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Neotectonic indications of Al-Shihaby fan on Iraqi-Iranian borders

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ABSTRACT

Al-Shihaby alluvial fan is considered a significant and major geomorphologic phenomenon that evolved on the east side of Mesopotamia. It is located in the Wasit Governorate, near the Iraqi-Iranian borders. The fandom's dominant trend is southwest-northeast. This study aims to enhance our understanding of the indications and continuity of the fan's neotectonic activity. To reach this aim, we used software such as Arc GIS, Global Mapper, and Surfer, in addition to using data from USGS to identify the stages of the fan. A merging of spectral bands (composite bands), a contour map, and longitudinal and transverse topographic sections were done to analyze and interpret the neotectonics of the study area. This study concluded that the fan has passed through five stages in different periods and that its continuation to the present indicates that the fan is still active. These five stages recognized within the fan belong to the Pliocene- Late Pleistocene age range. Each stage is a breakpoint in sedimentation, and when tectonic activity occurs, the next stage begins. Besides that, the study concludes that the elevation range of the area from the cross sections is from 15 m in the southwest of the area to 120 m in the northeast above sea level from the elevation map derived from the DEM file. Besides that, the increase in sediment thickness on the western side of the fan compared to the eastern side, which belongs to the streams on the west side of the fan, in addition to the deposition of the alluvial fan, was related to the Mandali-Badra-Amara Faults (Zagros Front Fault (ZFF)) and its activity, as well as the relative uplifting of the Hemrin structure versus the subsidence of the Mesopotamia Plain.

1. Introduction

Al-Shihaby fan represents an important fan in Wasit Governorate in Iraq, where it is situated in the low folded zone on the eastern portion of the Mesopotamia Plain (Fig. 1) (USGS, 2004), with coordinates of 32°50′ to 32°56′N and 46°05′ to 46°40′E, close to Iraqi-Iranian borders. The region is bordered on the east by the Iraqi-Iranian borders and on the west by the Tigris River in Sheikh Saad. The fan basin extends inside Iranian territory for more than 43 km. It stems from the western Iranian highlands, specifically from the Koh Kabir Mountain, which is an extension of Hemrin with an area of 455 km^2, all within the Iranian borders (Al-Akkam, 2008). The study area represents the extreme margin of the low folded zone located between the High Mountain and Mesopotamian Plain provinces of Iraq (Yacoub et al., 2012; Al-Shwaily and Al-Obaidi, 2019).

Different studies have been carried out concerning fans in the region in general and the Shihaby alluvial fan in particular.

A study was made for the microearthquake in Badra, east Iraq, by Al-Shukri (1976), which was conducted during the period from November 1975 to March 1976.

Buday (1980) clarified that the foothill zone is a division of the unstable shelf (the low folded zone). It includes two longitudinal units: the Makhul-Hemrin in the southwest and the Butmah Chemchemal in the northeast.

Domas (1983) prepared a report for the modern classification of the quaternary deposits and geological mapping of the Karbala- Al-Kut- Ali Al-Gharbi areas.

Yacoub (1983) studied the alluvial fans of the Mandali-Al-Fak'ak area and divided them into five stages.

Azhar (1985) studied the landforms from satellite images and drew a map of the area.

Hasan (1985) prepared a report that involves interpretations of the regional photogeological and geomorphological mapping of the Mandali, Badra, Zurbatiyah, Sheikh Fars, and Al-Tib areas.

Harvey (1990) studied the AL-Shihaby Fan, which involves several factors in its development and growth. Still, several factors stood out clearly and were greatly relied on by the fan that led to its development and reaching its current form, which is as follows:

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1. Evolution and growth of the fan based on climate change.
2. Evolution and growth of the fan based on the distribution of sediments.
3. The fan's development and growth are based on the stream's presence and migration to another place.

These factors are one of the rapid factors that depend on each other, as the second factor is related to the third in forming the fan.

Parsons company (1957) studied the hydrological aspects (groundwater), but the main attention was limited to water quality and validity.

Al-Lassi (1992) studied the Chabbab River basin in Iraq and its investment, but the fan was not studied geologically.

Jassim and Goff (2006) showed that the Mesopotamian area was most elevated throughout the Hercynian movement, but it began to decline in the late Permian period. In the eastern edge, the fold structures mainly extend northwest to southeast, while in the southern edge, the trend is north to south.

Sissakian (2006) studied in Al-Kut Quadrangle a series of geological hazard maps of Iraq. According to this study, the geomorphological units developed in the area are structural-denudation, alluvial, and aeolian units.

Al-Akkam (2008) pointed out the factors affecting the formation of this fan, which are three main factors: The geology, which is represented by the unstable tectonics of the region due to the continuous rise of the mountains, as well as the type of formations and rocks and their ability to resist erosion, the climate directly or indirectly, and the hydrology are represented by surface water, which is the only means of delivery of sediment and materials to the fan.

Yacoub (2011) described the alluvial fans in the Mesopotamia Plain.

Sissakian and Al-Jibouri (2012) gave a general description of the alluvial fans within the Low Folded Zone.

Bahrami (2013) explained the factors that influence the geometry and progress of fans, such as tectonic activity, climate, gradient, and lithology.

Al-Hussaini (2013) showed the geomorphology and sedimentology of alluvial fans in the Wasit area with the assistance of image data.

Al-Akkam (2014) pointed out that the fan has taken two directions in development: the first is an internal development and represents all the additions to the surface of the fan from the thickness of the fan or increasing its area; the second is the external development, which represents the construction of an integrated fan outside the boundaries of the original fan.

Sissakian et al. (2014) described the alluvial fans in the High Folded Zone.

Abdulnaby et al. (2016a) mentioned that along the Badra-Amarah fault, which is the southern part of the Makhul-Hemrin fault, from Badra in the northwest to Amara in the southeast, alluvial fans have formed on the eastern part of Mesopotamia.

Sayl et al. (2017) used the GIS-SRTM approach to enhance the area, volume, and elevation curve for rainwater collection in dry areas.

Sayl (2018) identified suitable dam sites and assessed current land degradation using combined remote sensing (RS) and geographic information system (GIS) approaches to look for changes in the land surface.

Mahmoud et al. (2018), from a topographic point of view, studied area descends in relief from its NE part, where the mountainous area exists, towards the west and southwest parts, where alluvial fans and sheet run-off areas are well developed.

Al-Musawi et al. (2019) pointed to the segmented alluvial fans alongside the Hemrin South Anticline to show neotectonic activity by studying the quantitative analysis of the geomorphological indicator of the area.

Al-Sahlani (2020) studied the morphotectonics of middle and southern Iraq using geomorphometric analysis and remote sensing methods to gain information about dynamic tectonics by studying elected alluvial fans in the Mesopotamia Plain.

Most previous studies have reached many conclusions related to the topography, hydrology, depositional system, and the development and

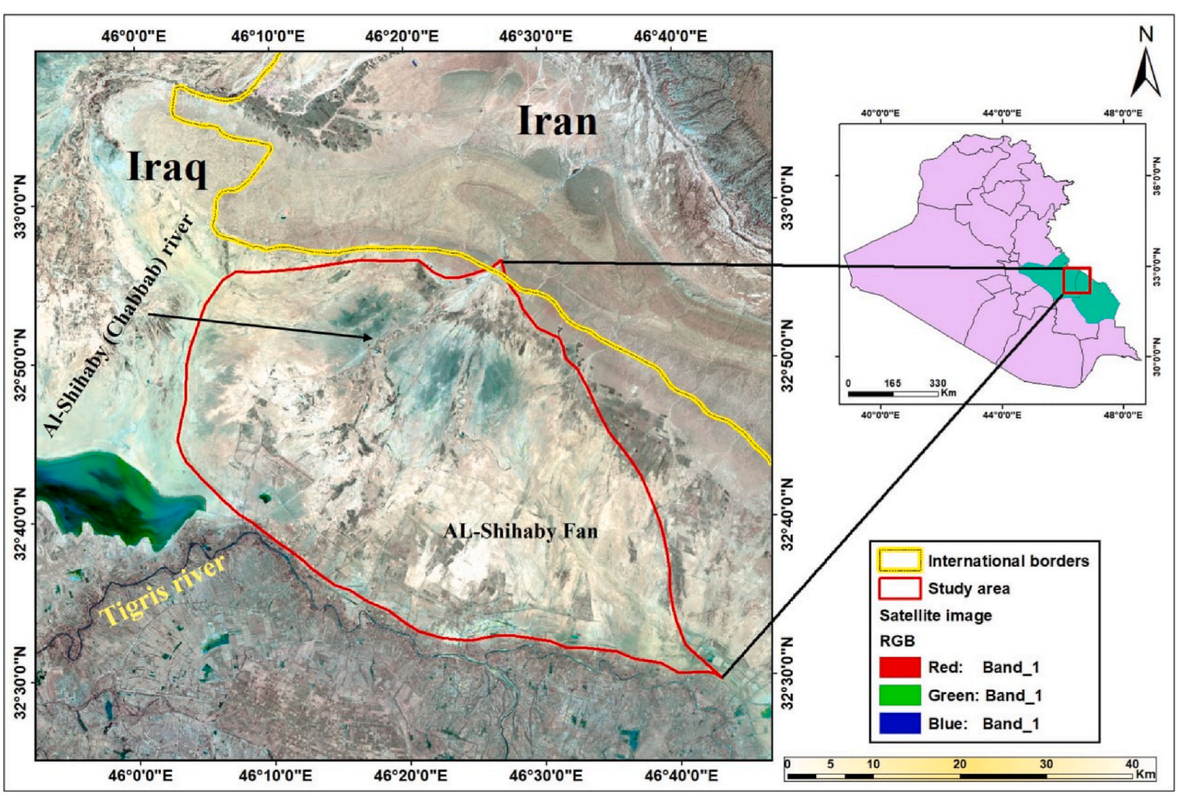

Fig. 1. Map of study area location (Landsat 9 OLI, RGB: 742) (prepared by the authors).

growth of the fan. All these studies did not deal with the structural and tectonic aspects that the region has gone through, hence this study, which focused on the structural and tectonic side of the area and the continuity of neotectonic activities in it, which had not been studied previously for this region.

Mohammed et al. (2022) developed a groundwater recharge model by utilizing remote sensing (RS) and geographic information systems (GIS) to determine the locations and amounts of recharge needed to maintain a healthy groundwater system in the Western Desert of Iraq. Mohammed et al. (2023) show groundwater demarcation has been effectively achieved with the application of contemporary geospatial tools, such as the use of geographic information systems (GIS) and remote sensing (RS) data, in conjunction with multi-criteria decision--making (MCDM) methodologies.

Sameer et al. (2023) studied the purpose of counting sedimentation on different spatial scales; a geographic information system (GIS) can provide useful information.

This study intends to improve our knowledge of the indications and continuity of the fan's neotectonic activity in the study area. To achieve this aim, we used many software programs, such as ArcGIS V.10.4.1, Global Mapper V.22.1, and Surfer V.21, in addition to DEM and Satellite Image. We have tried to assume the neotectonic activity of the fan by identifying the fan stages (breakpoints) by analyzing satellite images, drawing the thematic map, and drawing the sections that pass through the fan. To gain a better understanding of the study area's neotectonic activity, a comprehensive interpretation of sections was achieved.

2. Research software and methodology

2.1. research software

Many software programs were used to achieve the aims of the study, as follows:

1 Satellite images and DEM.
2 Various image processing software is used, such as ArcGIS V.10.4.1, Global Mapper V. 22.1, and Surfer V.21, to process and analyze satellite images and draw the thematic map
3 Tectonic map, scale 1:1000000 (modified after Fouad, 2012a,b) to identify the structural elements located in the study area, especially folds and faults.
4 Geomorphologic Map, scale 1:1000000 (modified after Hamza, 1997) to identify more details about the alluvial fan morphology. For more details, note Table 1 and 2 and Fig. 2.

2.2. methodology

The study area is considered a border area between Iraq and Iran, and it is a former arena of military operations. The area is full of mines, so there was difficulty in obtaining maps and information from government departments. This is also one of the important reasons for the use of satellite images and GIS information systems, which made it easier to obtain maps and thereby more easily increase the information received about the region.

The data of satellite images used in this study include (1) one scene of the Landsat 9 OLI satellite image, which was obtained on 4/5/2023, and two zones of the Space Infrared Topographic Survey data (DEM) with a resolution of 12 m, which was acquired on 30/6/2006. These data were obtained by downloading from the Earth Explorer (USGS) webpage and Earth Data (ASF), respectively.

Table 1
The software use in this study.

No.	The software	The task
1	ArcGIS V. 10.4.1	Process and analysis of satellite images; thematic map preparation; and measuring slope.
2	SURFER V. 21	Process and analysis of digital elevation models and counter maps.
3	GLOBAL MAPPER V.22.1	Process and analysis of digital elevation models; topographic and cross-section profiles.

Table 2
The abbreviations used in the methodology of this study.

No.	The abbreviation	The words
1	GIS	Geographic Information Systems.
2	OLI	The Operational Land Imager.
3	DEM	Digital Elevation Model.
4	USGS	United States Geological Survey.
5	ASF	Alaska Satellite Facility (ASF data search).
6	RS	Remote Sensing.
7	SWIR	Shortwave Infrared Band.
8	RGB	Red, Green, and Blue.

The digital processing of satellite images yields many data points about image features. RS and GIS techniques allow for the same georeferencing technique to be used for the integration and analysis of nonspatial, multispatial, geological, and structural maps. Therefore, it could be more instructive to integrate GIS and remotely sensed data applicable to image interpretation. Besides, advancements in image study provide geologists with the chance to improve, influence, and mix digital remotely sensed data with various types of geographic data, which in turn increases the amount of extracted data correlated to topographic and geologic features (Figs. 2 and 3) documents the stages of the study methodology. A geographic information system (GIS) can offer useful information to count sedimentation on different spatial scales (Sattar et al., 2024).

Thematic maps (tectonic and geomorphologic) with DEM and satellite images were used to identify the five stages of the fan. GIS techniques were used to interpret and study the details of the study's geomorphologic unit area. Various images processing software, such as ArcGIS V.10.4.1 has been used to implement the data, e.g., color composite bands and stages of the alluvial fan. Global Mapper V.22.1 was used to draw topographic cross-sections. The Surfer V. 21 was also used to derive topographical contour lines.

In addition to the above, the work steps can be summarized in three stages, which are:

1 Merging spectral bands (composite bands) is an important step in analyzing spectral images and extracting different spectral information. The bands (SWIR2, red, green) were combined to obtain the color combination (7, 4, 2) using Landsat 9 OLI images (30 m).
2 A contour map with a contour interval of 8 m was created in Surfer V.21, using DEM data (12 m). Surfer V. 21 provides many tools for creating and customizing contour maps accurately and efficiently. Through the map, the highest and lowest levels of the alluvial fan (the study area) were determined.
3 In the Global Mapper V.22.1, cross-sectional and longitudinal topographic sections were drawn using DEM data (12 m), which reflect the tectonic influence that the region witnessed, represented by the emerging stages of the alluvial fan.

3. Geological setting

The region's geological history started in the Miocene Period (Middle Miocene) when Tethys was partially buried at the end of the Oligocene Period beneath a semi-enclosed basin. Following its return, the Tethys flooded the region, and the extension tended to create basinal deposits in the Miocene in the study area as well as in southeast and northwest Iraq (Al-Janabi and Ghalib, 1982).

In general, the stratigraphy of Iraq is strongly affected by the structural position within the main geostructural units of the Middle East and by the structure of the country itself. The Arabian Plate is considered a

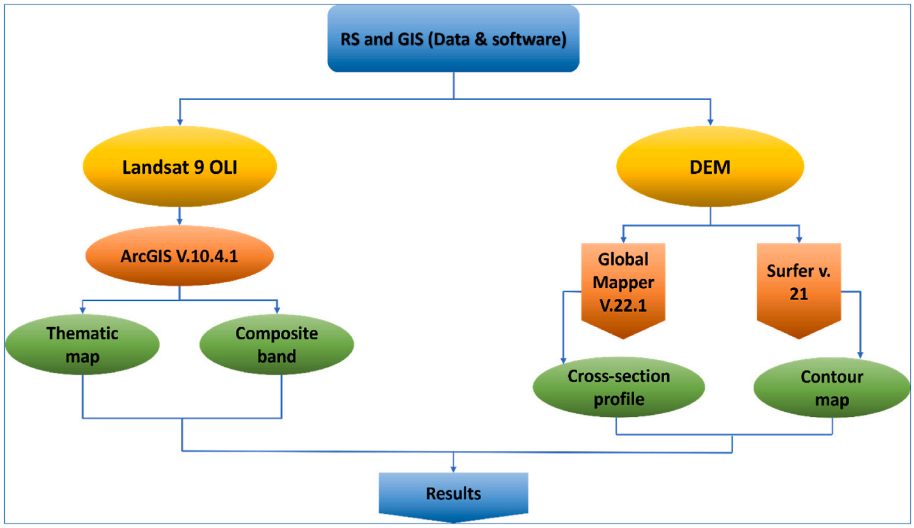

Fig. 2. Flow chart of study steps.

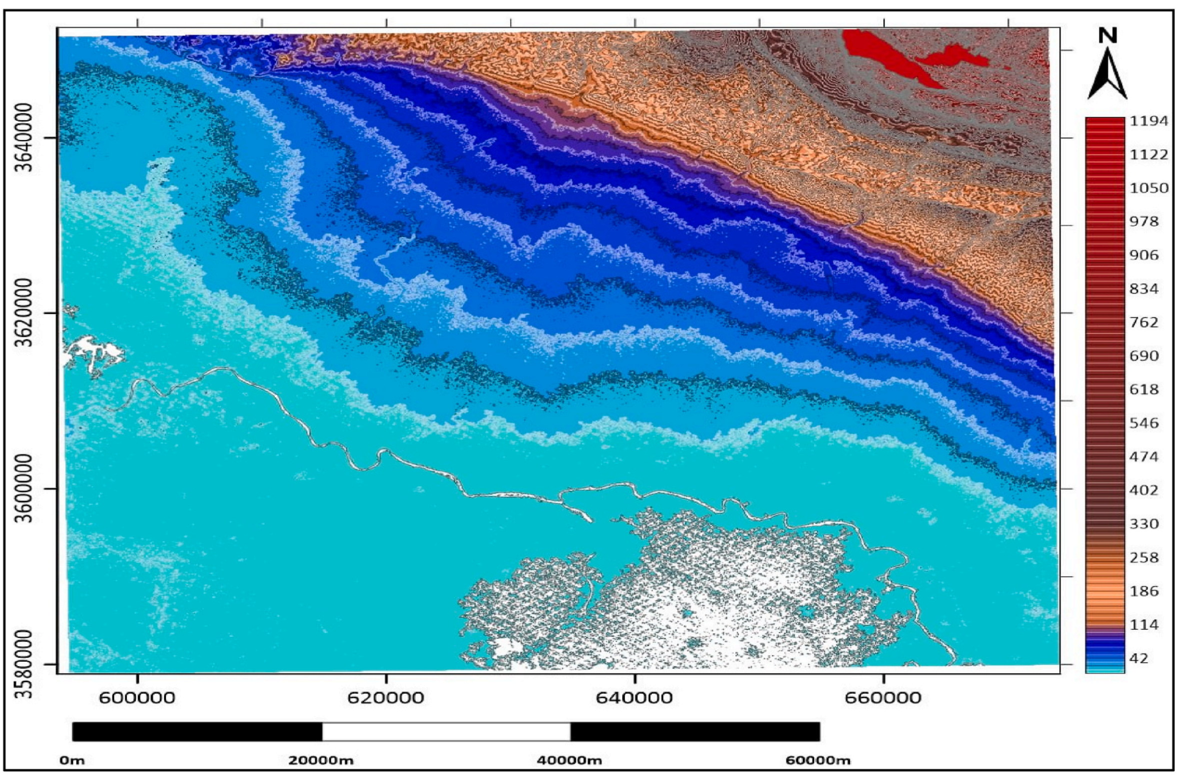

Fig. 3. Contour map of Al-Shihaby Alluvial Fan (DEM, 12 m) (prepared by the authors).

large plate, which Iraq forms on its northern and northeastern edges. It is limited from the north and northeast by the Taurus and Zagros Mountains (Deikran, 2003). Stratigraphically, there are two main stratigraphic units in the study area: pre-quaternary and quaternary deposits. The first unit was exposed on the east side of the area, extending to the northwest-southeast as the major structure of the Hamreen range and extending farther to the east in the Iranian regions. The sediments were described at several documented sites located far from each other. The second unit was deposited and situated near the contact with Quaternary (Yacoub, 1983).

The general topography of the study area was represented by the elevation map, which was derived from the DEM file. The elevations range from 15 m in the southwest of the area to 120 m in the northeast above sea level (Figs. 3 and 8).

Mahmoud et al. (2018) mentioned the main geomorphological units in the study area, which are: The first one is units of structural-denudational origin, which include fault escarpments, hogbacks, and questas. The second are units of fluvial origin, developed as numerous alluvial fans, Khalaf (2022) referred to the geomorphological features that are present in the area, such as Structural units represented by the homoclinic structure features are developed in the study area when rock beds vary in their resistance to weathering and erosion, such as hogbacks and questas. The major difference between the two features is related to the steepness of the dip. The hogbacks are sharp-crested ridges that develop where the rock dips are steep, roughly over 45°. The questas develop where beds dip gently or moderately, roughly less than 45°. Hogbacks and questas are common in the high-folded and foothill zones (Hamza, 1997) (Fig. 4).

Fluvial origin units are represented by alluvial fans. Floodplain units are formed by rivers. The geomorphological features are shown in more detail in Fig. 4, which was modified after Hamza (1997), where compiled the geomorphological map of Iraq at a scale of 1: 1000 000 and presented the main alluvial fans in Iraq in addition to the fact that the anticlinal ridges of the foothill zone are better preserved than the ridges of the high-folded zone. The reason for that is the low relief, less disturbance by tectonic forces, and probably the absence of ice sheet cover during the Pleistocene. The study area is characterized by hilly terrain in the eastern and northeastern parts and gently sloped terrain in the southwestern parts. In addition, the area is crossed by two main valleys, the Badra and Chabbab Rivers, from north to south of the alluvial fans. The geomorphologic development in the study area is controlled basically by structure and lithology.

The research area is tectonically between the Mesopotamian Zone (Tigris Subzone) and the Foothill Zone (Makhul-Hemrin Subzone).

Buday (1980) showed that the stable shelf's easternmost unit is called the Mesopotamian Zone, and it is subdivided into many subzones: the Tigris, Euphrates, and Zubair. The portion of the unsteady part is low-folded and represented by the foothill zone. The subzones of Makhul-Hemrin in the southwest and Butmah Chemchemal in the northeast comprise its two longitudinal units. According to Al-Kadhimi et al. (1996), who divided Iraqi territory into three main tectonic regions, within the foothill zone of the Unstable Shelf region, the Hemrin subzone lies where the study area exists. Though it subsided in the late Permian period, the Mesopotamian Zone was elevated throughout the Hercynian movement (Jassim and Goff, 2006).

During the Mesozoic, the area was influenced by tension forces; during the Cenozoic, compression forces were applied. Some surface and subsurface morphological features resulting from tectonic movements, the salt structure, and basement rocks (uplift) emerged as a result of these different impacts (Darweesh et al., 2017).

Structurally, the Mesopotamia Plain is an extremely mobile zone that involves many main structural elements that are recorded in the study area and involve many tectonic structures: folds, diapiric structures, and faults. The tectonic features are noted in more detail in Fig. 5, which was modified after Fouad (2012a,b).

3.1. Folds

Many folds can be distinguished in the region and may be surface or subsurface, including Badra anticlines, Hemrin anticlines, and Kani

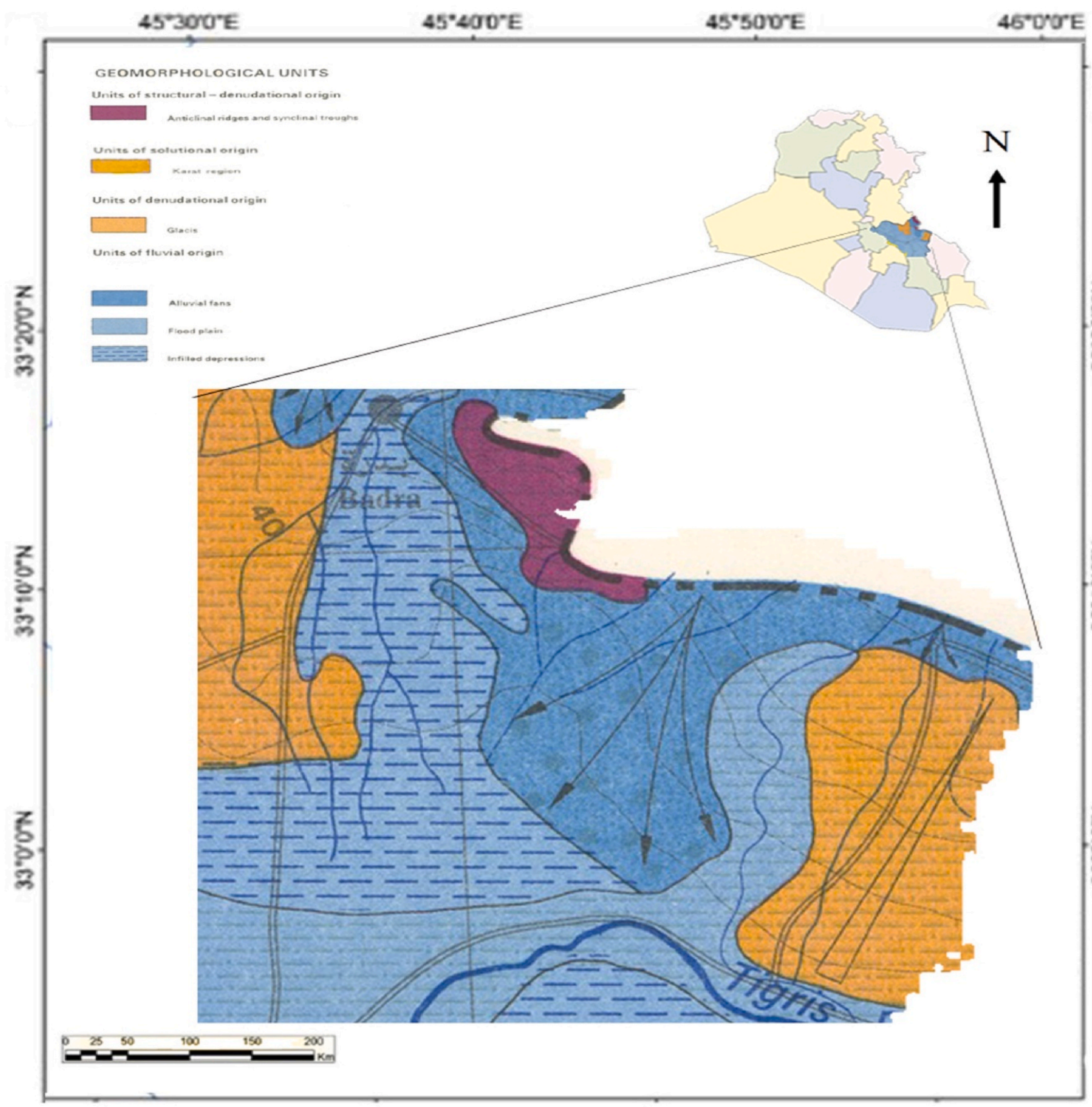

Fig. 4. Geomorphologic map of the research area (updated after Hamza, 1997).

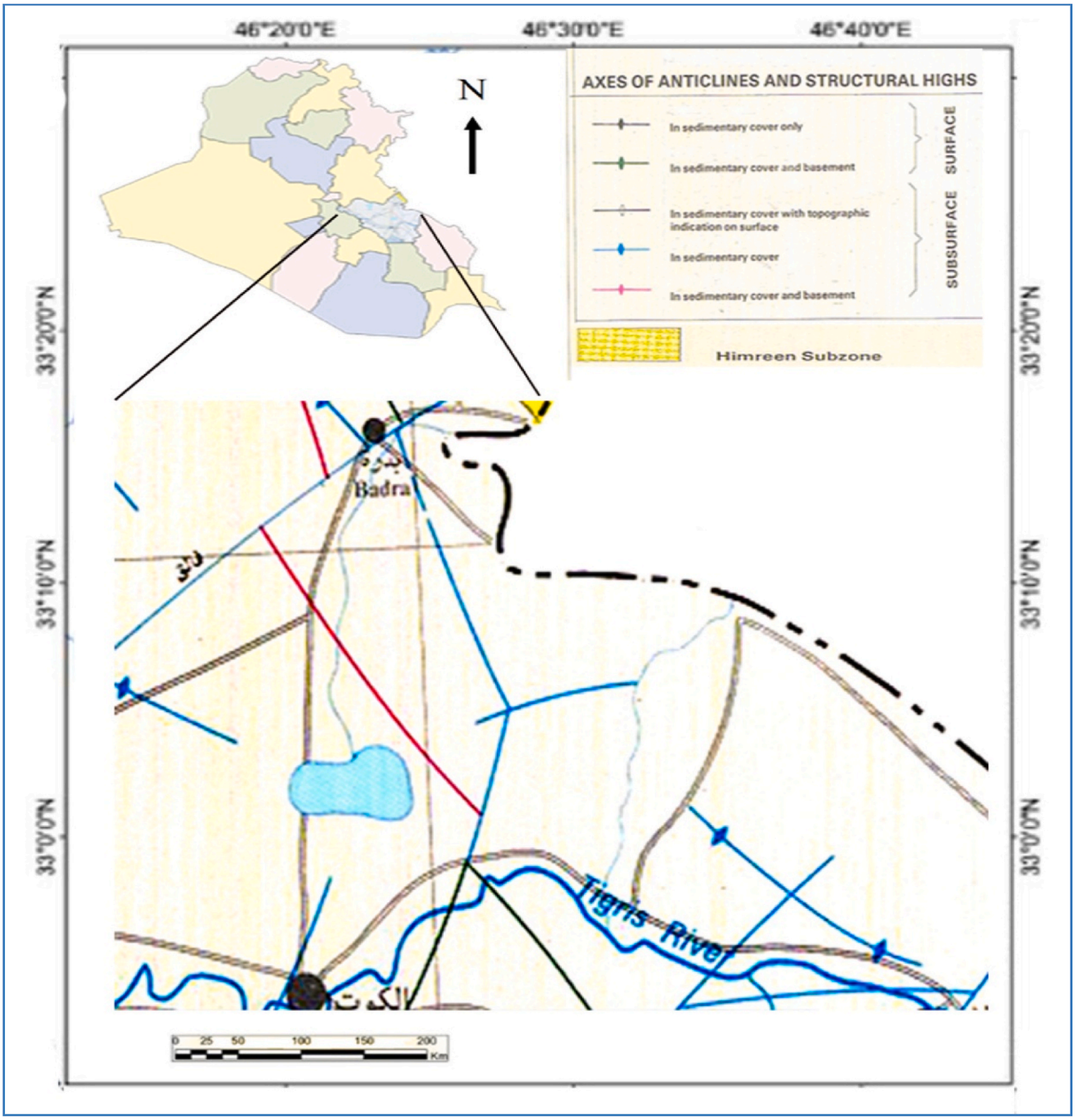

Fig. 5. Tectonic map of the research area (updated after Fouad, 2012a,b).

Sakht anticlines. Fold structures primarily follow an NW-SE trend in the eastern portion and an N-S trend in the southern portion of the zone (Jassim and Goff, 2006). Numerous of the subsurface structures are neotectonically dynamic. Their current action can be recognized due to its impacts on the present geomorphological landforms and the Pleistocene-Holocene strata (Fouad, 2010).

The Anticlines of Badra are located southeast of Mandili near the boundary and relate to the maintenance of the Hemrin anticlines (Al-Kadhimi et al., 1996).

Hemrin Anticline is in its current shape as the result of one of the various thrust faults that propagated from the most important Zagros mantle fault. This fault is viewed as the prime structure that generates all the branching thrusts in the foreland direction in such a trend as a deep-rooted trailing imbricate fan thrust system (Al-Janabi, 1996).

Kani Sakht Anticline is approximately 30 km long and varies in width up to 1.5 km, situated on the eastern edge of the Hemrin growth. It is a narrow asymmetrical fold, and the NWN-SES trend is seen. The southwestern limb dips between 400 and 650, whereas the northeast limb dips between 470 and 520 (Al-Shwaily and Al-Obaidi, 2019).

3.2. Faults

There are major thrust faults exhibiting the Northwest-Southeast trend that have developed in the study region. Kachaa Cea Koran, and Koolic; two major longitudinal faults (Makhul-Hemrin and Tikrit-Amara faults); and two major transversal faults (Kut-Dezful Fault) in addition to Mandali-Badra-Amara faults.

The Makhul-Hemrin fault extended all over the Iraqi boundary from the middle of the country, traversing the Makhul and Hemrin folds before ending at the cities of Badra and Amarah. It creates the division between the folded zone and the unfolded zone, or Mesopotamia. According to Jasim and Goff (2006), the Mandali-Badra-Amara faults are part of the Makhul-Hemrin longitudinal fault (also called the Zagros Fordeep Fault of the ZFF). During the Pliocene this fault was reactivated and continuing to be active nowdays. The path of the Badra-Amarah fault is distinct from that of the Makhul-Hemrin listric fault (Abdul-naby et al., 2016a).

The Kachaa Fault is 25 km long, the **Cea Koran Fault** is 25 km long, and the **Koolic Fault** is 12 km long. These faults stretch perpendicular to the international boundary between Iraq and Iran (Al-Shwaily and Al-Obaidi, 2019).

The Mandali Badra Amara Fault is situated along the border between Iraq and Iran on the northeastern side of the Mesopotamian sagged basin. They stretch from Mandali City to Amara City, passing through Badra City. The fault is roughly 200 km long, though it might stretch farther. The fault is identified by the alluvial fans in the northeastern part of the Mesopotamian Zone (Abdulnaby et al., 2016a). Abdulnaby et al. (2016a) also pointed out that the Dezful Embayment in Iran and the Mesopotamian Zone in Iraq are separated by the Badra-Amarah fault.

The Najd Fault System (Northeast-Southwest trending), the Transversal Fault System (Northeast-Southwest trending), and the Nabitah Fault System (North-South trending) are examples of trending fault systems. During the Nabitah Orogeny of the Late Precambrian, these fault systems were created (Jasim and Goff, 2006).

4. Results and discussion

4.1. Characteristics of Al-Shihaby Alluvial Fan

The eastern margin of the Mesopotamia Plain is characterized by an

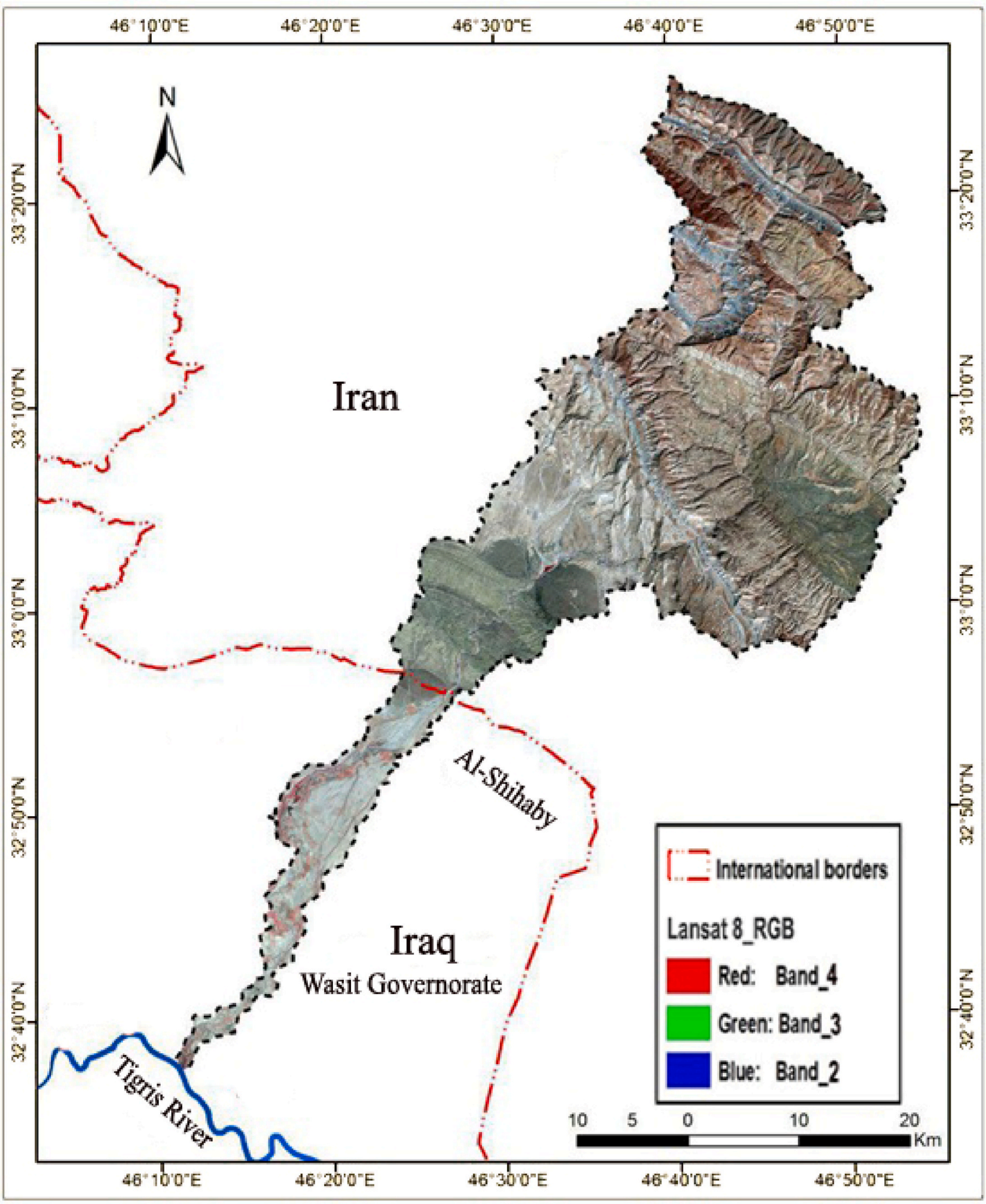

Fig. 6. Al-Shihaby Valley Basin (Landsat 8 OLI, RGB: 432) prepared by the authors.

alluvial fan system alongside the foothill slopes, especially reaching through the north of Mandali, in the northwest, to the north of Amara, in the southwest. Al-Shihaby fan is a principal geomorphic feature that emerged on the Mesopotamia Plain's eastern portion.

Yacoub (1983) demonstrates how the alluvial fans are creating a constant Bajada belt. In actuality, the area of the catchment and associated stream determine the size of the alluvial fan. Generally, the fans' surfaces are level and slightly slope from the apex to the flanks.

Al-Shihaby basin is one of the young basins with steep slopes capable of supplying rivers with a high density of sediments. Besides that, every catchment associated with the alluvial fan system in the research region is situated beyond the boundaries of Iraq (Al-Akkam, 2008) (Fig. 1). Their streams and valleys emanate from Zagrose Mountain to provide water as well as sediment to the fans, such as the Al-Shihaby River (Al-Chabbab River). Al-Shihaby Valley Basin (Fig. 6) (USGS, 2016) is one of the basins shared between Iraq and Iran. The part located within Iraqi territory includes the administrative borders of the Wasit governorate. The mainstream of the basin descends from the Iranian Koh Kabir Mountains, located at the eastern border of Iraq. The stream passes through several villages on both sides of the river. This valley collects a lot of water from the Highlands coming from Iran, especially in winter, the peak of precipitation, where it supplies water to the areas through which it passes and participates in supplying the Tigris River with water in the rainy season. There is no discharge in the summer, Al-Shihaby valley is 102 km long, and the maximum height of the valley is 2790 m at the headwaters, while its height at the mouth is 5 m above the sea level. The area of the valley is about 1454.93 km^2 (Al-Akkam, 2018).

Al-Shihaby fan is distinguished by the presence of two types of drainage: braided channels and single channels. The braided channel is confined to the right part of the fan, as the main channel of the fan is on this side. As for the single channel, they are found at the left part and the center of the fan. Most of the single channels have an unknown end, and the single channel abandons its location from time to time, leaving a good area of recent sedimentation. The fan was developed from large catchments and large feeder channels where it has multiple feeder sources.

The geometry of the fan is: the area of the fan is very large; the total area of the fan is 1850 km^2; the slope is 2°-5° with the fan shape and active (Al-Hussaini, 2013). The area and slope are measured using the Arc GIS program, which assumes slopes and gradients (elevations) (Figs. 3 and 8).

The fan was deposited next to the mountain front; the general alluvial fan shape can also provide insight into the tectonic activity pattern at and around a mountain front (Fig. 7). Using the region's DEM images, two cross-profile segments (yy', xx') are depicted in Fig. 8 using the DEM imagery of the region. The attributes of geomorphology for the Shihaby Alluvial Fan are:

The longitudinal profile (yy') in Fig. 6 shows the five stages of the fan and the fan's abrupt, where the abrupt decreases from the apex to the toe. This is further evidence that the fan has undergone five stages of uplifted activities on the mountain front, and the action of faults in the study area, for example, the fault of Badra-Amara, comes from the slope's notable fractures, which denote borders between largely straight-line fan segments.

That signifies that during the growth of the fan, the area observed several uplift periods that corresponded with the ongoing Alpine Orogeny to the present. The development of the phases, which is a sign of its activity due to the frequent earthquakes that occur along the east

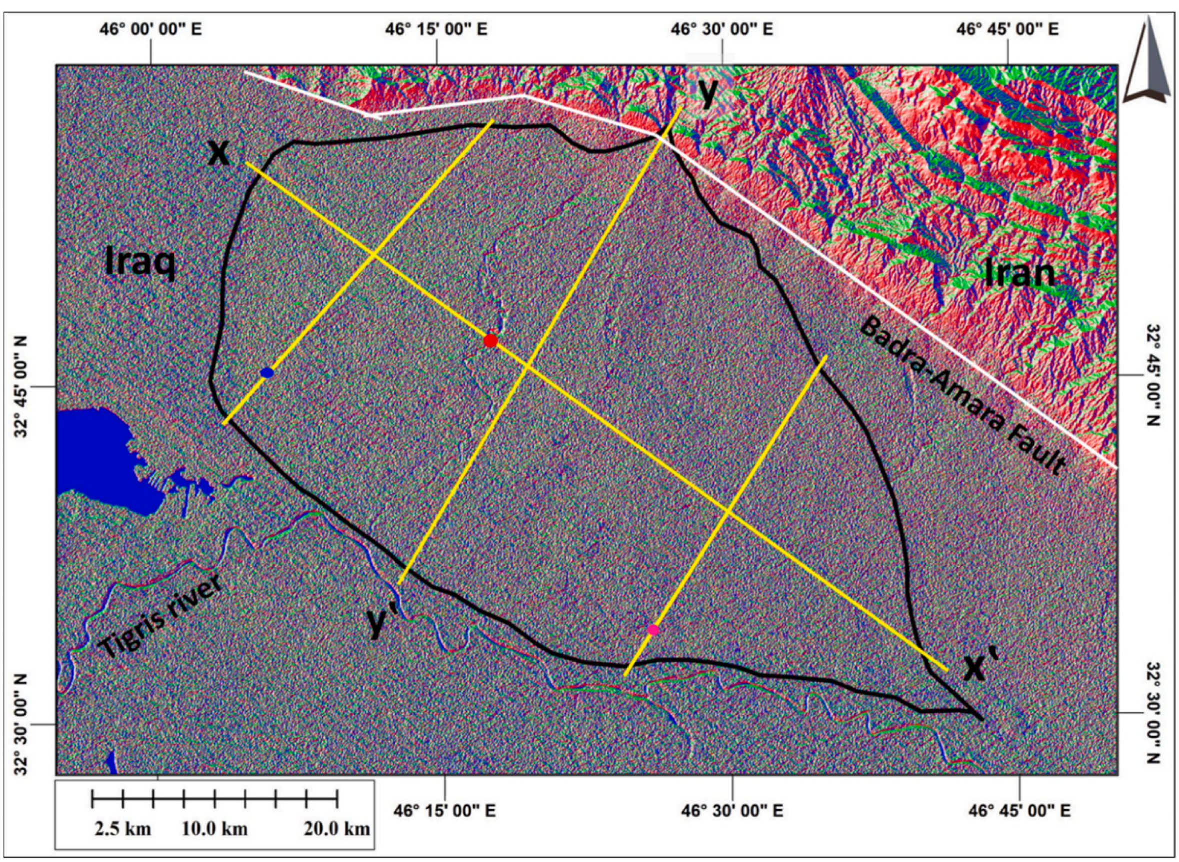

Fig. 7. The study area. (xx') is the longitudinal section, (yy') is the transverse section, (aa') is the right side section, and (bb') is the left side section. The red dot refers to the Al-Shihaby (Al Chabbab) valley. The red dot represents the mainstream feeding the fan, which is about 12 m in depth. The blue dot indicates one of the rivers that incision the fan's body, and it has a shallow depth of about 10 m. The pink dot indicates one of the rivers that penetrate the fan's body, and it has a shallow depth of about 4.5 m. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

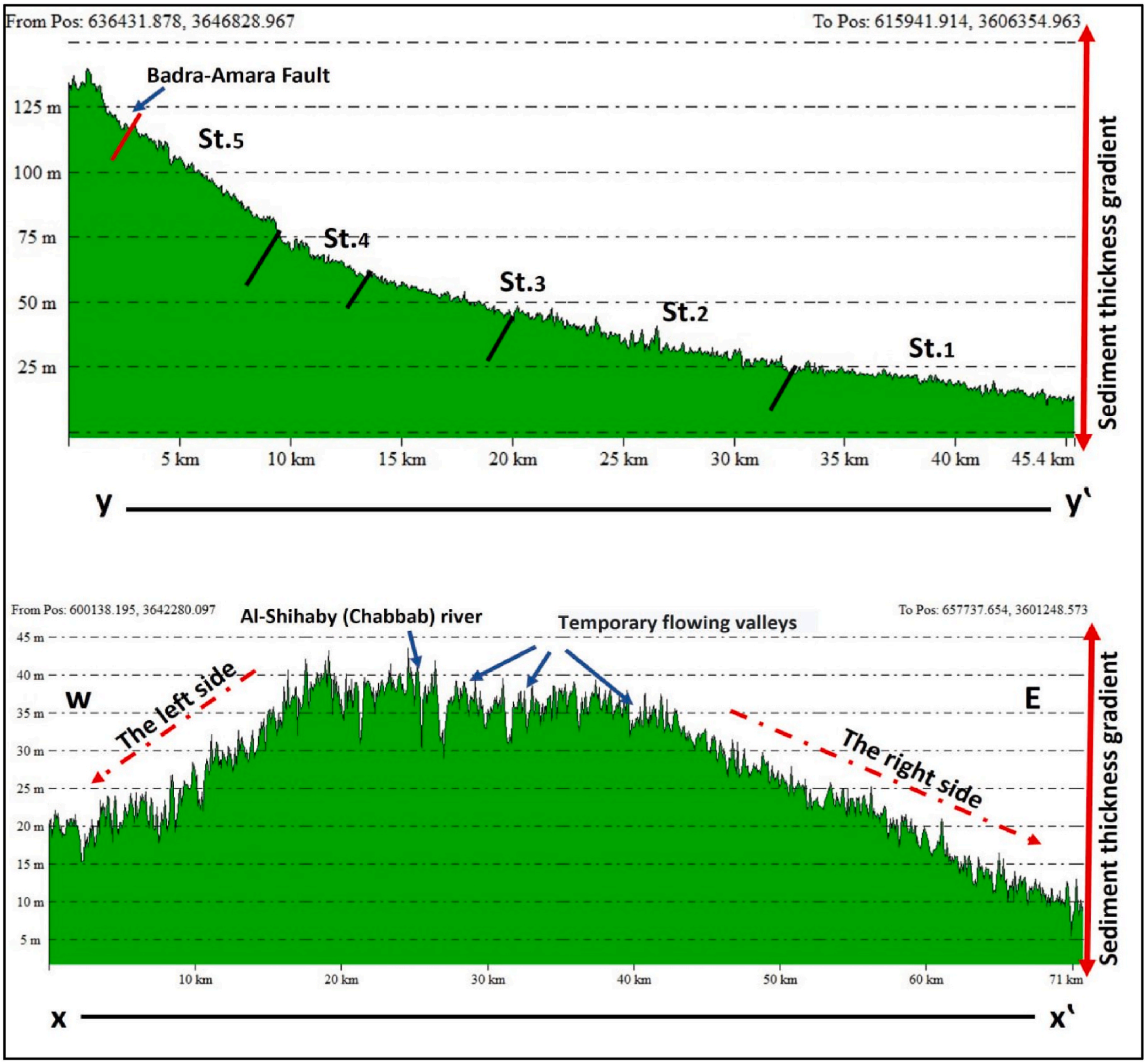

Fig. 8. Profiles of sections of the Al-Shihaby alluvial fan. The longitudinal section (xx') and the transverse section (yy') prepared by the authors.

side of the Mesopotamia Plain, is all that appears on the fan surface. As a result, the area is an active zone.

The profile's layout (xx') (Figs. 7 and 8) has a convex shape in the center of the Al-Shihaby fan, having two distinct edges. The south-southeast portion has a sharper slope than the other part, as shown in red in the arrows, which may be attributed to the thickness of the sediments that grew in the fan's southeast and middle. The Al-Shihaby fan is angled towards the southeast of the research region, which reflects the activity of the mountain front and is the best evidence of the neotectonic impressions on the Mesopotamia Plain's eastern edge.

The convex shape of the fan appears in the center, as the eastern border of the fan is inclined more due to the interference with neighboring fans in the area, as the fan is located in the foothills of the mountains, where the fans form the Bajada.

The study area is a plain of fans overlapping each other (Bajada), so there is difficulty in distinguishing between the boundaries of the overlapping fans. The study alluvial fan overlaps with Al- Teeb fan to the east and the Badra fan to the west.

The profiles' layouts (aa') and (bb') in Figs. 7 and 9, which are derived from the DEM file, show there are many streams incision the fan, which are temporary streams that depend on torrents that descend from the mountains in the rainy seasons and feed the fan with sediments. These streams are medium to shallow in depth. Moreover, these sections show that the deepest stream is 5 m on the east and 10–12 m on the west. All the above explains the reason for the increase in the thickness of sediments on the western side, about 70 m, compared to the eastern side, about 60 m, where the presence of deeper streams increases the amount of sediment that spreads the area. Increased sedimentation can also indicate low tectonic activity compared to the other side, which is less sedimentary and more active.

Furthermore, tectonic activity has also caused the minor streams to incise the fan surface and modify it; the highest deposition point in the fan core is up to 40 m. There are several carved channels on the fan surface, as seen by the profile's varying shape.

The development of the fan was divided into two directions: the first developed on the same fan area, which led to an increase in its thickness, and the second developed based on the expansion of the future area of sediments and took three aggregate forms moving away from the original fan depending on the volume of discharge (Al-Akkam, 2014).

The Al-Shihaby fan is developed into five stages; its areas are 1.8 km^2, 42.4 km^2, 45.4 km^2, 73 km^2, and 63 km^2, respectively (Al-Hussaini, 2013), as shown in Fig. 8. The five stages differed in terms of weathering, lithological variances, and geomorphic placements. The first stage represents the oldest stage of alluvial fan, and it was deposited at the start of the Pliocene-Pleistocene. The first stage was characterized by severe erosion, and it was formed after the formation of the Hemrin

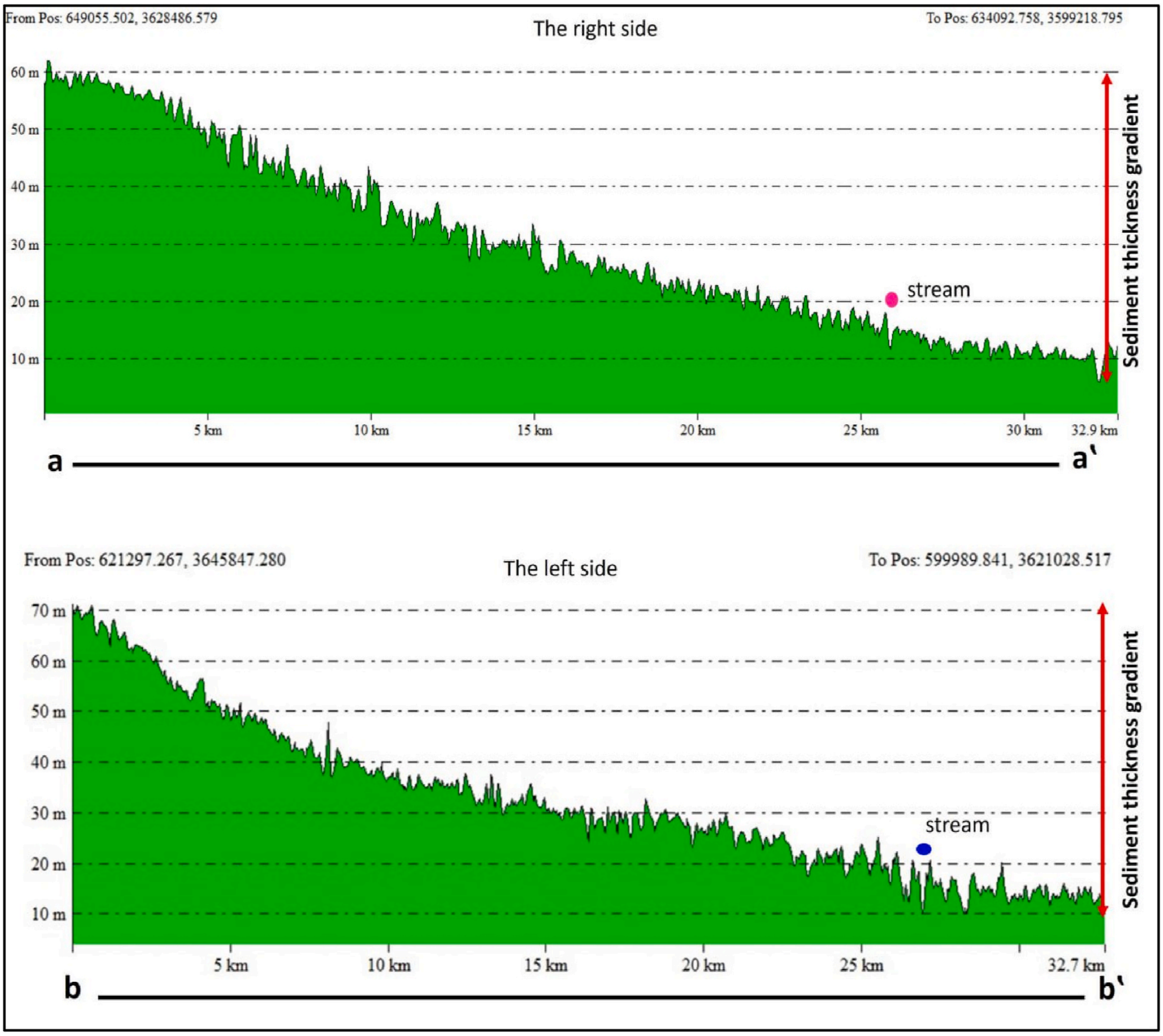

Fig. 9. Profiles of sections of the Al-Shihaby alluvial fan. The right side section (aa') and the left side section (bb') prepared by the authors.

Mountains.

At the foot of the first stage, the age of the second stage was assigned to the early Pleistocene, and it is well developed in the Zurbatiya vicinity. The second stage was characterized by being intermittent and cracked by the many rivers that pass through it.

The third stage was deposited in the Middle Pleistocene, and it was the most widespread and extensive stage. It was separated from the previous stage by clear morphological borders. This stage is widespread with respect to the early two stages, and a distinct gap between them denotes an erosion episode.

The fourth stage was deposited during the Late Pleistocene. In comparison to earlier stages, it is located toward the Bajada's periphery and is distinguished by softer surfaces and softer clastic deposits. This stage was the last stage that occurred in the Pleistocene, with radial water drainage, and it is represented by the current fan. Finally, the last stage, the youngest stage (fifth stage), was deposit, and deposits from large valleys and channels from the Holocene consist of minor fans and are considered the final stage of alluvial fans because they have multiple feeder sources. This stage was not very clear, and it was formed in the last dry period represented by the Holocene.

Slope breaks of a particular type divide these stages apart. Younger cycles erode the apical portions of the oldest layer, whereas the newest alluvial fans are largely intact. The geomorphic placements, lithological alterations, and erosion of these fan phases in Mesopotamia Plain resulted in variations (Al-Hussaini, 2013; Sissakian and Jabbar, 2014; Domas, 1983; Yacoub, 1983).

Yacoub (1983) referred to the fact that the earlier four stages were most probably developed in the Plio-Pleistocene and Pleistocene ages. The most recent channel fill is the Holocene Age, which represents the fifth stage.

The top of the fan is interrupted by a number of old and modern watercourses, most of which have lost their characteristics where natural erosion factors have started to hide their appearances. It enters the Al-Shihaby Valley on its only path towards the southwest and then branches out from its left side, a group of valleys spreading on the surface of the fan (Al-Akkam, 2008).

4.2. Alluvial fan activity

The development of alluvial fans is primarily caused by a decrease in the energy of the sediment-laden channel as a result of the stream's steep drop. The alluvial fans represent depositional landforms that reflect the active areas of non-marine foreland basins (Bull et al., 1977; Bull, 2009). Cohen et al. (2002) reported that the proximal part of the fan is continuously decreasing, as indicated by the active fan, while the idle fan suggests that the fan's distal portion has risen. The weather is changing, though, and this cannot be disregarded. Cohen et al. (2002) and Jones and Arzani (2005) mentioned that fan activity is also provided by neotectonic movements. However, an extensive network of alluvial fans is found close to the Badra-Amarah fault-the southern portion of the

Makhul-Hemrin fault-along the Mesopotamia Plain's eastern edge. This fault extends from the northwest region of Badra to the southeast region of Amara. The Badra-Amarah fault originated as a normal fault as a result of extensional forces during the Late Triassic period, based on the region's tectonic history (Numan, 1997). The Badra-Amarah fault displays reverse movement with a tiny dextral strike-slip displacement as a result of the compression tectonic pressures in the collision zone between the Arabian and Eurasian plates, according to the focal mechanism solutions derived from the GCMT project. (Abdulnaby et al., 2016a). Pleistocene age is attributed to all alluvial fans (Sissakian, 2000). As a sign of the Mesopotamia Plain's ongoing subsidence, several of them are still active.

There is a strong direct relationship between the geology of the basin and the fan, as whenever there is geological instability, it is offset by instability in the size of the fan or its development, and it was noted that the flood fans formed due to instability in the tectonics of the basin are larger, thicker, and have more continuous development than the flood fans formed due to a climatic or topographic factor (Blair, 1987).

The impact of the neotectonic activity that is represented by the relative uplifting of the Hamreen structure versus the subsidence of the Mesopotamia Plain has now not been excluded either (Yacoub, 2011).

The geology and relief of the source area, tectonic activity, the amount of sediment added to the fan, and the drainage basin's size are examples of tectonic events that affect the alluvial fans' morphological features (Al-Sahlani, 2020).

The area of the study is affected by tectonic activity in two ways: the first is the fan gradient, and additionally, the anomaly affects the sediments all through deposition or after it. The second indirect activity is the erosion process through the improved supply place, which then expands by adding sediments.

The phenomenon of multi-stages that the fan passed through and is still going through (the five stages) is one of the most important indications of the continuous tectonic activity (neotectonic) in the region (as was mentioned before).

The Zagros Front Fault (ZFF) is connected to the occurrence and growth of the fans on the east side of the Mesopotamia Plain and its activity. It is situated on the NE part of the Mesopotamia Plain at the Iraq-Iran boundary and is the mainly seismically active fault in Iraq, extending from Mandali through Badra and ending in Amara Cities. It was situated in a seismic zone where severe damage might occur in the future. The fault spans approximately 245 km in length and may extend to a depth of 10–12 km within the basement rocks (Abdulnaby et al., 2016a, 2016b).

5. Conclusions

From the above, it can be noted that all previous studies of the region have focused on the sedimentary and hydrological sides of the region, and the region has not received comprehensive and detailed compositional studies, hence this study, which links the fan formation with the tectonic side, which was previously missing in previous studies.

According to our results and interpretations, the neotectonic activity is continuing in the study area, and it was identified by passing the fan through many breakpoints in sedimentation until the present day. Each breakpoint is a stage, and when tectonic activity occurs, the next stage begins. These breakpoints indicate that the fan has been uplifted along the western edge of the mountaintop because of the active fault in the region.

In addition to the relative uplifting of the Hemrin structure versus the subsidence of the Mesopotamia Plain, the fan's tilt toward the southeast of the study region is indicative of the mountain front's activity and provides strong support for the neotectonic marks found along the Mesopotamia Plain's eastern edge.

According to our results and interpretations for the sections derived from the DEM file (xx'), (yy'), (aa'), and (bb'), indicating the elevation range of the area from 15 m in the southwest of the area to 120 m in the northeast above sea level. Many temporary streams feed the fan with sediment in the rainy seasons. Moreover, these sections show that the deepest stream is 8 m on the east and 8–10 m on the west; therefore, there was an increase in the thickness of sediments on the western side, about 70 m, compared to the eastern side, about 60 m.

That signifies that during the growth of the fan, the area observed several uplift periods that corresponded with the ongoing Alpine Orogeny to the present. The development of the phases, which is a sign of its activity due to the frequent earthquakes along the east side of the Mesopotamia Plain, appears on the fan surface. As a result, the area is an active zone.

Data availability

The data supporting this study's findings are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Hanan Abdulqader Darweesh: Writing – review & editing, Writing – original draft, Supervision, Project administration, Data curation. **Hawraa Daway Jaddoa:** Writing – review & editing, Software, Methodology, Data curation. **Suad Mohammed Ali:** Writing – review & editing, Resources, Methodology.

Declaration of competing interest

The authors declare that none of their personal or financial conflicts could have influenced the work presented in this study.

Data availability

Data will be made available on request.

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