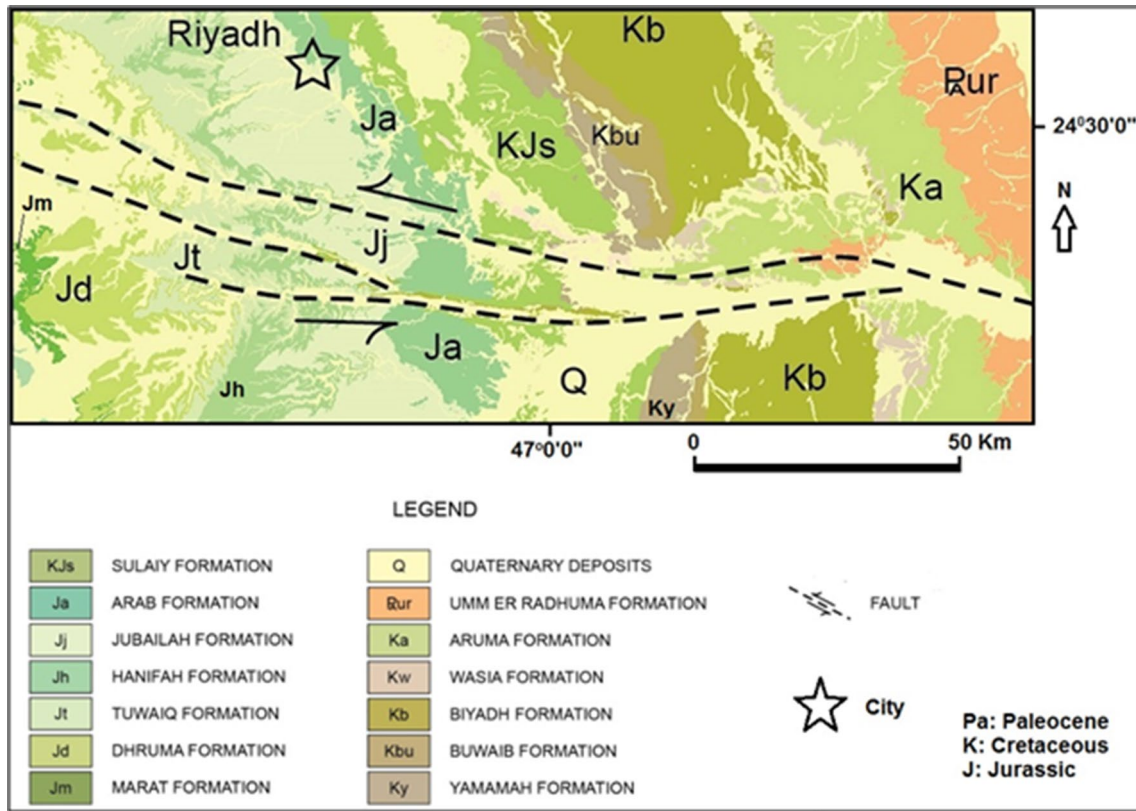


Fig. 2 Regional geology map of the study area showing interpretation of Druma-Nisah-Sahaba strike-slip fault (after Bamousa et al. 2017)

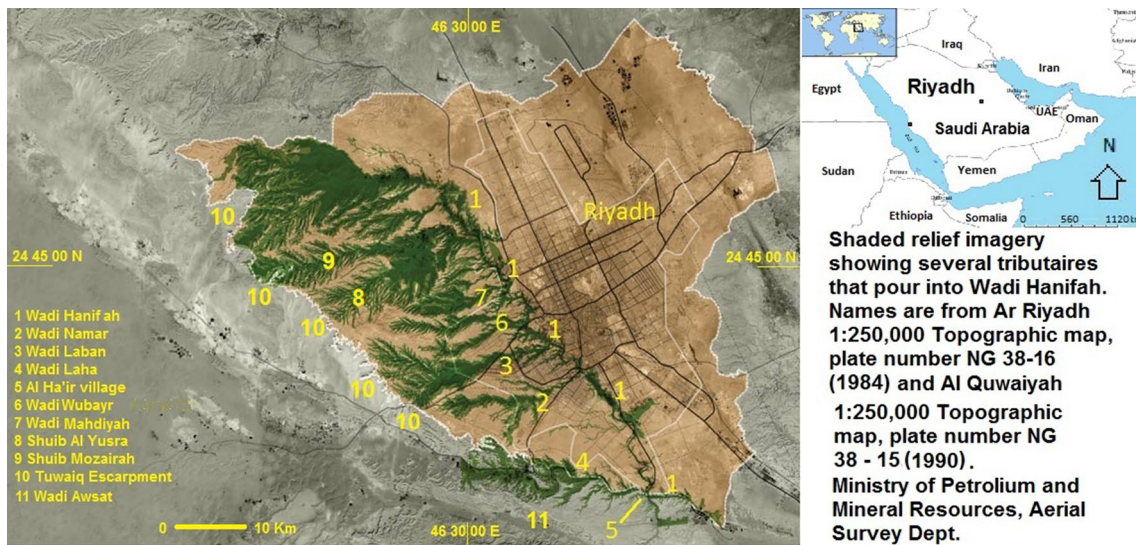
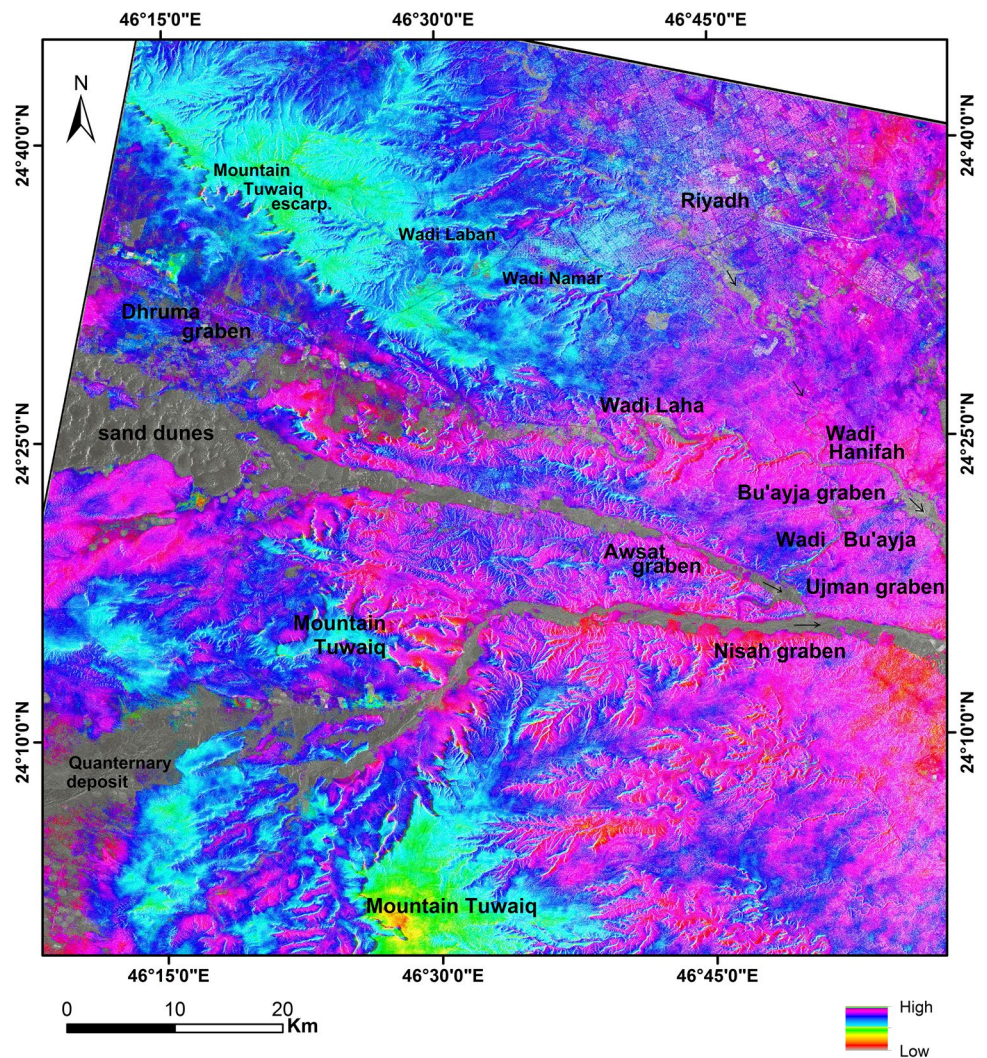


Fig. 3 Wadi Hanifah watershed showings eastwards running tributaries with respect to Riyadh and Ha'ir village. Annotated relief imagery and geographic names are from Royal Commission for Riyadh City, (2019)

**Fig. 4** Portion of intensity/phase image of ENVISAT draped on digital elevation map showing tectonic and geomorphic elements concerning Riyadh and Al-Kharj cities



## Materials and methods

The ERS-1/2 and ENVISAT satellite images are single look complex (SLC) data that are processed by pulse compression in radial direction in distance and by SAR in azimuthal direction from the same processing and archiving centre (UK-PAF). In this type of product, each pixel is represented by a complex value (real and imaginary part), from which the amplitude and phase of the signal are extracted. These images have 4904 columns and 29,715 rows for ERS-1/2 and 5164 columns and 27,326 rows for ENVISAT. They cover an area of (100 km by 100 km) with a resolution of 4 m (in azimuth) and 20 m (in distance) for SLC. Acquisition is downward (daytime acquisition) in a downward azimuthal direction. The scene is illuminated to the right from a lateral view at an incidence angle of  $23^\circ$ , in the C band of wavelength (5.65 cm), and it has a vertical polarization (V/V).

SAR is a useful technique due to its ability to operate during all weather conditions and above any landscape. SAR sensors, which are active sensors that are on board satellites

in orbit, measure the two components of the backscattered signal (amplitude/intensity and phase). The signal amplitude is a function of the physical and dielectric characteristics of the imaging element. The phase depends on the geometric characteristics and contains the distance information between the radar and the target; it therefore makes it possible to measure the vertical movements of the ground in the order of  $1/2$  a wavelength. Amplitude characterises the reflectivity of the pixel for the high frequency wave. It can be used directly and is comparable to an optical image. It is directly related to the surface conditions; thus, a radar amplitude image allows for the collection of instantaneous information about the imaged region, and as the radar is a tool that can be used at any time and in any weather condition, the coloured composition enables the collection of information on landscape changes between two different dates. Diachronic (coloured composition) images taken at different periods are translated by looking at the change in pixel radiometry between the two dates, allowing for better interpretation of the landscape in the region. Wet surfaces

are represented by high values of radiometry, while arid landscapes appear as low values.

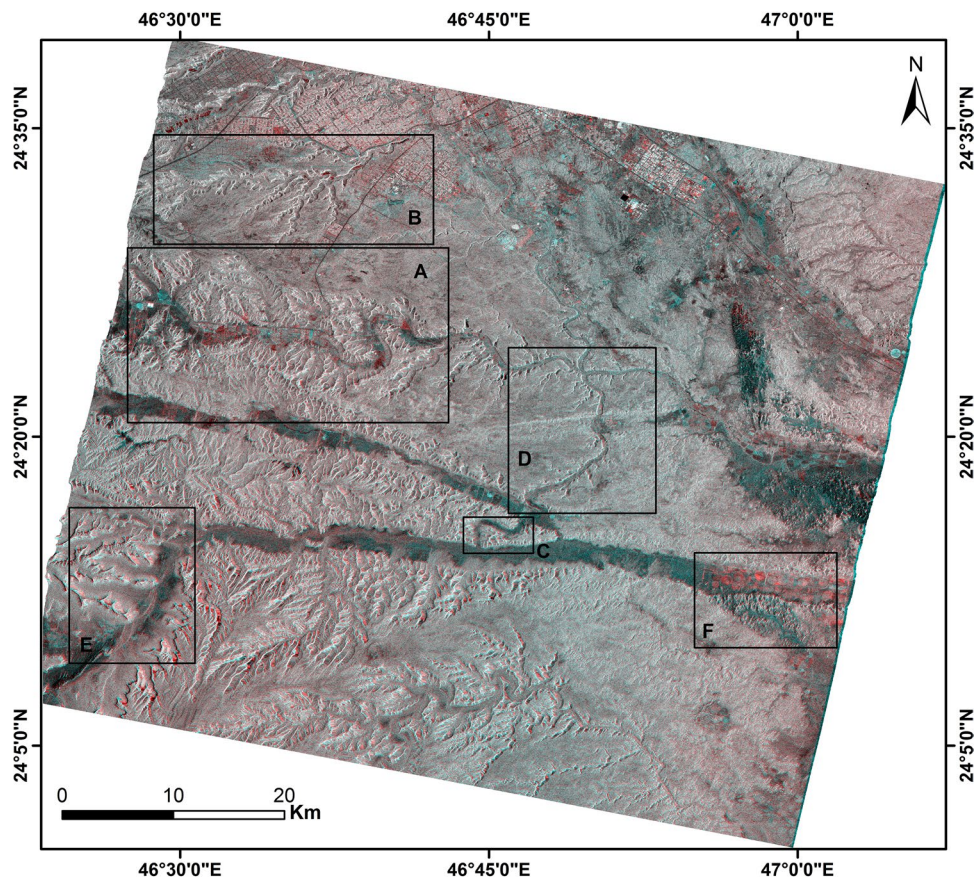
Detailed fieldwork has been carried out to document several geological and morphological features in the study area, including all of the structural elements and the tracing of the relationship between the different tectonic features and its impact on the surface landform. SAR radar images from the ERS-1/2 and ENVISAT satellites' radar data that was obtained from ESA were calibrated, filtered, geo-referenced and ortho-rectified at 20 m resolution. Geo-referencing allows the images to be produced in the same cartographic projection system (UTM zone 38-N, WGS84). Ortho-rectification consists of correcting an image's amplitude or intensity according to the shape of the DEM terrain model. A diachronic colour composite of two different capturing years, namely 1996 and 2008, was utilised to show

tectonic and geomorphic developments (Fig. 5). This image tracks changes in the landscape. It reveals older features, such as a valley, in the colour blue and younger features, such as circular farms, in the colour red (Fig. 5F). Table 1 shows the specification of the two bands used to build the diachronic imagery. Finally, the SAR data was draped on a shuttle radar topography mission-digital Terrain Model (SRTM-DTM) to show the morphology of the area at different time intervals (Fig. 6).

### Results

Four important indications were detected during the analysis of the multi-temporal radar amplitude imageries. These are discussed in detail below. First, superposition and

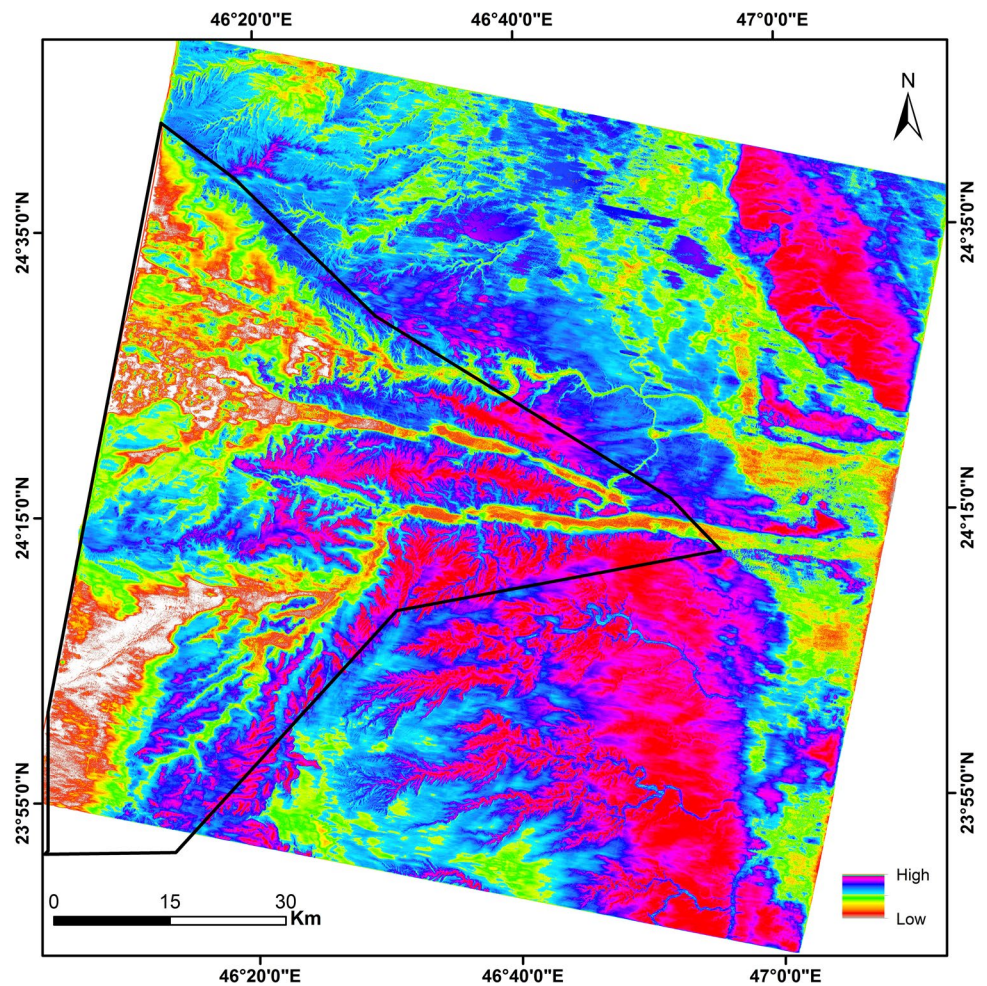
**Fig. 5** Colored composition intensity image of ERS-1/2 captured in 1996 (blue) and ENVISAT captured in 2008 (red), calibrated, georeferenced and orthorectified for the study area with a resolution of 20 m. They show changes occurred between 1996 (blue) and 2008 (red). This color composite image has a 3D view by looking at them with red and blue glasses. The imagery shows irreversible erosion (A), development of new drainage pattern along the Tuwaiq escarpment, namely Wadi Namar (B) capturing of older drainage pattern (C–E) and development of a new drainage pattern after Nisah graben development (F)



**Table 1** Specification of the diachronic image in Fig. 5

No.	Date	Time of day	Satellite	Orbit	Track	Center (Lat/Long)	Incidence angle	Band	Wavelength (cm)	Polarisation	Resolution (m)
1st	12/05/1996	07:27:37.25	ERS-1	09,839	3118	24.36/46.56	23,147°	C	5.65	V/V	20
2nd	21/01/2008	06:57:18.00	ENVISAT	30,807	3118	24.25/46.59	22,921°	C	5.65	V/V	20

**Fig. 6** An arrowhead eastward pointing depression, base map is Intensity/phase image of Envisat draped on digital elevation map. SRTM-DTM showing the morphology of the area at different time intervals



intervening of the Tuwaiq Mountains series by a new drainage system in the middle part of the study area is indicated (Fig. 4). In addition, the data clearly shows capturing and redirection of the old drainage pattern by the new drainage system. Moreover, the effect of irreversible erosion on Mountain Tuwaiq is shown by the radar data. Finally, using the radar data, a reconstruction of the valley system before the deformation event took place is performed.

### Superposition of the Tuwaiq Mountains and development of a new drainage system

Intensity/phase imagery from ENVISAT draped on a digital elevation map (Fig. 4) indicates the superposition of the Tuwaiq Mountains by tectonic subsidence related to the development of the Central Arabian transtensional fault zone. A blue-green colour reflects high topography, whereas discontinuity of this colour is evidence of the breakage of the Tuwaiq Mountains. Figure 4 clearly shows intervening of the Druma, Awsat and Nisah grabens (grey colour) with Mountain Tuwaiq (purple colour) in

the middle of the image. These three segments (Druma, Awsat and Nisah) form a tectonic subsidence with a triangular shape (Fig. 6). This shape has probably developed due to the superposition of an older feature, which is the closure (hinge) area of the Arabian arch of the Interior Homocline that developed earlier during the Hercenian orogeny. The Druma graben cross-cuts the Tuwaiq Mountains in the north and forms the Tuwaiq escarpment. The Nisah graben captured SW-NE trending and controls the Wadi Nisah flow direction in the southern section. Thus, Wadi Nisah flows SW to NE and shifts its course towards the east once it enters the graben, which then becomes the main course of the wadi (Fig. 5E). Moreover, the overall pattern of all of the grabens and wadis within the triangular area of Nisah depression segment is parallel, with them pointing towards the east, where Wadi Sahaba is located near Al Kharj city. The Sahaba segment has an elongated shape (Fig. 2), and Quaternary deposits are cross-cut by two parallel transtensional faults (Fig. 1). Therefore, the elongated parallel drainage pattern is part of the recent drainage system.

## Irreversible erosion

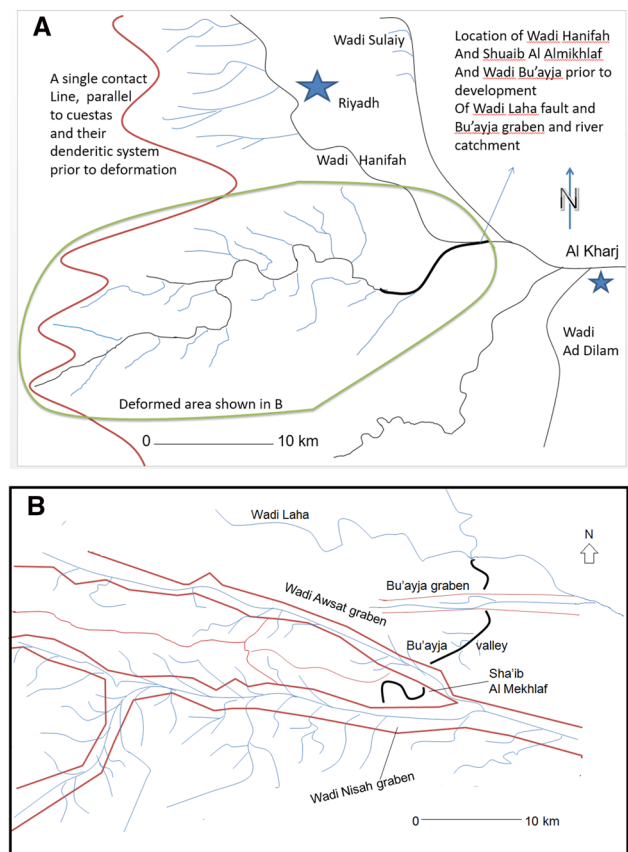
The coloured composition intensity image of the ERS-1/2 captured in 1996 (blue) and the ENVISAT captured in 2008 (Fig. 5A) shows the superimposed normal faulting of the Druma graben on the Tuwaiq Mountains in the north and developing of Wadi Laha. This superposition forms the Tuwaiq escarpment and caused irreversible erosion along the Tuwaiq escarpment, where the rock units retreated towards the north near Al Mezahmiah. This irreversible erosion appears clearly in the radar image due to the subsidence of Tuwaiq Mountain (Fig. 5A). The subsidence formed new erosional wadis that cut southwest of the escarpment, eroding the soft beds and pouring into the depression, running from NE to SW, and causing the irreversible erosion and increasing the area of depression. Moreover, a new drainage pattern has developed NE of the escarpment and has become part of the Wadi Hanifah (Fig. 5B).

## River re-catchment and redirection

Based on the analysis of the thematic maps and geomorphological interpretation, the Sha'ib al-Miklaf segment is no longer an integral part of the regional drainage network (Fig. 5C). Sha'ib Al M-Miklaf is currently bound by two normal faults that form a horst between the Nisah and Awsat grabens. The wadis at the bottom of the Nisah and Awsat grabens currently serve as a watershed that was once drained by the Sha'ib al-Miklaf segment. The subsidence of the Bu'ayja graben has been intercepted, which has resulted in the original north and south rout of the Bu'ayja canyon being crossed and destroyed (Fig. 5D), and the drainage network has manifested at the bottom of the Bu'ayja graben. The captured intermittent flow of the Bu'ayja canyons that remain in the graben is now progressing eastward due to drainage channels being dug along the bottom of the Bu'ayja graben and connecting to Wadi Hanifah. The Wadi Laha wadi was formed and connected to Wadi Hanifah after the development of a strike-slip fault, and it is catching Wadi Hanifah and re-directing Wadi Hanifah, causing it to flow west to east near the Al Ha'ir village (Fig. 5D). Wadi Laha, which is to the west of the village, is running almost parallel to the recently developed escarpment of Tuwaiq Mountain after the development of the depression. The fault has also cut the original course of Wadi Hanifah, and the radar image shows a clear left-lateral displacement.

## Reconstruction of the original valley system

The change at the base level of erosion has resulted in a complex reorganisation of drainage systems. After capture, incision rates increase 10-fold over most networks (Fig. 7). Detailed network evolution in the most sensitive areas can



**Fig. 7** Reconstruction of the valley system. **A** Before and **B** after transtentional central Arabian fault system

be followed by the reconstruction of old drainage channels using abandoned drainage passes, as well as the alignment and degree of incision. Three stages of evolution can be identified, namely stage 1 of pre-capture, which is the original drainage resulting from it, stage 2 early stage, which is the subsequent aggressive drainage developed along the structure (lineaments) after capture, and late stage 3, which is after obsessive drainage has developed on the topography of the stage 2 drainage. However, the importance and need for regional approaches to examine long-term changes in river systems and the geomorphic environment of adjacent watersheds must be emphasised (Mather 2000). The interpretation of the radar images suggests that Wadi Hanifah's rectangular pattern near Al-Ha'ir village transpired after the left-lateral movement. To the south of the Al-Ha'ir village, there is a north to south flowing wadi segment that seems to be an abandoned course. This course would fit with the original course of Wadi Hanifah; therefore, this suggests that Wadi Hanifah was also originally running in a centripetal shape towards the Sahba valley.

The radar data were helpful for the reconstruction and for identifying the original courses of Wadi Hanifah and the Shaib Al Mikhlaf valley. The Shaib Al Mikhlaf valley

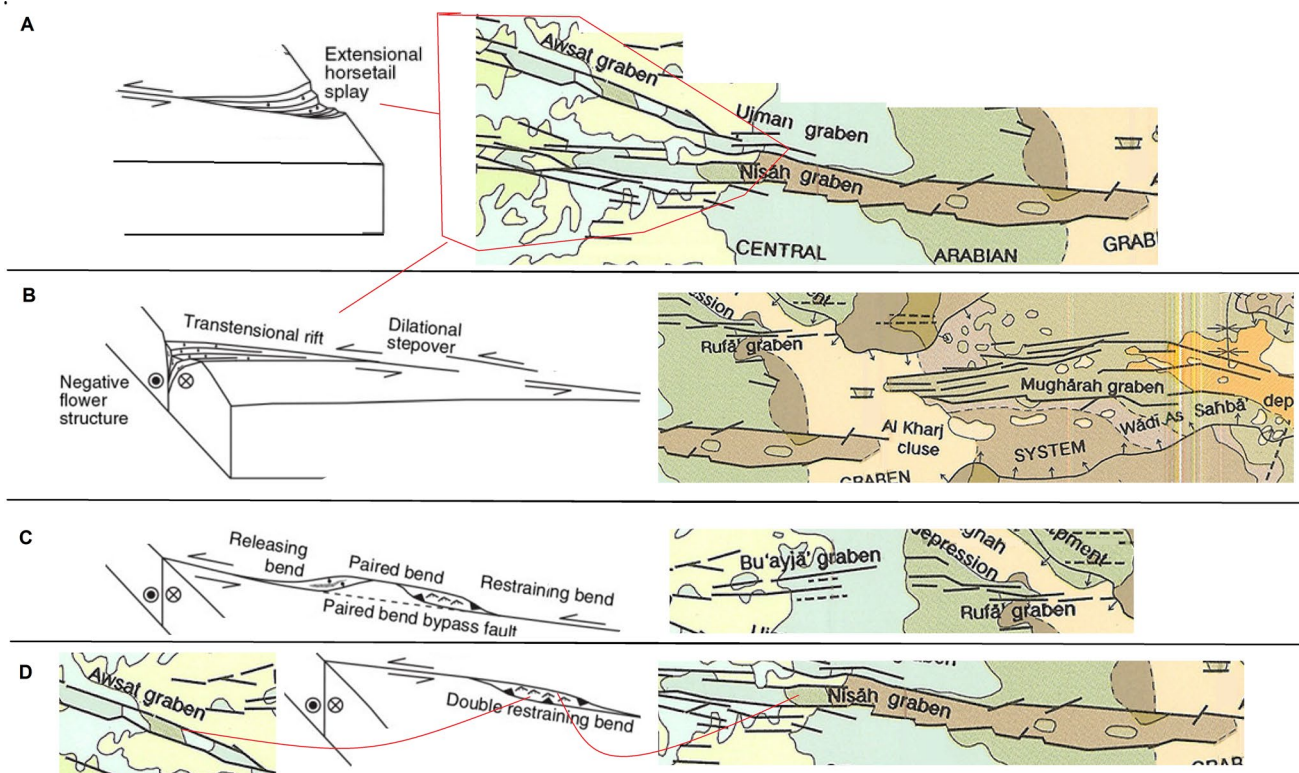


is probably the abandoned W-E course of Wadi Hanifah; it is currently captured in a horst between the Nisah and Awsat grabens (Fig. 5C). Another northern segment of this old course may be captured in another horst between the Awsat and Bu'ayja grabens, which has the local name of the Bu'ayja valley (Fig. 5D). Thus, it is likely that these two courses were once one valley that was interrupted by the three grabens that are running SW-NE. This feature is a very well-known feature that is called inverted relief or geomorphology. The original dendritic pattern on top of the cuesta developed earlier during the development of the Central Arabian arch. It is the typical dendritic drainage pattern on the top of the Tuwaiq that extends eastward of the regional homocline of the Hanifah and Jubailah formations. All of these features are illustrated in Fig. 7, which is a model that summarises the original wadis flow before and after tectonic subsidence and the consequent geomorphic phenomena.

## Discussion

The landform and tectonic development resulted from the formation of the Central Arabian arch (Al Hinai et al. 1997), which was followed by the development of the Central Arabian graben and trough system (Hancock and Khadi 1978).

This tectonic history has broken the Tuwaiq mountain series into several dismembered mountainous areas. These ups and downs are separated by a textbook example of a graben and horst if only looking at the N-S cross-section view, where the topography varies in altitude from 450 to 1000 m (Figs. 4, 5, 6). However, the graben system is a more complicated system, as it curves and diverges in the west and is linked diagonally in the east into one regional transtensional left-lateral strike-slip fault. This west divergence and east linkage has left a v-shaped depression behind it that points towards the east. This depression falls under tectonic landform criteria of localized divergence with minor convergence along strike-slip system (Cunningham and Mann 2007; Fig. 8). Moreover, the development of this splay in the west suggests that the western part of the study area represents the damage zone area of the strike-slip fault and that the fault is at the termination mechanism westerly (Pratt 2012). Also, the transform faults in the intraplate settings and continental interior suggest a plate collision (e.g., Cunningham and Mann 2007). They represent escape structures in the hinterland of plate collision zones (Allen 2010). Thus, Central Arabia most likely represents the hinterland and this fault, together with other E-W strike-slip faults, represents the westward escape structures of the Mountain Zagros thrust belt that resulted from the collision between



**Fig. 8** Block diagrams showing interpretation of the localized divergence and convergence features along the Drumah-Nisah-Sahba strike-slip system (A–D), modified after Cunningham and Mann (2007) and Vaslet et al. (1991)

the Arabian and Eurasian plates. Consequently, the Arabian plate was divided and the EAB micro-continent developed and is holding the most important oil fields in the world (Fig. 1).

Moreover, the dip-slip tectonic features in the study area may also fit the tectonic features associated with strike-slip fault regions, reported by Cunningham and Mann (2007). For example, the Bu'ayja and Rufa'a grabens fit with the paired bend bypass fault; thus, their apparent effect they have on the Tuwaiq, Arab and Sulaiy formations is the vertical displacement (Fig. 8C). The Mugarah graben occurs in the central part of the fault and displays Tertriary rock bounded by late Cretaceous rock. This suggests both vertical and horizontal displacement (transtensional tectonics), as well as dilational stepping over of the Bu'ayja, Rufa'a and Nisah grabens (Fig. 8B). The Nisah, Awsat and Ujman grabens are stepping over each other and the younger Cretaceous rocks are bounding the older Jurassic rocks, which suggests that these are also transtensional features (Fig. 8D). However, some softer rocks have developed a double restraining bend in the middle of the graben, as suggested by the Sulaiy Formation (Fig. 8D). The western part of the depression has an eastward-pointing arrowhead depression; therefore, with the presence of the transtensional tectonics, it is interpreted as a transtensional horsetail splay with a negative flower structure (Fig. 8A, B). Thus, these features confirm that the fault is in the termination mechanism of the changing style extensional tectonism in the central part of Arabia, because it cannot penetrate further towards the west, especially due to the Red Sea's active rifting.

## Conclusion

The results obtained show how radar imagery contributes to the detection of the different geomorphic features of the south Riyadh region. Based on the geomorphological interpretation and analysis of the radar imageries, it can be said that the quaternary drainage system was cross-cut by Central Arabian grabens and strike-slip faults. New drainage systems have developed following the last tectonic event, and the wadis at the bottom of the Nisah and Awsat grabens currently accommodate all hydrologic waters coming from the west and pour them into the Sahaba segment towards the east. These recently developed valleys have formed a parallel drainage pattern that overprints the older centripetal pattern. In terms of flash flood hazards, the current wadi system has no effect on Riyadh City, but it could affect Al-Kharj City. Thus, urban planning in the area should consider the recently developed relief and drainage pattern as a geohazardous area to protect people and their assets and should avoid the graben system and the banks of their valleys.

In terms of tectono-geomorphic development, the Interior Homocline developed the N-S aligned cuestas of the Jurassic rocks of Tuwaiq Mountain, which is bound by subsurface vertical faults during the development of the Alpine-Himalayan orogeny, where Cretaceous rocks form N-S features, such as the Binban and Jabal Al Jubail anticlines, that are fault-related folds. The cuestas and anticlines are topographically high and control the sub-parallel drainage patterns of Wadi Suliy and Wadi Hanifah. West to east dendritic wadis above the cuestas have been established and they act as tributaries to the main N-S wadis. The N-S cuesta system in Central Arabia in the study area was regionally folded by the E-W central Arabian arch, which is plunging towards the east, followed by the central Arabian transtensional system. As a result, a new depressional area has developed, with it receiving the southward and northward valleys that pour into the Al-Kharj rural area from the Riyadh area and from the Al-Hawtah area in the south and forming a centripetal system. This has shaped a recently developed eastward river system that crosses the entire region towards Al-Kharj City, and the Al-Mikhlaif and Bu'ayja valleys are considered to be river catchment features within the two horst areas. The growth of the Central Arabian transtensional system developed the horsetail transtensional area and negative flower system that hosts the horst and graben system. The study area in the Tuwaiq Mountains has been affected by the Sahaba strike-slip fault at the terminating mechanism that forms a series of grabens and horsts.

**Acknowledgments** The Deanship of Scientific Research (DSR) King Abdulaziz University funded this project for its financial Jeddah, under Grant No. (DF-615-125-1441). The authors, therefore, gratefully acknowledge DSR technical and financial support. Thanks to the European Space Agency (ESA) for providing us with SAR images of the ERS and ENVISAT satellites as part of a research project (No. 28248). The work is based on the exchange of experience between three universities (the Department of Geography and Geographic Information Systems, King Abdulaziz University, Geology Department, Taibah University, and the Physical Geography Laboratory of the University of Paris and University of Paris-Est).

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