

## **Landslides in Hareer Anticline, Central Northern Part of Iraq**

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### **Abstract**

Hareer anticline is a double plunging anticline with NW – SE trends, very strange and special hinge zone, hence its northwestern plunge is normal but towards southeast the hinge zone becomes very wide. The northeastern limb is very gentle with dip amount that ranges from (5 – 15) whereas the southwestern limb is very steep with dip amount that ranges from (45 – 85). The well bedded and very hard carbonates of the Bekhme Formation form the carapace of Hareer Mountain, with small exposures of the Qamchuqa Formation in the southwestern limb within few deeply cut valleys. The main reasons of the landslides are the presence of soft to fairly hard succession of marl and limestone in the lowermost part of the Bekhme Formation and the steeply dipping beds of the southwestern limb of Hareer anticline. The wet climate during the sliding and the gravitational forces have played significant role in triggering and acceleration of the two landslides that have moved short distance from the mountain. This is attributed to the presence of cliffs of the Khurmala and Pila Spi Formation at the end of the slope; the cliffs played as retaining walls to stop the sliding. To estimate the age of the two landslides in Hareer anticline, the Exposure Dating Method is used. The diverted and blocked valleys, the developed small alluvial fans from the slid mass and the weathering status of the rock blocks within the slid mass are used to estimate the age of the two landslides. The age is estimated to be few thousand years, which means during late Holocene.

**Keywords:** Landslide, Alluvial fans, Debris flow, Iraq.

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# 1 Introduction

## 1.1 General

The central northern part of Iraq; Kurdistan Region is a mountainous area with rough topography that increases in relief differences and roughness towards north and northeast. Among those mountains is Hareer, which is located north of Erbil city; with length of 27.5 Km; width range of (1.5 – 3) Km. The highest peak is 1513 m, whereas the highest point in the study area is 1507 m (a.s.l.), the relief difference with the southern Hareer Plain ranges from (75 – 100) m.

Two very old landslides occur along the southwestern limb of Hareer anticline ended near Sisawa village; therefore, it is called in this article “Sisawa Landslide No. 1 and No.2”. The study area is located in Erbil Governorate, about 75 Km north of Erbil city, north of the main Erbil – Rawandooz road, southeast of Hareer town (Fig.1). The main aim of this study is to estimate the age of Sisawa Landslides using the Exposure Dating Method [1], besides revealing the reason of the sliding.



Figure 1: Flash Earth image of Hareer anticline. LS 1 and LS 2 = Landslide No. 1 and 2, PSh = Northwestern plunge of Shakrook anticline, F = fault

## 1.2 Previous Studies

No studies concerning Sisawa Landslides occur; however, as general mass movements' studies only few are present. Hereinafter are some of those studies.

Sissakian and Youkhann [2] conducted geological mapping of the area between Erbil and Hareer and recorded the landslides of geological pas at scale of 1: 20000.

Hamza [3] compiled the Geomorphological Map of Iraq, and considered the study area within the mass movement's areas.

Sissakian and Ibrahim [4] conducted a geological hazards study of the whole Iraqi territory and considered the study area as Active Mass Movement zone.

Sissakian and Ibrahim [5] compiled the Geological Hazards Map of Erbil and Mahabad Quadrangles at scale of 1:250000 and presented Sisawa Landslides on the map, but without mentioning the details, due to the scale limitations.

Sissakian and Ibrahim [6] compiled the Geological Hazards Map of Iraq and considered the area of Sisawa Landslides as Unstable Mass Movements Zone.

### **1.3 Materials and Methods**

In order to achieve the main aim of this study, which is to estimate the age of Sisawa Landslides, the following materials were used:

- Topographic and geological maps of different scales.
- Google Earth, Here Maps and FLASH Earth images.
- Different geological published articles and reports.
- Field observation data.

Using the available topographical and geological maps of different scales with the help of FLASH Earth, Here Maps and Google Earth images, the parameters of the landslide were measured. Field work was carried out during October 2016 to check and map the exact limits of the landslide, to record significant parameters of the landslide, crown area, shear plane and other significant geological aspects.

## **2 Geological Setting**

The geomorphology, structural geology and tectonics, and stratigraphy of the study area are given briefly; hereinafter, depending mainly on best available data[2,3,7,8,9,10].

### **2.1 Geomorphology**

The main geomorphological units in the studied area are:

- Anticlinal ridges: The well thickly bedded carbonates of the Bekhme Formation have formed obvious anticlinal ridges along the southwestern limb of Hareer anticline.
- Alluvial fans: Many alluvial fans are developed in the study area and near surroundings; locally form in Bajada (Fig.2). More than one stage can be seen.
- Flat irons: These are well developed due to the thickly well bedded carbonates of the Bekhme Formation (Fig.2). Their height and widths range from (40 – 220) m and (30 – 100) m, respectively.
- Mass movements: Many small phenomena occur in the study area, like toppling and rock fall, beside the two landslides (Figs.1 and 2), which are concerned in this study.
- Wine Glasses: Two large wine glasses are developed east of the slid masses (Fig. 2); others are in development process.

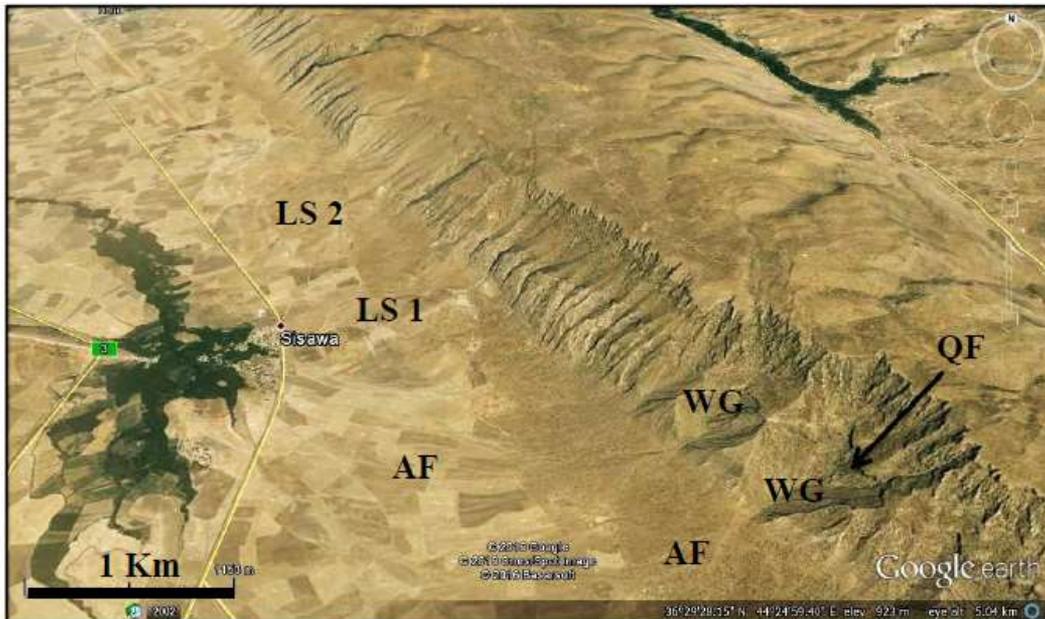


Figure 2: Google Earth image of the study area and near surroundings. Note the flat irons, alluvial fans and acute asymmetry between the two limbs of Hareer anticline.

WG = Wine Glass, QF = Qamchuqa Formation, AF = Alluvial Fan, LS1 and LS2 = Sisawa Landslides, No.1 and 2

## 2.2 Structural Geology and Tectonics

The study area is located on the southwestern limb of Hareer anticline, which is an NW – SE trending double plunging anticline. The length is 27.5 Km, whereas the width ranges from (1.5 – 3) Km; in the southwestern and central parts of the anticline, respectively. The southern limb is very steep; up to 85°, whereas the northeastern limb is very gentle; not more than 10°; therefore, the the anticline shows acute asymmetry (Figs.1 and 2), with very wide hinge zone that becomes wider in the central part; as compared to the southwestern plunge area; giving rise to curvature of the anticlinal axis. This acute asymmetry has formed many wine glasses (Fig.2) in the anticline with very steep valleys (Fig.2); some of them are canyon like; consequently, giving the possibilities of different mass movement phenomena.

Tectonically, the studied area is located within the High Folded Zone of the Outer Platform (Unstable Shelf) of the Arabian Plate [7]. The zone is characterized by narrow and long anticlines with wide and shallow synclines. Some of the anticlines exhibit thrust faulting; where the northeastern limb is thrust over the southwestern one or the northern limb is thrust over the southern one.

### 2.3 Stratigraphy

The following formations are exposed in the study area (Fig.3); the main lithology is quoted from [2,8,9,10]. Other formations; however, are exposed too but have no significant importance on the concerned landslide.

- **Qamchuqa Formation** (Lower Cretaceous): The formation consists of well bedded, massive dolostone, dolomitic limestone and limestone, it is exposed in two deeply cut valleys only; as windows (Fig. 2).
- **Bekhme Formation** (Upper Cretaceous): The formation consists of thickly well bedded dolomite and dolomitic limestone, and in the lowermost part there are marl and marly limestone beds, it forms the whole carapace of Hareer Mountain (Figs.2 and 3).
- **Shiranish Formation** (Upper Cretaceous): The formation consists of bedded marly limestone; followed by bluish green marl in the upper part, (Fig. 3).
- **Tanjero Formation** (Upper Cretaceous): The formations consists mainly of fine clastics of dark greenish black colour (Fig. 3).
- **Kolosh Formation** (Paleocene): The formations consists mainly of fine clastics of black colour (Fig. 3).
- **Khurmala Formation** (Paleocene): The formations consists mainly of well bedded limestone (Figs. 3 and 4).
- **Gercus Formation** (Eocene): The formations consists mainly of fine clastics of reddish brown colour (Figs. 3 and 4).
- **Pila Spi Formation** (Late Eocene): The formations consists mainly of well bedded dolomite and limestone (Figs. 3 and 4).
- **Fatha Formation** (Middle Miocene): The formations consists mainly of fine reddish brown clastics with rare thin limestone and gypsum beds (Fig. 3).
- **Injana Formation** (Upper Miocene): The formations consists mainly of fine reddish brown clastics (Fig. 3).
- **Mukdadiya Formation** (Upper Miocene – Pliocene): The formations consists mainly of fine grey clastics; some of the sandstone beds are pebbly (Fig. 3).
- **Quaternary Sediments**: These are represented by alluvial fan sediments, colluvial sediments and valley fill sediments (Fig. 3).

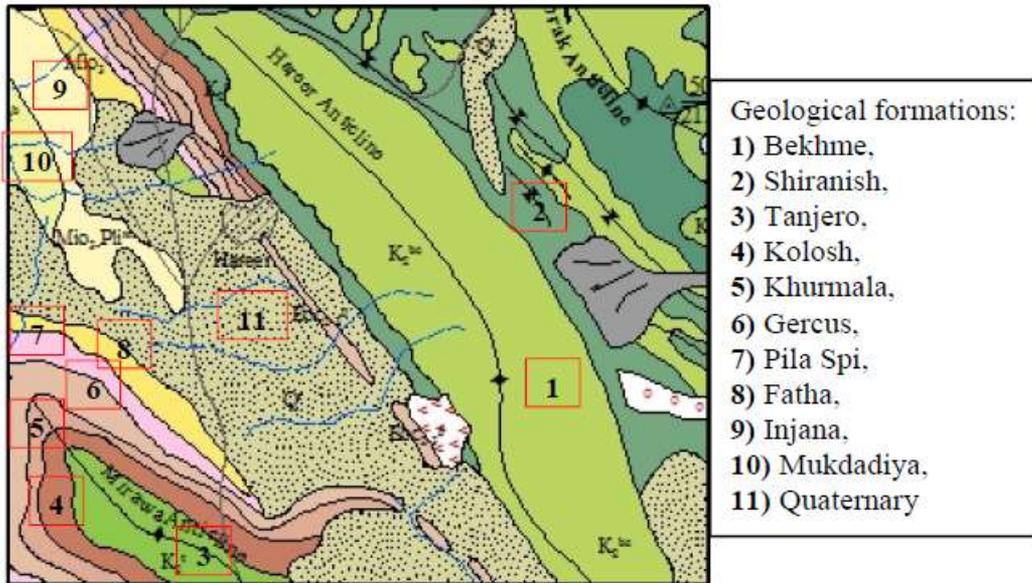


Figure 3: Geological map of the studied area and near surroundings (after [9]).

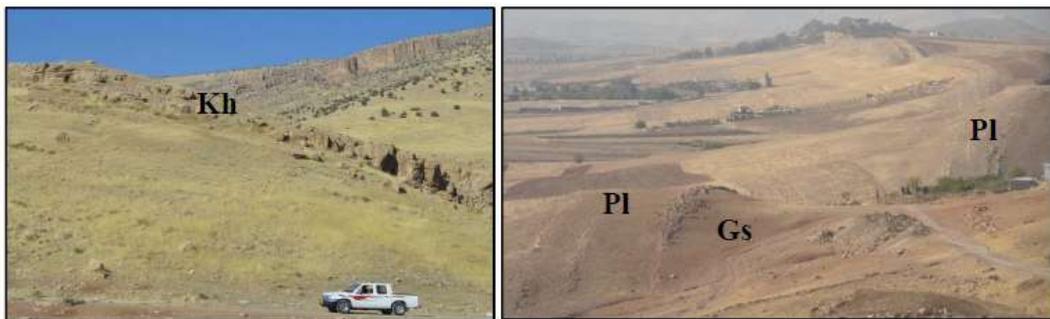


Figure 4: Left) Khurmala Formation (Kh), overturned due to down pushing of the slid mass, Right) Gercus (Gs) and Pila Spi Formations (Pl), note the very steep dipping due to down pushing of the slid mass and the offset of the ridge from its westwards continuation

### 3 Characteristics of Hareer Landslides

Two landslides occur east of Hareer town, along the southwestern limb of Hareer anticline; near Sisawa village (Figs.2 and 3) they are called Sisawa No.1 and Sisawa No.2; in this article.

#### 3.1. Geometry of Sisawa Landslides

The Sisawa Landslides have occurred along the southwestern limb of Hareer anticline (Figs.2, 3 and 5). The landslides are a rock slide type with domal-shaped; due to accumulations of thick Quaternary sediments on the slid mass.

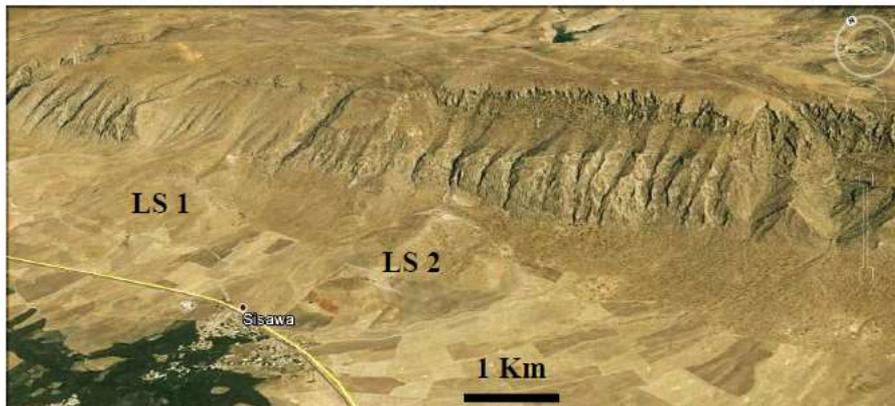


Fig. 5: Google Earth image facing NW of Sisawa Landslides No.1 and No.2

– **Sisawa Landslide No.1:** The coverage area of the slid mass is about  $973930 \text{ m}^2$ , if an average thickness of 5 m is considered for the slid mass; then the estimated volume of the slid mass will be  $4829650 \text{ m}^3$ . The moved distance; up to the toe area is about 1615 m (Fig.6). The height of the scar's bottom is 1240 m (a.s.l.), whereas the height at the bottom of the toe area is 774 m (a.s.l.), which means the gradient of the landslide is 28.85 %. The height at the top of the slid mass is 1006 m (a.s.l.); the maximum length of the slid mass is 1300 m; therefore, the gradient of the slid mass is 20.15 %. The length of the crown area is 850 m; the heights of its eastern and western sides are 1260 m and 1191 m, respectively; whereas the middle part is at height of 1312 m. The downslope length of the crown is 119 m; therefore, the gradient of the crown is 84.70 %.

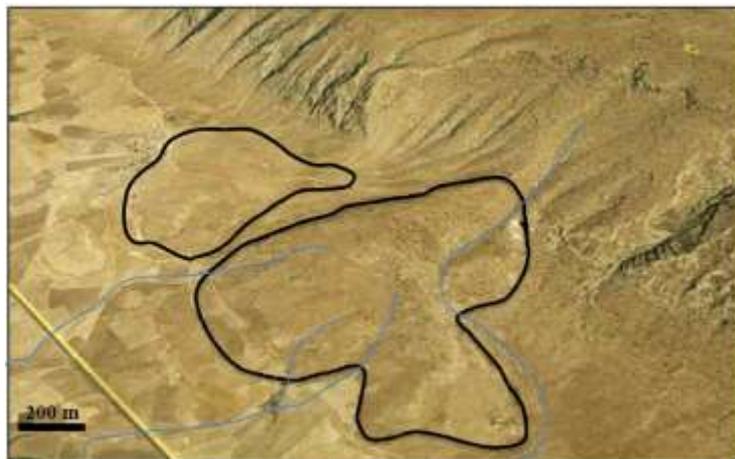


Fig.6: Google Earth image of Sisawa Landslide No.1

West of the main slid mass, there is another mass, which has fan shape. It is very difficult to elucidate whether it is part of the main landslide or an old alluvial

fan covered by rock debris. This is attributed to the fact that the landslide is very old; therefore, all the details are vanished by weathering and erosional processes.

**Sisawa Landslide No.2:** The coverage area of the slid mass is  $602640 \text{ m}^2$ , if an average thickness of 4 m is considered for the slid mass; then the estimated volume of the slid mass will be  $2410560 \text{ m}^3$ . The moved distance; up to the toe area is about 2052 m (Fig.7). The height of the scar's bottom is 1300 m (a.s.l.), whereas the height at the bottom of the toe area is 735 m (a.s.l.), which means the gradient of the landslide is 27.53 %. The height at the top of the slid mass is 878 m (a.s.l.); the maximum length of the slid mass is 1080 m; therefore, the gradient of the slid mass is 13.24 %. The length of the crown area is 1080 m; the heights of its eastern and western sides are 1306 m and 1312 m, respectively; whereas the middle part is at height of 1464 m. The downslope length of the crown is 173 m; therefore, the gradient of the crown is 94.79 %.

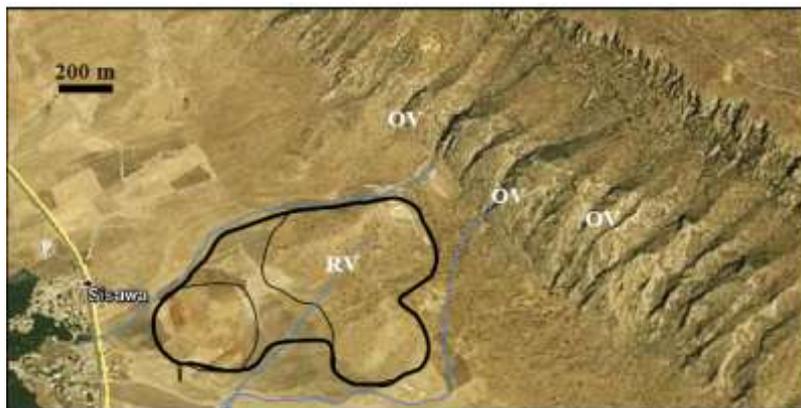


Fig.7: Google Earth image facing NE of Sisawa Landslide No. 2.  
OV = Old valley, RV = Recent valley

The slid mass includes two parts (Fig.7). It is very difficult to elucidate whether the two masses have slid at the same time or otherwise. This is attributed to the fact that the landslide is very old; therefore, all the details are vanished by weathering and erosional processes, and partly by agricultural activities within the soft materials. The authors; however, believe that the two masses have slid at the same time.

### 3.2 Crown Area

The crown area of Sisawa Landslides is a large one (Fig.8), since the length of the Sisawa Landslide No.1 is 850 m, whereas that of Sisawa No.2 length is 1080 m, with two side cliffs; the western one in both cases is more clear and steep (Figs. 5, 6 and 7). The indications for sliding on the crown area are vanished because it is very old landslide; however, the main and the western cliffs are still clear and active area for toppling and rock fall of small blocks. When comparing the shape of the

remained main cliffs and side cliffs, and the developed hollow below the cliffs with other neighbouring cliffs; then it is very clear that very large masses have slid downslope; in both cases (Figs. 5, 6, 7 and 8).



Figure 8: The crown area of Sisawa Landslides

### 3.3 The Slid Masses

The slid mass of Sisawa Landslide No.1 has a longitudinal shape with eastern bulge in its lower half part; with crescent shaped toe area. The maximum length of the slid mass is about 6120 m, whereas the coverage area of the slid mass is about 97393 m<sup>2</sup> and the volume is about 4829650 m<sup>3</sup> (Fig.6).

The slid mass of Sisawa Landslide No.2 has domal shape with two main masses; with crescent shaped toe area. The maximum length of the slid mass is about 1080 m, whereas the coverage area of the slid mass is about 602640 m<sup>2</sup> and the volume is about 2410560 m<sup>3</sup> (Fig.7).

The slid mass in both landslides belong totally to Bekhme Formation, of dolomite, limestone and dolomitic limestone. The rocks within the two slid masses show some smoothening due to weathering and erosional processes that have been acting on the blocks for long period of time. The maximum height on the top of the slid mass is 1060 m and 878 m (a.s.l.), for Sisawa Landslide No.1 and No.2, respectively. Whereas, the height at the end of the slid mass is 761 m and 748 m, for Sisawa Landslide No.1 and No.2, respectively. The height difference in the toe area with the surrounding plain is 41 m and 36 m, for Sisawa Landslide No.1 and No.2, respectively.

In Sisawa Landslide No.1, the slid mass is dissected by three valleys (Fig.6). The first one flows from Hareer Mountain and leaves the slid mass in its eastern part and continues flowing southwest wards; whereas the others run through the slid mass, which means they are younger than the sliding.

In Sisawa Landslide No.2, the slid mass is dissected by one valley, but surrounded from east and west by two valleys (Fig.7). The first one runs through the mass, which means it is younger than the sliding. Whereas, the other two valleys run from Hareer Mountain on both sides of the slid mass and continue flowing to Sisawa village.

### 3.4 Shear Plane

The shear plane of both Sisawa Landslides is not clear (Figs. 6 and 7). This is attributed to very old sliding in which the indications on the shear plane are vanished due to weathering and erosional processes. Moreover, the moved distances in both slides are small; therefore, the shear plane along which the slide had occurred is small too; consequently, the left marks were few and were vanished easily, by time.

## 4 Causes Of Sisawa Landslides

In Sisawa Landslides, multiple causes had developed the landslides; these are explained hereinafter.

### 4.1 Geological Causes

Among these causes are the presences of thickly well bedded carbonates of the Bekhme Formation (Fig. 9). The lowermost part of the Bekhme Formation, in the studied re and near surroundings has soft rocks interval [2,11]. This interval consists of alternation of soft marly limestone and marl, which has played as the lubricant agent after being saturated by water; consequently, facilitating of the sliding.

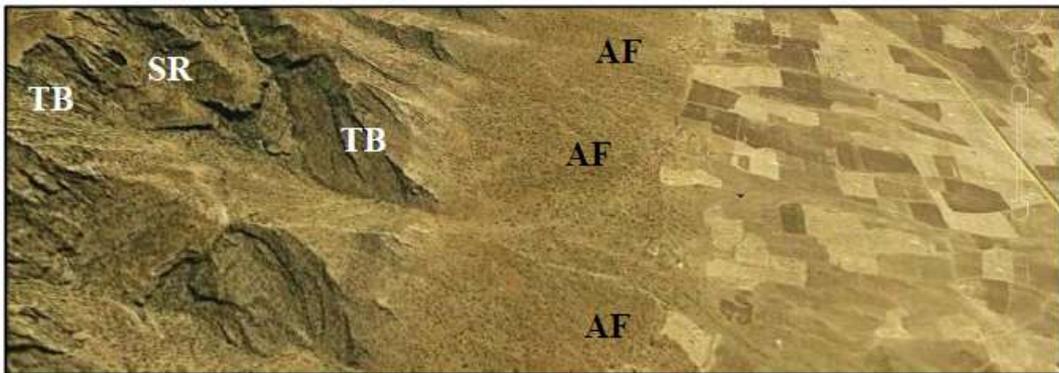


Fig. 9: Google Earth image facing NE. Note the thickly well bedded carbonates of the Bekhme Formation (TB) and the soft rocks (SR) interval forming the wine glasses and indicated by series of alluvial fans (Bajadas) (AF).

Moreover, the presence of joints, bedding planes and fractures (Fig.10), all have acted as weakness zones, besides being good passage for the rain water in between the weakness zones. During wet climate, the presence of open cracks, fishers, joints; all were filled with weathered soft clayey materials, may had caused formation of piping phenomenon by means of which the formed slurry in the opened voids has triggered and accelerated the sliding; acting as lubricant agent.

## 4.2. Morphological Causes

Among morphological causes, the main one is the fluvial erosion by the rain water, besides the freeze-and-thaw weathering and shrink-and-swell weathering. All these factors have played significant role in triggering the sliding. Moreover, the steep slopes (Fig.10), which are higher than the dip angle of the beds, had developed daylight slopes (Fig.10) that were easily triggered and accelerated the sliding living large open areas within the carapace of the mountain; from which the blocks were slid down. The smooth, large and steeply dipping flat irons (Fig.10) have played significant role as shear planes under the slid masses.

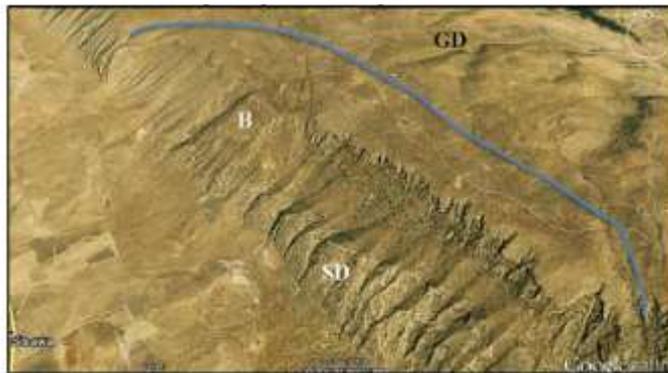


Fig.10: Google Earth image of the studied area. Note the steeply dipping beds (SD) in the southwestern limb and gently dipping beds (GD) in the northeastern limb.

Also, note the block (B), which still exists and forms daylight slope.

Proposed ditch for landslide controlling

Among the other morphological causes that have contributed in the sliding is the drainage system on the top of Hareer Mountain (Fig.11). Due to wide hinge zone of Hareer anticline, a flat lying area; plateau-shaped is developed on the top of the anticline (Figs. 1, 2, 10 and 11). Many shallow valleys run on the top of the plateau, which change to deep canyon-like valleys near the southwestern limb of the anticline. The shallow part of the valleys play as feeding the fractures of different types and the internal pore water by the rain water. Whereas, the deep parts of the valleys accelerate the weathering and erosion of the rocks and contribute in disintegration of the rocks and dividing of the carapace along the steep southwestern limb into small blocks; consequently, accelerating and triggering of the sliding down the slope.



Fig.11: Google Earth image facing SE. Note the shallow valleys (Sh V) on the top of Hareer Mountain that change to deep canyon like valleys (DV) downslopes.

### 4.3 Climatical Causes

From the presence of many alluvial fans near surroundings of the landslide area and even in the place of the landslides, it is obvious that the climate was wet with heavy rainfall [12,13,14,15] that has developed all those alluvial fans and in many stages (Figs. 2, 5 and 8). Locally, they coincide to form Bajada in particular areas (Figs. 2 and 5); along the southwestern limb of Hareer anticline.

The water in the voids of joints, fractures, bedding planes and even in those shallow valleys was frozen and melt continuously; enlarging the existing voids; consequently, breaking and breaking the carapace of Hareer Mountain; meanwhile accelerating the sliding. Moreover, the infiltrated water in the rocks of the Bekhme Formation has increased the internal pore pressure; consequently, the internal friction angle was decreased (Terzaghi and Peck, 1948); leading to the sliding.

## 5 Precautions and Landslide Control

As in each mass movement phenomenon, Sisawa Landslides' areas are prone areas for different types of mass movements, especially landslide, toppling and rock fall. It is worth mentioning that in each old landslide area, new mass movements are expected [16,17,18,19].

For each type of mass movement, there are certain types of precautions to control the movement [16,17]. In Sisawa Landslides, since it is of block-slide type, the presence of daylight slopes and steep dip slopes; due to highly dipping beds and intensely jointed, fractured and well bedded carbonates (Figs. 9 and 10); therefore, the most reliable processes to control and stabilize the unstable slopes is digging a ditch surrounding the upper part of the landslide and near surroundings (Fig.10). This precaution will preserve and/ or mitigate future landslide in the vicinity of Sisawa village and other small existing village; nearby.

## 6 Date Estimation

To estimate the age of Sisawa Landslides, the exposure dating method [1] is used depending on the size, depth and length of the existing valley on the slid masses and their surroundings, and the weathering status of the slid blocks within the slid mass.

### 6.1 Drainage system

In reviewing thoroughly in the slid masses of the Sisawa Landslide (Figs. 6 and 7), it is clearly seen that a new valleys started to be developed on the slid masses, beside those on the surrounding of the slid masses (Fig.7) or partly surrounding the slid mass( Fig.6). The shear plane should be free from drainage system, because all existing valleys were cleared and/ or filled during the sliding. This is attributed to the fact that the slid mass during the sliding on the shear plane had formed a new surface; therefore, no drainage would be on the surface, which represents the shear plane. However, in both slides; the shear plane is not free from drainage and started to include fine rills (Figs. 6, 7 and 10) indicating the effect of the water erosion on both surfaces. Certainly, development such rills will need thousands of years.

When comparing the size and the depth of the old valleys outside of the slid mass (OV in Fig. 7) with those developed on the top of the slid mass (RV in Fig.7), it can be seen that there is clear difference between them. This means that the valleys developed on the top of the landslide are younger in age as compared to those old valleys that exist out of the slid mass, which are almost early Holocene in age.

### 6.2 Age of the Existing Debris Flow

In Sisawa Landslide No.1, there is a complex phenomenon; it is not clear whether it is an alluvial fan or debris flow developed west of the slid mass (Figs. 6 and 12). Because it is very old and all the details are vanished; therefore, it is very difficult to decide what the exact phenomenon is. However, the authors believe it is a debris flow. This is attributed to the following facts: **1)** The domal shape; looks like debris flow not alluvial fan, **2)** The remained shell-like scar on the cliff (Sc in Fig.12), which resembles the shape and size of the domal shape mass, **3)** No outlet; as it exists in alluvial fans, and **4)** The curved rills on the scar indicate and point to the movement direction.

From the relation of the debris flow with the neighbouring Sisawa Landslide No.1, it is clear the the landslide is older; as evidenced from the small covered area of the landslide by the debris flow (Point 1 in Fig.12). This means that the landslide had happened before the development of the debris flow, which seems to be happened during upper late Holocene. This is estimated by comparing the depth and size of the shallow valleys (SV in Fig.12) on the scar area with those deep valleys

(DV in Fig.12) existing on both sides of the scar area on the cliff of Hareer Mountain. Therefore, the estimated age of the landslide is Holocene.



Fig.12: Google Earth image facing NW. Note Sisawa Landslide No.1 (LS 1), the debris flow (DF), shell-like scar (Sc), and the hanging block (HB), which forms daylight slope. SV = Shallow valley, DV = Deep valley. Limits of the shell-shaped scar.

## 7 Discussion

The main reasons of Sisawa Landslide are the water, dip angle; slope angle and internal friction angle, besides the presence of soft rocks interval bellow the well bedded carbonates of the Bekhme Formation (Fig.9). The decrease of the internal friction angle due to increase of the pore water pressure [20], is one of the main reasons for the sliding. This is attributed to the high rainwater fall and infiltration of the water in the present voids formed due to fractures, joints, bedding planes and the presence of shallow valleys on the top of Hareer Mountain (Fig.13).

The soft rocks interval in the lowermost part of the Bekhme Formation has played as the lubricant surface along which the sliding had occurred. This is attributed to the infiltrated water that has accumulated over the impervious mar and marly limestone beds, which are overlain by the well bedded carbonates.

The acute asymmetry between the northeastern limb (Gently dipping) and the southwestern limb (Very steeply dipping) has formed acute curvature in the flexure location of the beds (Fig.10), locally are broken forming daylight slopes. Main parts of the broken blocks were slid down. However, small parts still exist as hanging blocks (Fig.10), forming potential areas for new landslides, especially east of Sisawa Landslide No.1 (Fig.12).

The moved distance in all Sisawa Landslides is short; as compared to the size of the slid masses. This is attributed to:

1) The steep slopes of the Bekhme Formation (Figs. 10, 12 and 13) are followed by basin like area built up by soft rocks of Shiranish, Tanjero, Kolosh, Khurmala, Gercus formations (Figs.3 and 14).

2) This deep basin like area has retired the speed of the landslides and occupied the slid masses.

3) The basin like area is followed by steep cliffs of the Khurmala (Fig.4) and Pila Spi formations dipping in opposite to the sliding direction; therefore, acted as obstacle (retaining wall) for proceeding of the slid masses (Figs. 4 and 13).

However, the slid masses have almost overridden the cliff of the Pila Spi Formation in many places and very rarely have swept the cliff for short distances too (Figs. 4 and 13); forming pseudo-overturned beds. It is worth mentioning that the Pila Spi Formation in the studied area and near surroundings is very thin (3 – 8 m), as compared to its normal thickness that ranges from (56 – 189) m [21]. Therefore, the formed cliff is only few metres in height, not more than 10 m (Fig.13). Otherwise, the slid masses would move shorter distances and wouldn't be possible to override and/ or sweep the Pila Spi cliff. In other hand, if the Pila Spi Formation wouldn't be there, then the slid masses would move to farther distances.

The slid masses consist of the beds of the Bekhme Formation overriding the younger soft rocks of the Shiranish, Tanjero, Kolosh, Khurmala and Gercus formations (Fig.15). This is attributed to: **1)** The hanging blocks of the Bekhme Formation (Fig.10) met the steep slopes of the southwestern limb of Hareer anticline during the sliding; therefore gained more speed during sliding, **2)** The slid masses of the Bekhme Formation remained on the top of the younger soft rocks (Figs. 13 and 14), which were swept during the sliding until the sliding was stopped by the cliff of the Pila Spi Formation (Figs. 4, 13 and 14).

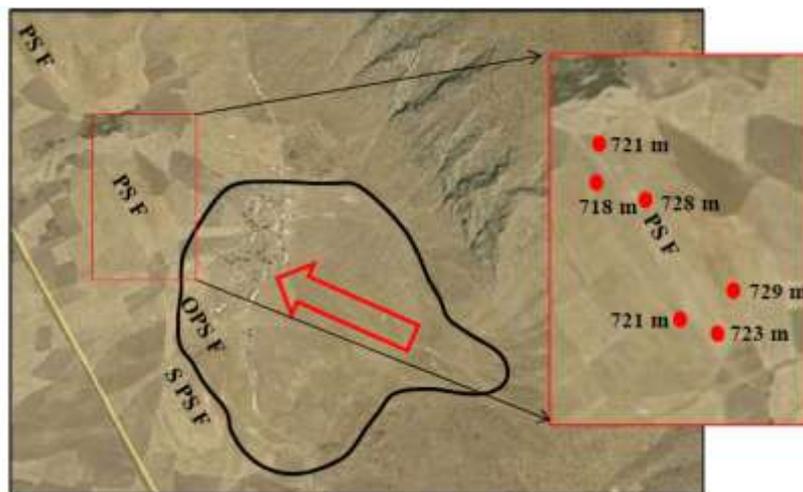


Figure 13: Google Earth image showing the cliff of the Pila Spi Formation (PS F), which is overridden by the slid masses (OPS F) and locally swept it for short distance (SPSF). Note the spot heights to indicate the height of the Pila Spi cliff.



Figure 14: The western limit of Sisawa Landslide No.1, note the deep basin like area between Hareer Mountain and the slid mass.



Figure 15: Sisawa Landslide No.1 (SL 1) and the pseudo-overturned and swept beds of the Kurmala Formation (OTKF)

As the age estimation is concerned, the most relevant estimated age for Sisawa Landslide Nos. 1 and 2 is more than 1000 years, which means late Holocene. The age estimation is based on: **1)** Shape and depth of the developed valleys on the top of slid masses as compared to other valleys out of the landslide areas, **2)** The age of the existing alluvial fans along the southwestern limb of Hareer anticline (Figs. 2, 5 and 8) is Late Pleistocene – Holocene [22,23]; and because no alluvial fans occur in the landslide area; therefore the landslides are younger than the alluvial fans, **3)** Small alluvial fans are developed from the slid masses (Figs.12 and 13), those fans are younger than the series of the old alluvial fans; therefore, the estimated age for those new fans is few tens of hundred years, **4)** The weathering status of the crown areas (Fig.8) and formed scars indicate it is very old, since no any indication is remained on those surfaces. Moreover, they are almost similar to the existing deeply cur valleys out of the landslide areas (Figs. 5 and 10), **5)** The absence of indications on the shear planes; means that they are very old; otherwise, some indications for shear movements should remain, **6)** Some of the fallen blocks have brecciated form (Fig. 16) indicating very old age to the brecciation; otherwise it would not be brecciated, and **7)** The accumulated blocks in the toe area (Fig. 17) show high degree of weathering status that indicates their very old age; otherwise the blocks wouldn't show such extremely high weathering features.



Figure 16: A fallen block within the slid mass exhibit brecciation



Figure 17: Blocks in the toe area, note the extremely high weathering status

The last aspect that should be explained and discussed is the reason for existing of the landslides in this particular area along the southwestern limb which, is about 27.5 Km in length with almost uniform dipping amount, lithology and morphology. The authors believe that the main reason for existing of the landslides in this particular area is the acute flexure of the anticlinal axis, which is concerned with a weakness zone due to existing of deep seated faults. This assumption is attributed to: **1)** The acute change in the trend of the axis of Hareer anticline (Figs. 1 and 5), **2)** The change in the width of Hareer anticline, **3)** The abnormal northwestern plunge of Shakrook anticline with adjacent plunge of the syncline (Figs. 1 and 5), and **4)** The presence of a set of faults across the cliff of the Pila Spi Formation adjacent to the area of the landslides (Fig.1).

## 8 Conclusions

The following can be concluded from this article:

The Sisawa Landslides are rock slide type, had happened in the well bedded carbonate beds of the Bekhme Formation. To the west of Sisawa Landslide No.1, there is another phenomenon, since it is very old; it is not clear whether it is a rock slide or debris' flow. The main causes of the landside are the increase of the pore water pressure and decrease of the internal friction angle, presence of marly limestone and marl beds within the lowermost part of the Bekhme Formation;

overlying the Qamchuqa Formation. The reason of relative short distance movement is the presence of cliffs of Khurmala and Pila Spi formations that have worked as retaining walls to retard and/ or stop the sliding. The age of the landslide is estimated to be 2000 – 3000 years, which means late Holocene. The reason of the presence of the landslides in Hareer Mountain at that particular area is attributed to a weakness zone formed due to the presence of deep seated faults in the concerned area as indicated from the acute change in the trend of the axis of Hareer anticline and the difference in the width of the anticline.

The landslides have domal shape; coverage area of the slid mass and estimated volume of the slid mass of No. 1 and No. 2 is about 973930 m<sup>2</sup> and 4829650 m<sup>3</sup>, 602640 m<sup>2</sup> and 2410560 m<sup>3</sup>, respectively. The gradient of the landslide No.1 and No.2 is 28.85 %, and 27.53%, respectively and the moved distance; up to the toe area is about 1300 m and 2052 m; respectively. The length of the crown area of landslide No. 1 and No. 2 is 850 m and 1080 m, respectively with gradient of 84.70% and 94.73%, respectively.

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