GEOMORPHOLOGY AND MORPHOMETRY OF SEGMENTED KIRKUK ALLUVIAL FAN, NORTHERN IRAQ

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Received: 06/ 05/ 2014, Accepted: 06/ 11/ 2014
Key words: Morphotectonic, Alluvial fan, Khas'sa Soo, Kirkuk, Iraq

ABSTRACT

The Khas'sa Soo River is one of the main tributaries of the Adhaim River. The Khas'sa Soo River runs in the central part of Iraq, It is a perennial stream, running almost in straight line, especially in its middle and upper parts of its course. The width of the Khas'sa Soo River ranges from 0.1 to 1.1 Km, whereas its length is about 90 Km. It is filled by valley fill sediments, indicating prevailance of very active fluvial climate; during the Pleistocene and the Holocene.

The catchment area of the Khas'sa Soo River consists of mainly fine clastics derived from Injana and Mukdadiyah formations and coarse clastics from Bai Hassan Formation. Along its course, the stream crosses many anticlines perpendicularly, some of these crossings have gorge forms with water gaps.

A main alluvial fan is developed in the outlet of the Khas'sa Soo River from Kani Dommilan Mountain, which forms part of Kirkuk oil field. The length and width of the fan is 42 Km and 20 Km respectively. The main constituent of the fan is sandy silt, underlain by gravels of different sizes. The shape of the fan has almost disappeared, due to human activities, but it is still clear on the topographic maps of scale 1: 100 000. The morphology of a segmented alluvial fan can be used as an indicator for active tectonics. The fan form may reflect different rates of tectonic processes, such as faulting, uplifting, tilting, and folding along and adjacent to the mountain front.

This study of the fans in Khas'sa Soo River found that tilting had produced segmented fan. Alluvial fan on the valley is shifted to the east as illustrated by remnant terraces (two levels for Early and Late Pleistocene age), consequently the location of the fan deposits is moved down-fan. Therefore, fanhead incision has occurred, and younger fan segments are located far away from the mountain front and fan apex, which represents the tectonic activity in the area.

In this study, topographic profiles and fan contours are used to identify the position of the fan apex, identify relic mountain fronts, and calculate the tectonic tilt. Modeling of alluvial-fan morphology is used in evaluating the amount of uplift, which the fan apex has experienced.

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دراسة جيومورفولوجية ومورفوميترية لمروحة كركوك الفيضية المتقطعة، شمال العراق

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المستخلص

يعتبر نهر الخاصة صو واحد من أكبر روافد نهر العظيم ويجري في وسط العراق غالبا بخط مستقيم خصوصا في الجزء الوسطي من مجراه، عرض النهر يتراوح من (0.1 – 1.1) كم ويبلغ طوله 90 كم ومملوء بالترسبات المالئة للوديان التي تشير الى فترة نشطة للمناخ الرطب.

يغطي حوض النهر والمنطقة المغذية له بالترسبات الفتاتية العائدة الى ترسبات تكوينات إنجانة والمقدادية وباي حسن ويقطع النهر خلال مجراه عدد من الطيات بصورة عمودية.

هناك مروحة نهرية قد تطورت عند مصب نهر الخاصة صو ذات طول 42 كم وعرض 20 كم تتكون بصورة رئيسية من الرمال التي تغطي أحجام مختلفة من الحصى، إن شكل هذه المروحة تلاشى تقريبا بسبب النشاط الإنساني ومورفولوجية هذه المروحة المقطعة يمكن أن تستخدم كمؤشر على التكتونية النشطة ولأن شكل المروحة ربما يعكس شدة العمليات التكتونية المختلفة مثل التصدع والطي.

ان دراسة المروحة الغرينية لنهر الخاصة صو جنوب غرب طية كركوك وجدت ان الميلان أنتج مراوح مهشمة أو مقطعة وتم إزاحتها الى الشرق وبالتالي أزاحت ونقلت الترسبات الى أسفل المروحة.

استخدمت في هذه الدراسة مقاطع طبوغرافية وخطوط تساوي الارتفاع للمروحة لتحديد موقع عنق المروحة التي تشير الى مقدمة الجبال بالإضافة الى انموذج مورفومتري لتقييم نسبة الارتفاع الحاصل في مقدمة المروحة.

INTRODUCTION

Descriptive and quantitative analysis of morphotectonics with remote sensing techniques can give important information about the development of geomorphological features such as alluvial fans. The geomorphic evolution of alluvial fan is controlled by catchment characteristics including drainage، basin area, relief, geology, tectonics and climate.

The Landsat TM false color composite imagery is used to distinguish alluvial fans in the southwestern limb of Kirkuk structure, depending on the tone, texture, size, and drainage pattern of the fans. These visual interpretations with drainage pattern created from (DEM) Digital elevation model with resolution of 30 m are matched by GIS software program after applying georeferencing.

From the same DEM, the study created topographic contour lines on the alluvial fan for two reasons. The first is to emphasis alluvial fan borders because the created contour lines express iso-transport energy lines. The lines are very uniform forming concentric arcs around the discharge point at the apex of the fan. The materials will tend to be deposited equally about these lines, forming the characteristic cone shape (National Aeronautics and Space Administration, 2009; in Sissakian, 2011), especially in typical alluvial fan. The second reason is to draw longitudinal profiles of each fan by 3D Analyst in GIS.

The studied area is located in the central part of Iraq; it covers an area of about 6537 Km^2. The Khas'sa Soo River starts from Cham Chamal North Mountain south and southwest of Sulaimaniyah city and passes through Kirkuk city (Fig.1). The Khas'sa Soo joins with Zghaitoon valley, which drains the extreme western basin of the Adhaim River and runs parallel to Himreen Mountain (NW – SE). The studied area is approximately bound by the coordinates (44° 00' 00'' – 44° 30' 00'') E and (35° 00' 00'' – 35° 30' 00'') N.

The aim of this study is to use the morphotectonics of a segmented alluvial fan, formed by the Khas'sa Soo River to deduce the tectonic activity in the studied area.

The material used for the present study are: topographic maps at scale of 1: 100 000 and 1: 250 000, geological maps at different scales, Landsat images, Google Earth images , ArcGIS and remote sensing software and techniques.

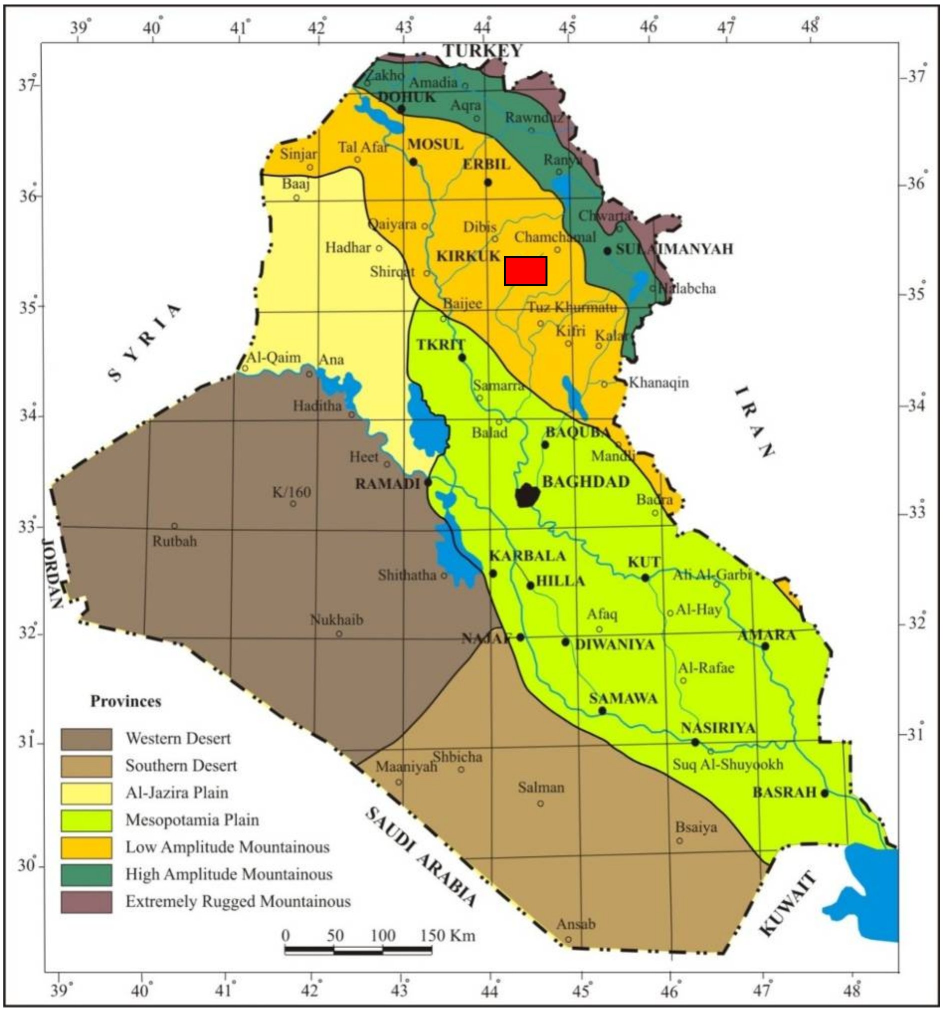

Fig.1: Physiographic Map of Iraq (after Sissakian and Fouad, 2012) and location map of the studied area

GEOLOGICAL SETTING

▪ Geomorphology

The studied area is generally characterized by flat terrain with small difference in elevations in southwestern part. The high terrain is mainly of structural origin, which is represented by Qara Botak, Jambor, and Kirkuk anticlines. The highest point in the studied area is 500 m a.s.l., located at the northeastern part, whereas the lowest point is 200 m a.s.l., located at the southwestern part of the studied area. The geomorphological map (Fig.2) of the studied area is prepared by Sissakian and Abdul Jabbar (2013); using Landsat image, aerial photographs, geological maps and topographic maps at scales of 1: 1000 000 and 1: 250 000, with field check (Fig.2). The geomorphic units developed are described hereinafter (Sissakian and Abdul Jabbar, 2013).

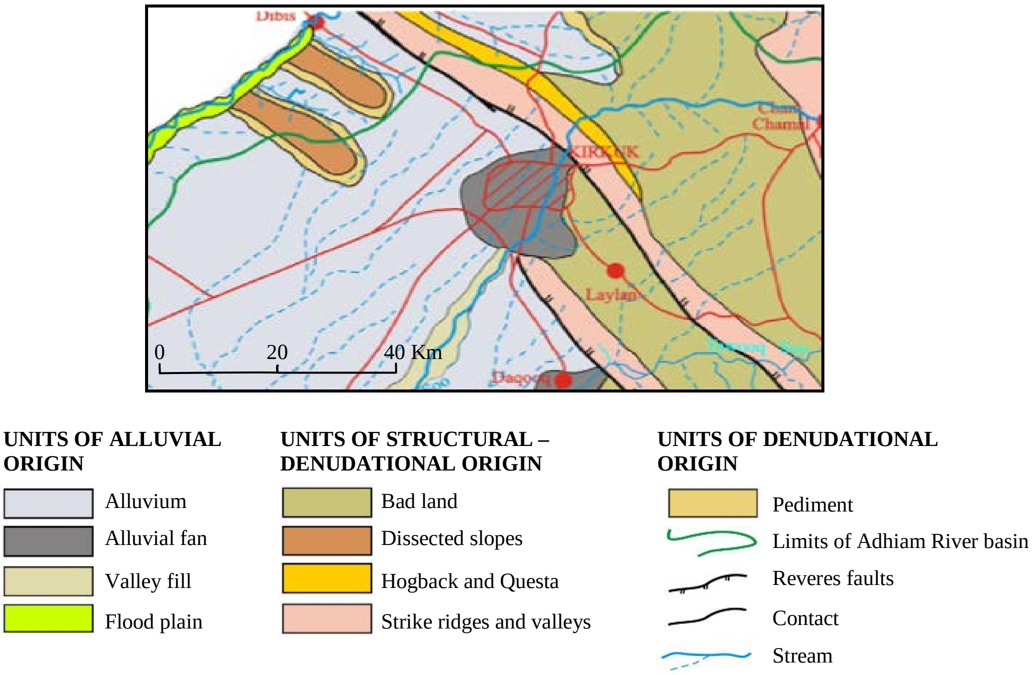

Fig.2: Generalized geomorphological map of the studied area
(after Sissakian and Abdul Jabbar, 2012)

- **Stratigraphy**

The exposed formations and Quaternary sediments (Fig.3) are reviewed briefly (Sissakian, 1995 and 2000).

— **Fatha Formation** (Middle Miocene)**:** Consists of alternation of reddish brown claystone, green marl and limestone, with thin gypsum. The thickness ranges between (100 – 200) m.

— **Injana Formation** (Late Miocene)**:** Consists of alternation of well bedded, reddish brown sandstone, siltstone and claystone. The thickness ranges from (100 – 400) m.

— **Mukdadiyah Formation** (Late Miocene – Pliocene)**:** Consists of alternation of bedded, grey sandstone; some of them are pebbly, siltstone and claystone. The thickness ranges from (50 – 1000) m.

— **Bai Hassan Formation** (Pliocene – Pleistocene)**:** Consists of alternation of thick conglomerate and reddish brown claystone, with thin grey sandstone. The thickness ranges between (300 – 2500) m.

— **Quaternary Sediments:** Different types of Quaternary sediments are developed in the study area; they include Pleistocene and Holocene ages. They are:

Terraces (Pleistocene): These are developed along the Khas'sa Soo River, and its main branches. The type and the thickness is the same in the alluvial fans.

Polygenetic Sediments (Pleistocene – Holocene): These are developed usually in the trough of some synclines, especially where the Bai Hassan Formation forms the exposed rocks. They consist of pebbles and rock fragments of different sizes and types, usually covered by thin venire of gypcrete. The thickness may attain few tens of meters.

Alluvial Fan Sediments (Pleistocene – Holocene)**:** The remnants of the fans are preserved in different parts within the studied area. They form flat tops of small plateaus, overlying folded rocks of pre-Quaternary formations. The main composition is pebbles of different sizes of different rocks, cemented by calcareous and sandy cement. In the outlet of the rivers; alluvial fans are developed, but they almost vanish due to erosion and man activities. The thickness is few meters.

Valley Fill Sediments (Holocene)**:** These are very well developed in the course of the Khas'sa Soo River, usually consist of pebbles of different sizes (few centimeters up to 25 cm. Rock types are mainly limestones, dolomite, silicates and subordinate igneous and metamorphic rocks. The thickness ranges from (< 1 – 5) m, occasionally more.

Flood Plain Sediments (Holocene)**:** These are restricted to the Khas'sa Soo River and usually consist of sand, silt and clay, rarely with some fine pebbles. The thickness ranges from (< 0.5 – 1.5) m, and may occasionally be more.

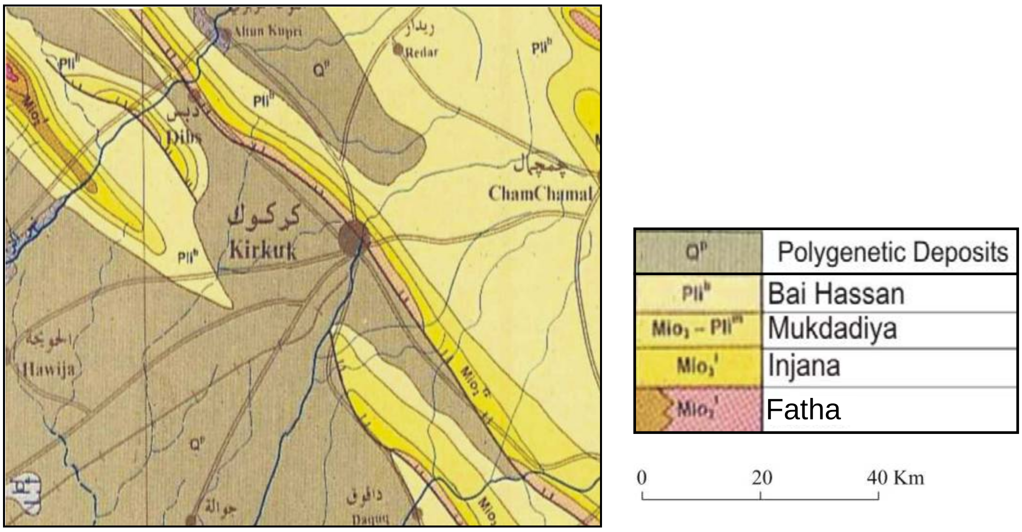

Fig.3: Geological map of the studied area
(after Sissakian and Fouad, 2012)

- **Structural Geology**

The studied area is located within the Low Folded Zone of the Unstable Shelf of the Arabian Plate (Al-Kadhimi *et al*., 1996 and Jassim and Goff, 2006). However, according to Fouad (2012a) the studied area is located within the Low Folded Zone of the Outer Platform of the Arabian Plate (Fig.1). Many anticlines and synclines are developed within the studied area; they all are in NW – SE trend. Some of them exhibit thrusting of their northeastern limbs over the southwestern limbs, causing the disappearance of the latter limb, as observed in Jambur, Qara Botak, and Kirkuk structure, which were thrusted during the Plio-Pleistocen age (Fouad, 2012b). They form the longest and largest structures within the study area.

Different types of faults exist within the area, all associated with anticlines. The thrust faults are believed to be developed simultaneously with the folding. The main faults are Kirkuk, Jambur, Bai Hassan thrusts, and Qara Bootaq faults (Fig.4).

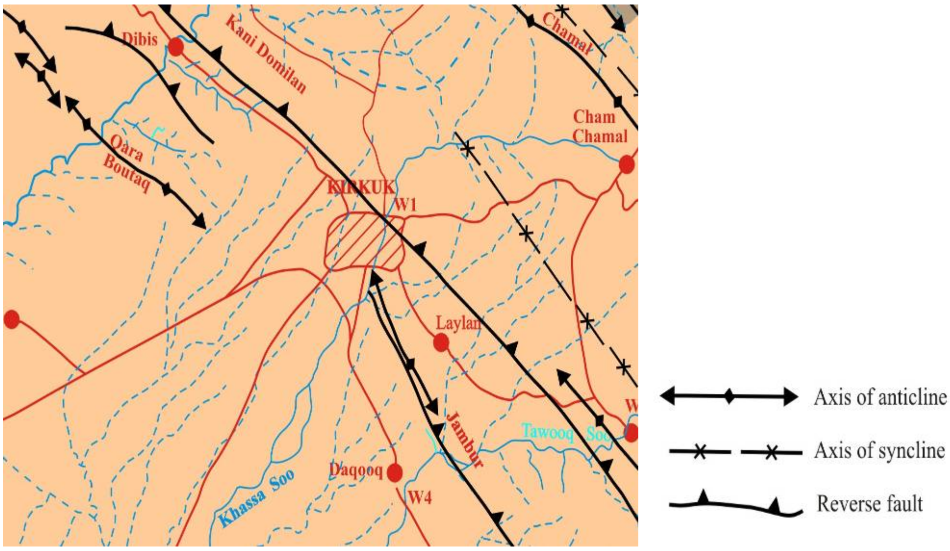

Fig.4: Structural map of the studied area (after Sissakian and Abdul Jabbar, 2012)

ALLUVIAL FAN DEVELOPMENT

Alluvial fans are depositional landforms created where steep high-power channels enter another zone of reduced stream power. This form can be modified by the presence of confining neighboring fans or valley walls. In addition, the burial of the fan apex area can cause backfilling into the mountain catchment (Bull, 1977 and Harvey, 2005).

The zone of deposition on the fan runs back from the break of slope between the fan apex and the flat terrain in front of the fan toe. It was once thought that, deposition was induced by a break of slope in the stream profile at the fan apex, but it has been shown that only rarely is there a break of slope at that point. The steepness of the fan slope depends on the stream power and the coarseness of the load, with the steepest alluvial fans being associated with small streams and coarse bed loads (Blair and Mc Pherson, 2009).

Although alluvial fan deposits are not the most significant in a sedimentary basin in terms of volume, they are important because fan deposition is sensitive to tectonic and climatic controls (Frostick and Reid, 1989; Bull, 1991; Ritter., 1995). Alluvial fans are developed at the margins of sedimentary basins and these can be sites of tectonic activity, with fault movements along the basin margin creating uplift of the catchment area and subsidence in the basin. It is therefore possible to see evidence of neotectonic activity within an alluvial fan succession, such as an influx of coarse detritus on to the previous fan deposits resulting from renewed tectonic uplift (Bull and McFadden, 1977, and Bull, 2009). Analysis of the bed thicknesses can therefore be used as a mean of identifying periods of tectonic uplift in the high ground adjacent to the basin.

A change in climate can also change the processes of deposition on a fan. For example, with an increase in rainfall, more water is available and this may result in a predominance of sheet flood and stream-channel processes, with less debris-flow events occurring (Harvey, 2002, and Harvey, 2005). The more resistant rocks break down into pebble and gravel size, which are transported and deposited by sheet flood and stream-channel processes (Ryder, 1971, and Blair, 2003).

ALLUVIAL FANS AND TECTONIC ACTIVITY AT MOUNTAIN FRONT

The geomorphology of mountain fronts reveals a great deal about the tectonic activity occurring there. For example, mountain fronts in arid and semiarid regions are often characterized by alluvial fans. An alluvial fan may be thought of as the endpoint of an erosional – depositional system in which sediment eroded from a mountain source area is transported to the mountain front. At the front, this material is deposited as a fan shaped body (segment of a cone) of fluvial and/ or debris-flow deposits (Keller, 2002). The connecting link between the erosional and depositional parts of the system is the stream. The morphology of an alluvial fan is a function of variables including size of drainage basin, contributing sediment to the fan, geology of the source area, relief of the source area, climate and vegetation of the source area, and tectonic activity. Profiles of alluvial fans in cross section are generally concave but often contain significant breaks in slope that mark boundaries between relatively straight-line fan segments. In fact, most alluvial fans are segmented and younger fan segments may be identified from older segments based on relative soil-profile development, weathering of surficial clasts, erosion of the surface, and development of desert varnish. They may also be numerically dated using exposure dating techniques (Keller, 2002).

The morphology of a segmented alluvial fan may be used as an indicator of active tectonics, such as faulting, uplifting, tilting, and folding along and adjacent to the mountain front. In the simplest case, if the rate of uplift along a mountain front is high relative to the rate of down-cutting of the stream channel in the mountain and to deposition on the fan, then deposition tends to occur in the fanhead area. The youngest fan segment is found near the apex of the fan. Such mountain fronts would also tend to have low values of mountain-front indices (S^{mf}). On the other hand, if the rate of uplift of the mountain front is less than or equal to the rate of downcutting of the stream in the mountain source area, then fanhead incision occurs, and deposition is shifted downfan. As a result, younger fan segments are located well away from the mountain front. Such mountain fronts would have relatively high value of S^{mf} suggesting relatively low rates of mountain-front activity. The mountain block wears down with time; the front is more eroded and sinuous and mountain-front valleys are wider (Keller, 2002).

The overall shape of an alluvial fan can also reveal the pattern of tectonic activity at and near a mountain front. Because alluvial fans are roughly conical in shape, topographic contours across simple fans are approximately circular (the intersection of a cone with a horizontal plane is a circle). However, where alluvial fans are not simple, and have undergone tectonic tilt, contour lines across the fans form segments of ellipses, not circles (the intersection of a tilted cone and a horizontal plane is an ellipse).

ALLUVIAL FAN IN THE SOUTHERN LIMB OF KIRKUK STRUCTURE

Digital enhancement of LANDSAT satellite images yields much information about image features. GIS techniques enable the integration and analysis of multi spatial and non spatial data that have the same georeferencing data. Therefore, the integration of GIS and remotely sensed data could be more informative and results would be more applicable to image interpretation (Change, 2006). This study, using previous studies and satellite image, has differentiated one large alluvial fan in the southwestern limb of Kirkuk structure, along Khas'sa Soo River.

- **Fan Morphology**

The Kirkuk fan is originated from main elongated catchment areas. The fan is formed through the escarpment of the Kirkuk thrust fault, which cut across the neck of the fan and separate the catchment area from the fan body (Fig.5). The main streams of the catchment area are of first order and they show highly incised valleys; they flow through Bai Hassan, Mukdadiyah, Injana and Fatha formations. This catchment area has created large alluvial fan which covers vast area.

The main streams of the catchment area are shifted to the eastern part of the fan as a result of relative uplift creating new incised stream course and new alluvial fan is formed along the Jambour thrust fault (Fig.5).

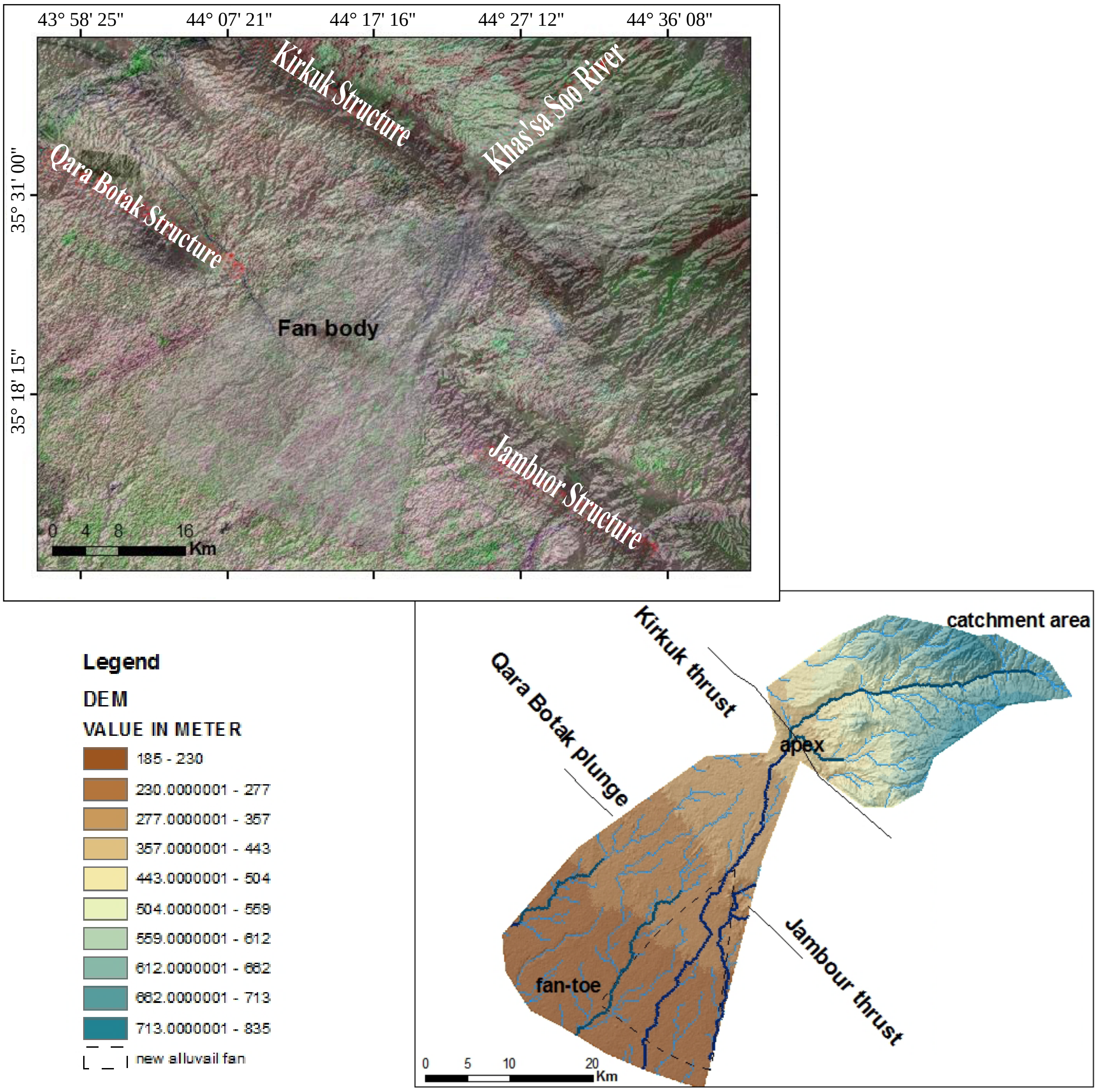

Fig.5: LANDSAT satellite image show Location and morphology of Kirkuk alluvial fan

- **Longitudinal Profile**

The longitudinal valley profile is the least transient expression of fluvial processes, reflecting the geological influence such as the effect of vertical tectonic movements of valley floor and base level change, due to climatic change on the processes of erosion and deposition, of the distribution of outcrops of different lithology, and to the increase in discharge due to entry of large tributaries (Al-Daghastani and Cambell, 1995 and Rantitsch *et al*., 2009). Fundamentally, the longitudinal profile of the river has an overall concavity upwards that reflects a progressive decrease of gradient, so that a concavity-convexity index describing profile form, locates segments affected by some of these modifying influences.

The longitudinal profiles were constructed on the main stream of the fan; they start from the highest point in the catchment area to the lowest point in the toe of the fan. The longitudinal profile of the main stream of Kirkuk fan (Fig.6) shows four knick points. The first one (Kp1) is at an elevation of 400 m due to presence of the major Kirkuk thrust fault, which separates the catchment area from the fan body. The second one (Kp2) occurs at an elevation of 360 m. It is due to presence of the Jambour thrust fault. The third knick point (Kp3) is at the elevation of 280 m. It is due to the change in lithology, which coincides with the contact between Bai Hassan and Mukdadiyah formations at the Qara Bootak southeastern plunge. The fourth one (Kp4) is at the elevation of 240 m and is due to the stream meandering as a result of continuous development of the plunge of Qara Bootak anticline.

This study, has found that the tilting has produced segmented fans. Alluvial fans on the valley are shifted to the east, which is illustrated by remnant terraces (two levels of Early and Late Pleistocene age) (Fig.7), and the shifted depositional locus of the fan is down-fan. That is, a fanhead incision has occurred, and younger fan segments are located well away from the mountain front and fan apex, thus recording the tectonic activity in the area.

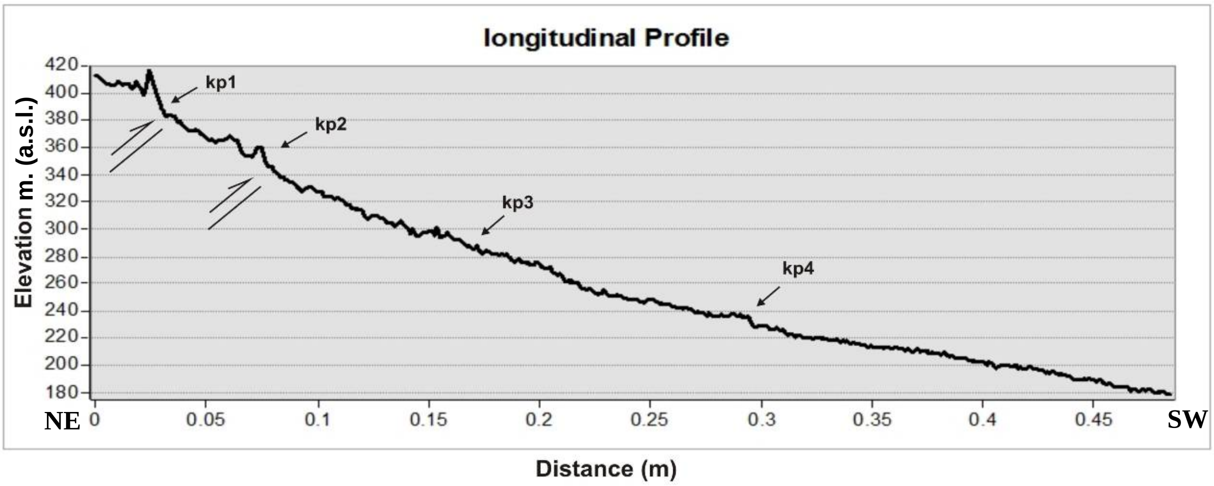

Fig.6: Longitudinal profile of the Khassa Soo River

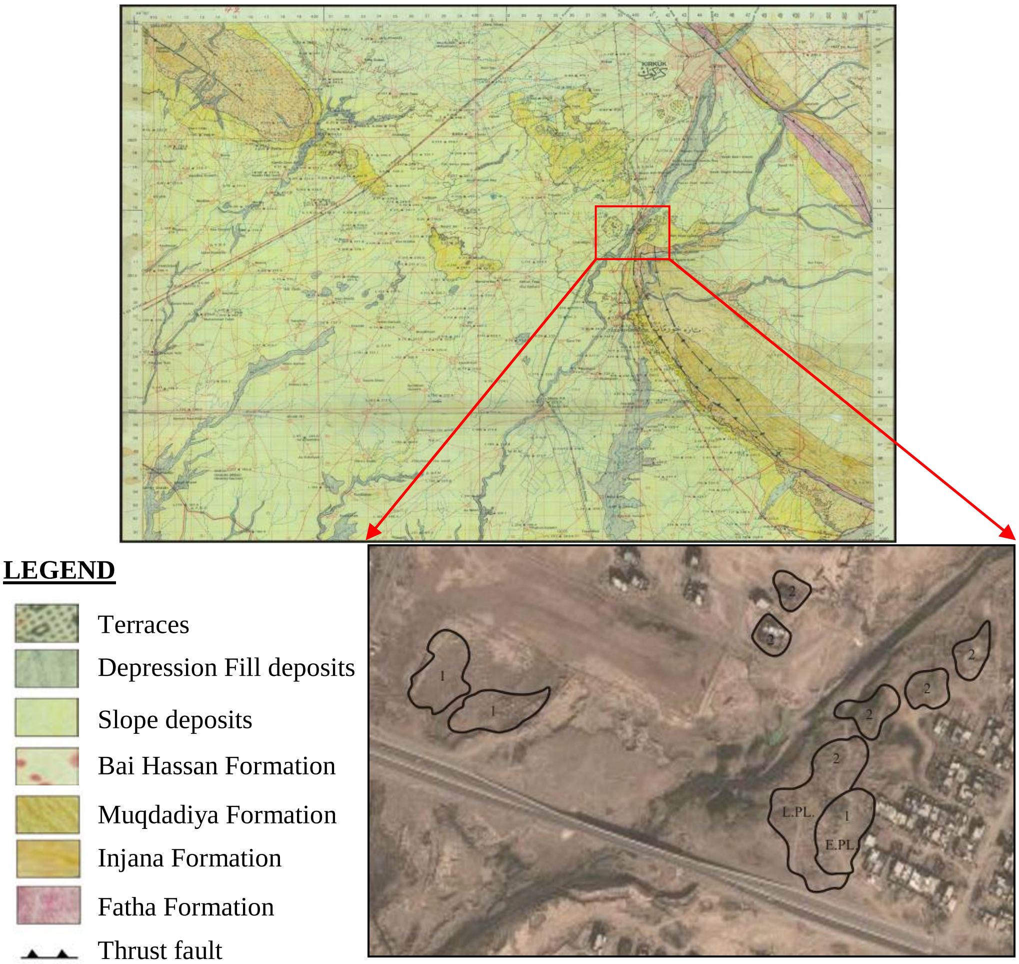

Fig.7: Geological map scale 1: 100 000 (GEOSURV) and Google image showing remnant terraces (Two levels of Early and Late Pleistocene age)

- **Morphotectonic Effect**

The study of the tectonic geomorphology of active folding in Kirkuk region provides information concerning the tectonic and geomorphic development of mountain fronts produced by active folding and faulting (Fouad, 2012b) and provide evidence of Plio-Pleistocene deformation at the present active range front (Fig.8). Studies of the tectonic effect on the surface of the alluvial fans and fluvial terraces suggest Early and Late Pleistocene vertical deformation. The amount of the down warping ranges between – 250 and – 2500 m, whereas the up warp ranges between 250 to 1000 m, and the rate of the up warp and downwarp are 0.8 and –1.6 cm/100 years, respectively (Sissakian and Deikran, 1998). Geomorphic evidence also suggests that the locus of active tectonic forces and vertical deformation along the northeastern limb of Kirkuk structure has migrated basinwards with time. This evidence includes a relic intermountain front, now occurring within the uplifted block, 13 Km from the present active mountain front (Jambour anticline), and existence of recently initiated folds 7 Km basinwards from the mountain front at the Qara Bootak fold plunge (Fig.9). The southwestwards migration of the tectonic activity has resulted in progressive widening of the uplifted block as the location of active folding moves basinwards. This migration of tectonic activity appears to occur through increase of vertical deformation along more southwesterly folds and faults accompanied by reduction of activity along the older, more northeasterly structures (Keller, 2002).

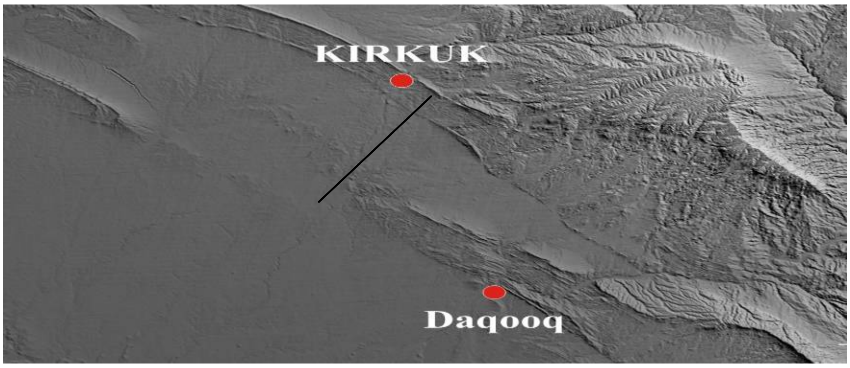

Fig.8: DEM of the studied area

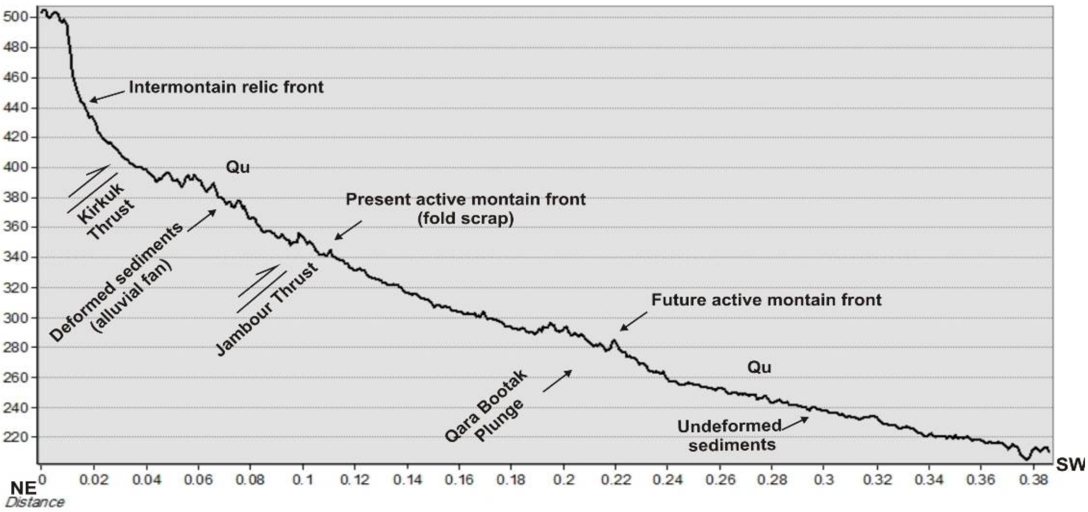

Fig.9: Idealized topographic profile constructed approximately perpendicular to structures

Alluvial fans have been accumulating since at least the Late Pleistocene on the southwestern limb of the Kirkuk structure. Because alluvial fans are sensitive to changes within the erosional-depositional system, geomorphic studies of alluvial fans can be used to evaluate tectonic perturbations that occurred during and after fan deposition (Summerfield, *et al*., 1999). Several segments occur on the Kirkuk fan, the largest and best-formed fan (Fig.10). The study of the fan suggests that the upper fan segments have different fan-head apex than the fan-toe segment. Vertical deformation along the active mountain front has produced the younger fan-head segments, the apex of which is at the active front. Although most of the fan-toe deposits are thinly buried by very recent valley fill or disturbed by farming, the fan-toe morphology is still clearly visible.

The Kirkuk alluvial fan can be reconstructed based on the assumption that contour lines are concentric arcs having their centers of curvature at the apex of the fan. Thus, by fitting alluvial-fan contours with circular arcs; the radii can be reconstructed and thus the location of the fan apex is determined at the time of deposition of that portion of the fan. Using this methodology, the fan-toe contours project back to a different apex from the mid-fan and fan-head contours. This may be interpreted as evidence for two alluvial fans, each with different apex (Fig.11). Reconstruction of the fan apex indicates that the apex of the older and larger fan is located south of the active front at a prominent topographic break (Kirkuk structure). This topographic break is hypothetically an older intermontane (relic) front. In order to reconstruct the morphology of the fan, it is assumed that the fan-toe segment of Kirkuk fan consists of nearly undeformed deposits, which is a reasonable assumption because the toe segment is several kilometers south of any identified deformation. Using topographic measurements from the fan-toe segment, the depositional morphology of the fan deposits is reconstructed using a series of equations developed by Troeh (Mogard, 1987). These equations utilize three points of known elevation and known radial distances from the fan apex to predict the elevation of any other point on the fan. The equations are as follows:

$$S = \frac{(E_a - E_c)(R_b^2 - R_c^2) - (E_b - E_c)(R_a^2 - R_c^2)}{(R_a - R_c)(R_b^2 - R_c^2) - (R_b - R_c)(R_a^2 - R_c^2)} \quad \ldots\ldots (1)$$

$$L = \frac{E_a - E_c - S(R_a - R_c)}{R_a^2 - R_c^2} \quad \ldots\ldots (2)$$

$$P = E_a - Sr_a - LR_a^2 \quad \ldots\ldots (3)$$

$$E_z = P + SR_z + LR_z^2 \quad \ldots\ldots (4)$$

Where:

E_a, E_b, E_c = elevation of any three known points A, B, C on the fan
Ra, R_b, R_c = radial distance from apex to points A, B, C
L = $\frac{1}{2}$ the rate of change of slope
P = elevation of fan apex
S = slope of fan at P
E_Z = Elevation of any point Z at known radial distance R_z

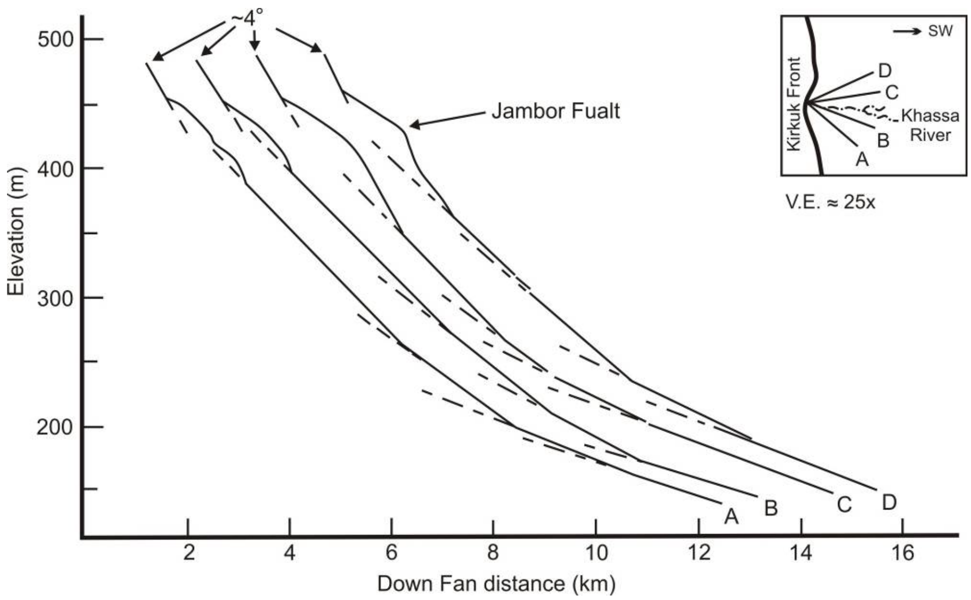

Fig.10: Radial profile of Kirkuk alluvial fan shows several segments of present fans

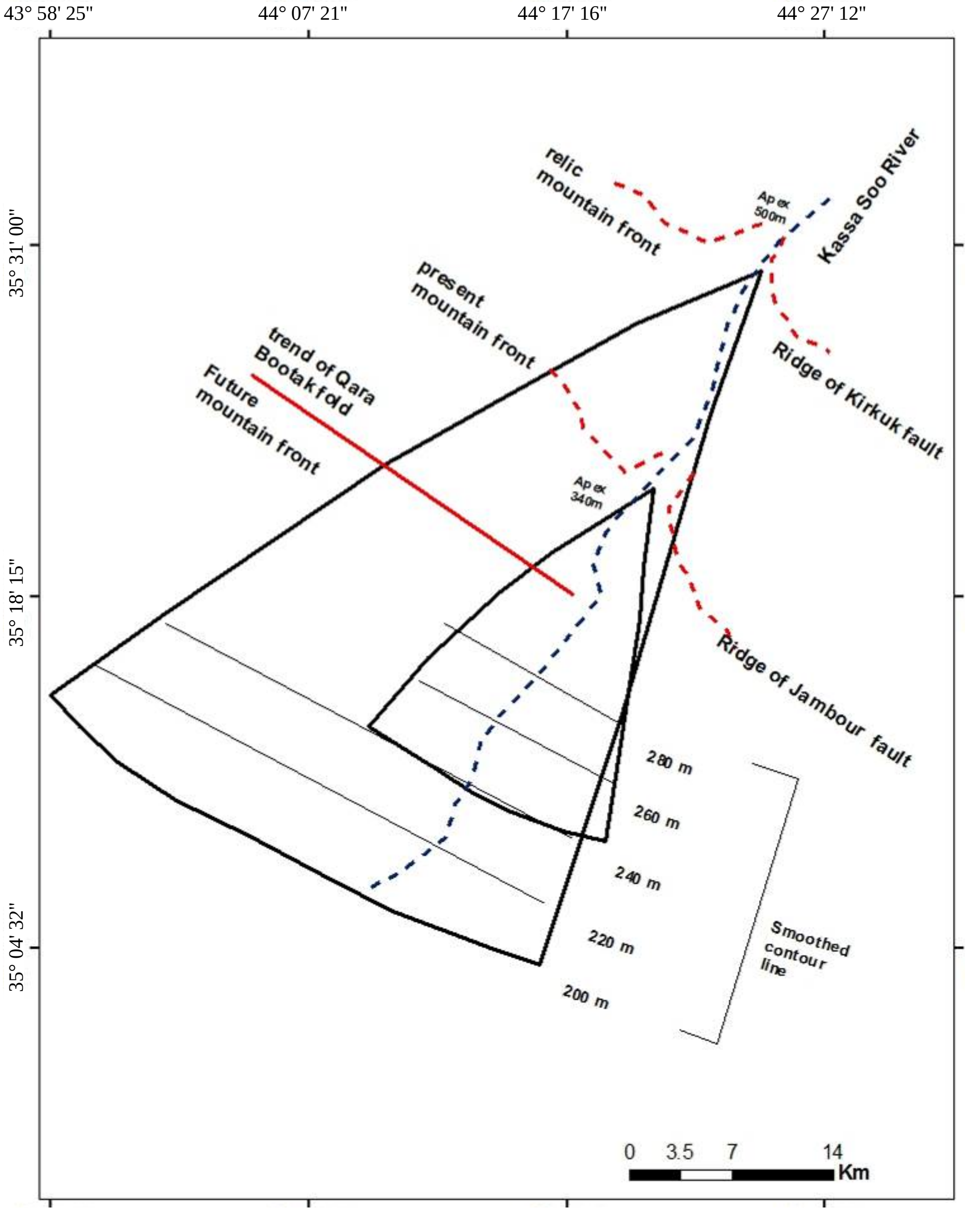

Fig.11: Reconstructed morphology of Kirkuk alluvial fan

The reconstructed morphology of the alluvial fan produced by Troeh's equations can then be applied to estimate vertical displacement since Early Pleistocene time. Using present-day data from the fan-toe segment (contours at 200 m, 220 m, and 240 m a.s.l.) (Fig.11), it is estimated that the average elevation of the fan apex at the time of fan-toe deposition was about 37 m. The present elevation of the apex is about 500 m, using the reconstructed profile; the amount of deformation that has occurred since fan-toe gravels were deposited can be estimated. The amount of the vertical deformation of the fan above Kirkuk thrust fault is 500 m, and by subtracting 37 m, about 463 m remains. The vertical deformation over the Jambour fault is approximately 303 m. Thus, 160 m of the vertical deformation is attributed to the Qara Bootak fold and therefore the rate of the upwarping is about 1.3 cm/100 years.

- **Relic and Intermontane Fronts**

Mountain Front Sinuosity Index (S^{mf}) represents a balance between stream erosion processes tending to cut some parts of a mountain front and active vertical tectonics that tend to produce straight mountain fronts (Keller and Printer, 1996).

The index is defined as (Keller, 1996):

$$J = Lj / Ls \quad \text{…………………………………………………….……..…… (5)}$$

Where:

Lj is the planimetric length of a mountain front along the mountain-piedmont junction
Ls is the straight line length of the front

This index is divided into three classes: **1** ($J < 1.1$), **2** ($1.1 \leq J < 1.5$) and **3** ($J \geq 1.5$) (El-Hamdouni *et al*., 2007). Three mountain fronts in the studied area are evaluated in terms of $\mathbf{S^{mf}}$ (Table 1) they are bounded by active folds or faults, which may produce a relative tectonic activity class.

Table 1: Mountain Front Sinuosity Index **(**S^{mf}) values and classes

Front name	S^{mf} value	class
Kirkuk	1.11	2
Jambour	1.19	2
Qara Botak	1.01	1

Mountain fronts suggestive of the highest tectonic activity are classified as class 1, which typically have low values of $\mathbf{S^{mf}}$. These fronts are usually associated with an uplift rate of greater than 1cm/yr (Keller and Pinter, 2002). Class 2, mountain front is associated with less tectonic activity, reflected in a higher $\mathbf{S^{mf}}$.

Mountain front sinuosity and the discussion of Kirkuk alluvial fan morphology indicate that some mountain fronts are more tectonically active than others. Older mountain fronts, located within ranges (intermontane fronts), may remain active or may be on longer active. Similarly, a mountain front at the piedmont may no longer be tectonically active or have much reduced activity. Such fronts are relic landform produced by processes that are no longer active or experiencing greatly reduced rates. Hypothetically, mountain fronts formed early in a range development are active for a period of time, then deformation migrates towards and beyond the edges of the range, and new mountain fronts form. Therefore relic intermontane fronts at one time had the same basic morphology as the present active front. Streams that emerged from the intermontane fronts commonly fed a series of alluvial fans on what were the margins of the ranges. When tectonic activity shifts, the old alluvial fans are sometimes consumed by the active mountain-building process as new fronts developed (Fig.12). As the mountain ranges grow outward (wider with time), they consume their own alluvial fans (Gregory, 2000).

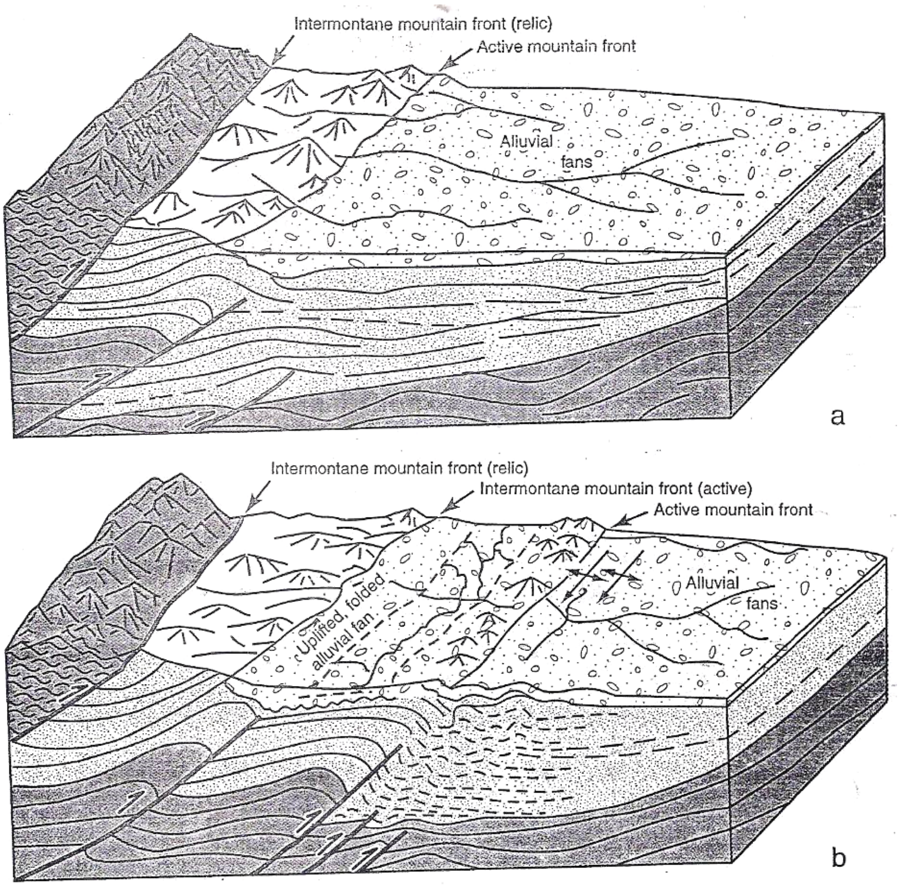

Fig.12: Idealized model illustrating the concept of mountain front migration (after Keller and Pinter 2002)

This study has shown that alluvial fans are potential indicators for relatively active tectonics. Most alluvial fans are segmented, the age and location of the segments are related to tectonic activity of a mountain front. Topographic profiles and fan contours may be useful in identifying the position of a fan apex, identifying relic mountain fronts, and calculating tectonic tilt. Modeling of alluvial fan morphology may be useful in evaluating the amount of uplift experienced by a fan apex. The presence of relic intermontane fronts is evidence that with time a mountain range may grow wider. As a result, older alluvial fans may become incorporated into the growing range.

CONCLUSIONS

The following conclusions are drawn from this study:

- Kirkuk and Jambour thrusted anticlines are tectonically active terrains which have controlled the fan morphology. The morphological variations of Kirkuk alluvial fan in the southwestern limb of the structure are related to the slope difference of Khas'sa Soo River, a difference caused by tectonic movement of the faults.
- Longitudinal profile analysis of Kirkuk alluvial fan by GIS software shows many knick points due to active tectonic movements of the southwestern limb caused mainly by thrust faulting and folding and lithological changes.

- Tilting had produced segmented fans. Alluvial fans on the valley are shifted to the east, which are illustrated by remnant terraces (two levels of Early and Late Pleistocene age), consequently the locus of the fan deposition was shifted downfan. Therefore, fanhead incision has occurred, and younger fan segments are located well away from the mountain front and fan apex, which represents the tectonic activity in this area.
- Morphometric analysis performed by GIS software for alluvial fan in Kirkuk structure shows more precise result reflecting the shape and size of the alluvial fan.
- The amount of the vertical deformation of the fan above Kirkuk fault is 500 m – 37 m, (= 463 m). Vertical deformation over the Jambor fault is approximately 303 m. Thus, 160 m of the vertical deformation is attributed to the Qara Botak fold then the rate of the upwarp is about (1.3 cm/ 100 years).
- Mountain front sinuosity and morphology of the Kirkuk alluvial fan shows that some mountain fronts are more tectonically active than others

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