Equilibrium-Line Altitudes of Late Quaternary Glaciers in the Zardkuh Mountain, Iran

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Abstract
Equilibrium-line altitudes (ELAs) of former glaciers in the Zardkuh Mountain of the Zagros Mountain Range were reconstructed from glacial-geologic data on former ice limits by using various methods. In the study area various types of glacial landforms such as outwash fans, moraines and well developed glacial cirques are observed. The results suggest that ELA were depressed 1433 m below to present ELA (3067 m asl) during the maximum glacier extension. By comparison of the calculated ELA depressions (ΔELAs) and the amount of the ELA depression around the world, maximum glacier extension in Zardkuh was correlated with Last Glacial Maximum. The ELAs and ΔELAs related to youngest moraines in the study area were about 3800 and 700 m asl, respectively. The calculated ΔELAs are more comparable to the latest phases of Late Glaciations or first phases of Neo-glaciations. The study showed that the depression of the annual temperature during the LGM glaciations was about 9.74°C and it was about 4.76 °C probably during the youngest glaciation stage. This study shows that the former glaciers in maximum extension were mostly firn-basin glacier with valley glacier tongue which their tongues had reached to elevation about 2400 m above present sea level, during the LGM.

Keywords: *Last Glacial Maximum; ELA depression; Zardkuh; Zagros; Iran.*

Introduction

During the past 25,000 years, earth climate system has undergone a series of dramatic transitions. The most recent glacial period peaked 21,000 years ago (between 24 and 19 ka ago) during the Last Glacial Maximum, or LGM. At that time, the northern third of North America and many smaller mountains in Africa and the Middle East was covered by the glaciers. Deglaciation commenced in the Northern Hemisphere approximately 19,000 years ago, and in Antarctica approximately 14,500 years ago which is consistent with evidence that this was the primary source for an abrupt rise in the sea level 14,500 years ago. (Flint, 1971, Mayewski *et al.,* 1981, Dyke *et al.,* 2002, Ivy-Ochs *et al.,* 2004, Clark *et al.,* 2009, Kuhle , 2001, 2007, 2013).

A prevailing issue in paleoclimatology is the ELAs of paleo-glacier during the former glaciations. Paleo-climatic interpretations based on snowlines are constrained by difficulties in separating the effects of temperature, precipitation, and net radiation changes. Despite these difficulties, snowline altitude changes between the former and present glaciers are one of the few methods available for investigating the late-Pleistocene glaciations of some areas, such as mountainous regions of Iran (Seif, 2015).

Main centers of former glaciations in Iran were in the Alamkuh in the Central Alborz (e.g., Bobek 1937; Pedrami 1982; Yamani, 2001, 2011), the Kuh-e Savalan (Schweizer, 1970, 1972), the Irano-Turkish and adjoining Irano-Iraqi border ranges (e.g., Wright, 1962; Schweizer 1972; Sarikaya *et al.,* 2011), the Zardkuh and Oshtorankuh in the Central Zagros (e.g., Desio, 1934; Wright, 1962; Pedrami 1982; Preu, 1984; Seif & Ebrahimi, 2014; Seif, 2015), Kuh-e Jupar, Kuh-e Lalezar and Kuh-e Hezar (e.g., Kuhle, 1974, 1976, 1987, 2004, 2007) and Shirkuh (e.g., Hagedorn, *et al.,* 1975) (Fig. 1). The main objective of this research is reconstruction of the altitude of paleo-glacier equilibrium lines (ELA; Equilibrium Line Altitude) during the Last Glacial Maximum (LGM) and Late Glacial periods. These studies have shown that former ELA of the central part of Iran were between 3200 meters above sea level (m a.s.l.) (Kuhle, 1974, 1976, 2007), 3500 m a.s.l. (Hagedorn, 1975) and 3700 m a.s.l. (Dresch 1982). Some evidences of Würm glaciation have been provided from Kuh-i-Jupar in the central mountains of Iran, (east of Kerman or west of lut depression; Kuhle, 1974, 1976, 1987, 2004, 2007). Kuhle showed that climatic ELA of LGM ran at 3050 m a.s.l. (1500 m below the current ELA). Other evidences have also been provided from a mountainous glaciation in across the north flanks of Oshtorankuh region in the Zagros during the Würm glaciation (Seif, 2015) (Fig. 1).

Several studies have been done on the amount of ELAs during the former glaciations across the Zagros Mountains and north-western Zagros Mountains (on the junction between the Turkey's Taurus Mountains and the Iran's Zagros Mountains). Ramesht and Shooshtari (2004) used meteorological data of Salafchegan and Ghom stations and position of some cirque like features to estimate the height of the Würm snowline in central part of Iran. They mentioned that the ELA line in central part of Iran ran at about 2100 m a.s.l. Ramesht and Kazemi (2007) and Nematollahi and Ramesht (2005) also mentioned to some geomorphological evidences of former glacial activity in Fars provinces (Namdan and Eghlid). The amount of ELAs during the former glaciations across the north flanks of Oshtorankuh region (located about 110 km North West of the Zardkuh) was evaluated about 3120 m a.s.l. (3067 to 3165 m a.s.l.) (Seif, 2015). According to the Seif (2015), the modern ELA of the Oshtorankuh area is about 4500 m a.s.l. and ELA in the Oshtorankuh area was depressed in the Pleistocene approximately 1380 m to an elevation of 3120 m, and the glaciers extended down at least as low as 2400 m a.s.l. Mount Agri (Mount Ararat; 39.70° N, 44.30°E, 5137 m a.s.l.), located in the far east of Turkey (Fig. 1), with a modern snowline at 4300 m a.s.l.. Pleistocene snowline elevation of 3000 m was calculated on this mountain (Sarikaya *et al.,* 2011). Mount Suphan (38.93° N, 42.83° E, 4053 m a.s.l.), situated to the north of Lake Van in Eastern Turkey with a modern snowline elevation at 4000 m a.s.l.. The LGM snowline elevation was estimated at 3100 m a.s.l. for the northern side, and 3300 m a.s.l. for the southern side of the mountain (Sarikaya *et al.,* 2011; Kesici, 2005). The modern snowline, calculated from 20 small glaciers in the Buzul Mountains (Fig. 1), varies between 3100 and 3600 m a.s.l. (Bobek, 1940; Messerli, 1967), whereas the LGM snowline was estimated to have been either 2100 (Wright, 1962) or 2800 m a.s.l. (Messerli, 1967). The Kavussahap Mountains, also known as (38.21° N, 42.86° E), located about 20 km south of Lake Van (Fig. 1), contain numerous cirques on the northern slopes, many of them (particularly those above 3000 m a.s.l.) littered with rock glaciers. The satellite image analysis of Google Earth and ASTER scenes acquired, revealed the presence of very well-developed lateral moraines at altitudes as low as 2100 m a.s.l. (Sarikaya *et al.,* 2011) (Table 1).

Several estimates have been made on the temperature depressions during the Last Glacial of Iran including i) up to 5 °C in the Alborz and Zagros Mountains (Bobek, 1963), ii) 5-8 °C during the LGM in central Iran (Krinsley1970), or iii) between 8 and 10 °C for the mean annual temperature, and between 10 and 12 °C for the mean February temperature for southern Iran during the LGM (Frenzel *et al.,* 1992). The latest study in Oshtorankuh area shows that depression of the annual temperature during the Würm period ranged from 9.5 to 10.2 °C (Seif, 2015). Yamani *et al* (2007) also show that depression of the annual temperature during the last Glacier time in Karkas northern slopes (border of Band-e-Rig in the east of Kashan) ranged from 12 to 14 °C.

Small glaciers (mostly cirque glaciers) were first reported on the northern slopes of Zardkuh during August 1933 (Desio, 1934). Desio described four small glaciers with a total area of 150 ha. Each glacier occupied a span of about 200 m elevation, with the minimum occurring at about 3600 and the maximum at 4200 m a.s.l. He expressed that small glaciers of Zardkuh are relicts of the bigger ones belonging to LIA (The Little Ice Age about 1850).

Wright (1962) mentioned moraines which located in small valleys on the northern faces of the Zardkuh with 2600 m a.s.l. altitude and large outwash fan at the north face of the mountain. Based on the Wright (1962), Pleistocene snowline was apparently relatively high in the Zardkuh because this region is farther inland from the Mediterranean source of moisture and because it is an isolated high mountain that does not attract so much moisture as a great mass of high ridges like the Cilo Dagh-Algurd Dagh area.

Schweizer (1972) used the work of others and his own analysis of aerial photographs to estimate the height of the present snowline in Iran. Based on his study, the height of the present snowline in Zardkuh Mountain is above 4200 m. a.s.l. Grunert *et al.* (1978) studied the glaciers, firn patches, snowline and climate of the Zardkuh area. They described and sketched the location of five glaciers. The largest was described as 500 m wide and spanned 150 m height from 3900 to 4050 m a.s.l. Preu (1984) reported two small glaciers in cirques on the lee side of Zardkuh surrounded by moraine deposits.

He mentioned small recent glaciers in some valleys on the north faces of Zardkuh. Based on the Preu (1984), the highest peaks of the study area do not reach the present snowline.

Table 1. Former and Present ELA in various regions of Iran.

Regions	Former ELA (m a.s.l.)	present ELA (m a.s.l.)	Refrences
Alborz Mountain / Masuleh, Chalus, Gorgan,	1350-1700	-	Pedrami (1982) / Hoofer Method
Kopet Dagh / Bajgiran	2100	-	Pedrami (1982) / Hoofer Method
North West of Iran / Kurdestan / Baneh, Marivan	1650-1850	-	Pedrami (1982) / Hoofer Method
North West of Iran / Razhan (Urumieh)	2000	-	Pedrami (1982) / Hoofer Method
Zagros Mountain / Zaghaleh (Khoram abad)	2150	-	Pedrami (1982) / Hoofer Method
Zagros Mountain / Fars (Dashte Arzhan)	2300	-	Pedrami (1982) / Hoofer Method
Central part of Iran / Jiroft (Barez)	2550-2650	-	Pedrami (1982) / Hoofer Method
Alborz Mountain / Bojnord, Mashhad	2100-2300	-	Pedrami (1982) / Hoofer Method
Zagros Mountain / Borujerd and Doroud	2100-2300	-	Pedrami (1982) / Hoofer Method
Central part of Iran / Shirkuh	2500-3000	-	Pedrami (1982) / Hoofer Method
Central part of Iran / Kerman	3000-3200	-	Pedrami (1982) / Hoofer Method
Alborz Mountain / Shahrestanak	2616	-	Yamni, (2007)
Alborz Mountain / Jajroud Basin	3095	-	Yamni (2011) / Cirque floor Method
Central part of Iran / Jupar and Lalehzar	3050 -3200	4550	Kuhle, 1974, 1976, 2007 / Hoofer Method
Central part of Iran / Shirkuh and Jupar	3500	-	Hagedorn, 1975
Central part of Iran	3700	-	Dresch, 1982
Zagros Mountain/Oshtorankuh	2950-3050	4500	Seif, 2015 / Ebrahimi, 2014 / Kuhle Method
Central part of Iran	2100	-	Ramesht & Shooshtari (2004)
North west of Iran / Iran-Turkey border - Mount Agri	3000	4300	Sarikaya *et al.*, 2011
North west of Iran / Iran-Turkey border- Mount Suphan	3100 - 3300	4000	Sarikaya *et al.*, 2011; Kesici, 2005
North west of Iran / Iran-Turkey border - Buzul	2100	3600	Wright, 1962 / Based on Cirque floor
North west of Iran / Iran-Turkey border - Buzul	2800	3600	Messerli, 1967
North west of Iran / Iran-Turkey border - Kavussahap	3000	-	Sarikaya *et al.*, 2011
Zagros Mountain	-	4000-4400	Schweizer, 1970, 1972
Zagros Mountain/ Zardkuh	-	4800	Yamni (2007)
North west of Iran / Satdagh and Cilodagh	2600-3000	3100-3400	Bobek, 1937 / Based on Hoofer Method
North west of Iran	-	4000-4200	Schweizer, 1970, 1972
Central part of Iran / Yazd and Kerman	-	4800-5000	Schweizer, 1970, 1972
North east of Iran / Mashhad and Kopet Dagh	-	3800 - 4000	Schweizer, 1970, 1972
Alborz Mountain / Central part	-	4000 - 4400	Schweizer, 1970, 1972
North west of Iran / Cilodagh	2100	3300	Wright, 1962
Zagros Mountain/ Zardkuh	3600	>4200	Preu, 1980
North west of Iran / Iran-Turkey border	3000-3100	-	Zomorodian, 2002
North west of Iran / Sahand, Sabalan	3600-3700	4450-4500	Zomorodian, 2002
Alborz Mountain / Takht e soleyman	3300	4100	Zomorodian, 2002
Alborz Mountain / Damavand	3700	4500	Zomorodian, 2002
Zagros Mountain/ Zardkuh	3350	4100	Zomorodian, 2002
Central part of Iran / Shirkuh and Jupar	3200-3400	4600-4740	Zomorodian, 2002

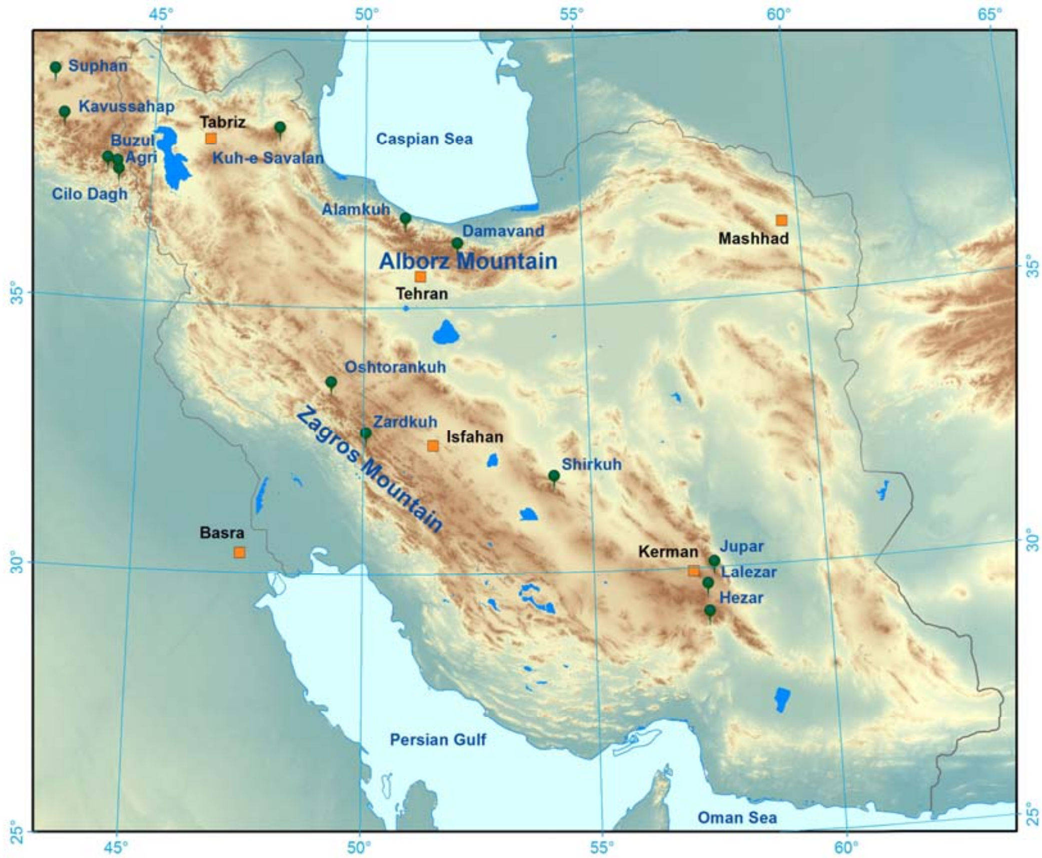

Figure 1. Location map of the main glaciated mountains.

He mentioned that the depression of ELA (ΔELA) during the last glacial period amounted to maximum 600 m, so that the ELA line in the area ran at about 3600 m a.s.l.. Ferrigno (1991) shown that the glaciers in Zardkuh had thinned considerably and the toe had receded at least 20 m of the total 100 m elevation it spanned. Mousavi *et al.* (2009) prepared a new glacier inventory for glaciers of Iran (according to GLIMS guidelines (Global Land Ice Measurements from Space, Rau *et al.,* 2005) and works supported by fieldwork). Based on Mousavi *et al*. (2009), the greatest glacier concentration in Zardkuh is observed around 1) Joftzarde and Shahe Shahidan (Zarkuh) summits, 2) around Sirdan summit and 3) Haft-tanan (Iluk) region with about 20 km^2 total surfaces.

Seif and Ebrahimi (2014) studied the morphometric characteristics of glacial cirques in the Zardkuh Mountain. According to their study, at least nine cirques with the classical characteristics of glacial cirques have developed in the lee side of the Zardkuh Mountain at altitudes above 3650 m asl. In addition, 19 cirques were classified as "Well-defined" and "Definite cirques".

Yamani (2007) mentioned to some glacial cirques in altitude 3400 and 4000 m asl and old alluvial fans which locates in the outlet of the basins. He outlined 15 glacial cirques in N face of Zardkuh and also pointed to glacial moraines which have altitude about 2500 m asl. Based on his study, height of present snowline is above 4800 m asl. Based on his study, height of present snowline is above 4800 m a.s.l.

Although several studies were done for reconstruction of former ELA in various regions of Iran (Table 1), most of them limited to application of Cirque Floor method. However, the elevation of the cirque floor/basin does not have a close relationship with the ELA of the glacier that formed it (Benn & Lehmkuhl, 2000). In addition, in many glaciated tropical mountain ranges and on large volcanoes, glaciers expanded beyond cirques to form valley glaciers, and in these circumstances ELAs lay below (often well below) the altitudes of cirque floors. In such cases, snowline reconstructions based on cirque-floor altitudes may substantially underestimate actual snowline depression. Furthermore, cirques develop cumulatively over many glacial cycles and they can therefore not be attributed to any particular glacial event. In addition of above disadvantages, there is some discussion on the nature and the origin of the cirque form features which used in studies. The main purpose of this research is reconstruction of the altitude of paleo-glacier equilibrium lines during the Last Glacial Maximum (LGM) and Late Glacial periods in the north flank of Zardkuh Mountain (central part of the Zagros Mountain Range, Iran) based on reliable methods.

Regional setting

Over 2000 km long NW-SE trending Zagros Mountain belt extends from the east of Turkey to the Makran Mountains, forming a morphological boundary between the Iranian plateau and the Mesopotamian and Persian Gulf basins. The Zardkuh Mountain lies along the central Zagros Mountain Range (32°14'–32°38'N; 49°50'–50°15'E) in Chahar-Mahal and Bakhtiari province, Iran (Fig. 2). The highest summits of this mountain chain are Kolonchin with 4220 m altitude and Shahe Shahidan with 4163 m altitude (National Cartographic Center of Iran). There are several small (relict) glaciers in this region, mostly cirque glaciers, from which two well-known rivers originate (Kuhrang and Bazoft). The greatest glacier concentration in this region is observed around Joftzarde and Shahe Shahidan summits and around Haftanan summit.

The climate of the Zagros Mountain is typically Mediterranean with dry summers and precipitation during fall, winter, and spring. The spring and summer precipitations are resulted from the cyclonic storms moving as cold fronts and are characterized by snow at higher elevations. The winter precipitation is a result of anti-cyclonic, gentler fronts.

Zardkuh area is one of the rainiest areas of the country that in terms of rainfall height are placed after west bank of Caspian Sea and equal to south banks. Great height and the general inclination of the mountains which are exposed to west and Mediterranean diagonal air masses causes' large amount of rain and snow fall in this area. In winter, several meters of snow cover is normal in mountainous area of Zardkuh.

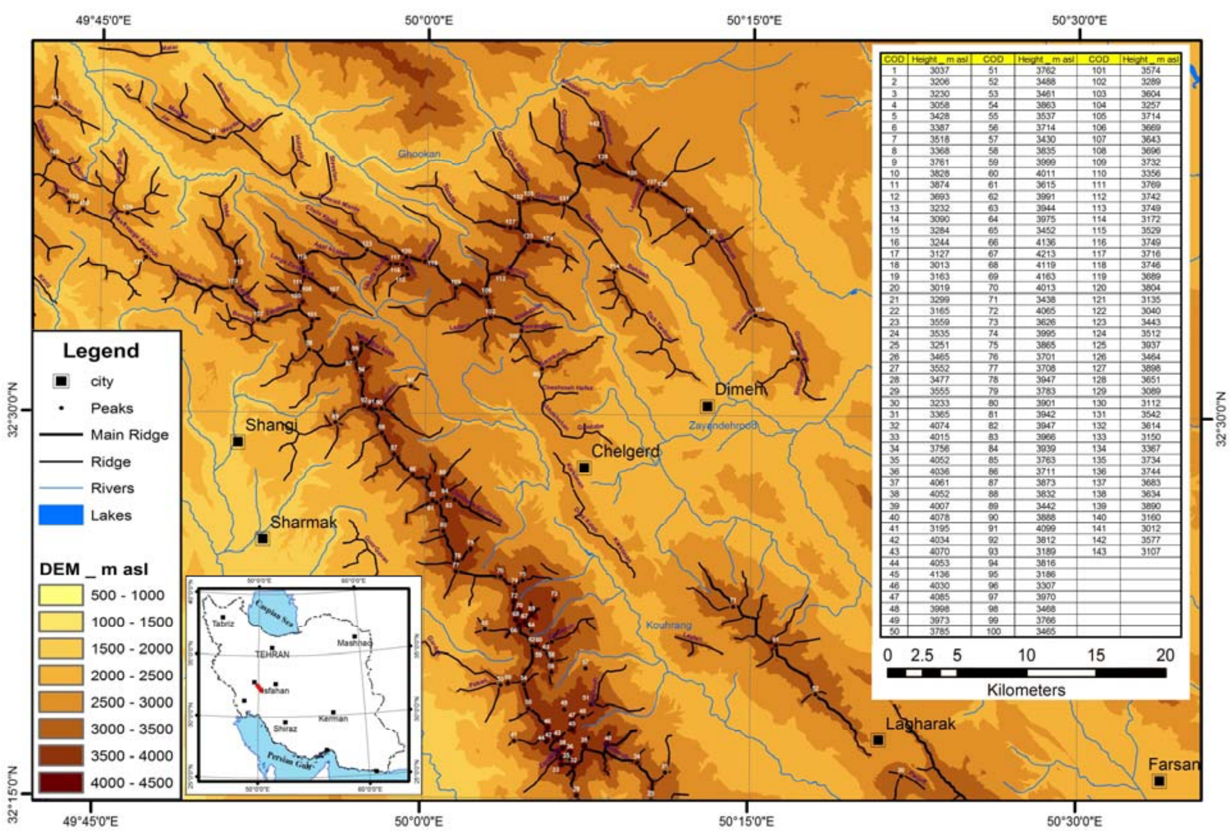

Figure 2. General topographic map of Zardkuh Mountain.

Based on the precipitation data, the northeast of Zardkuh receives 1468 mm precipitation per year in its piedmont area (at Chelgerd station with 2400 m a.s.l. altitude). The mean annual temperature of the study area is 9.6 °C (in Kuhrang station), too.

Geologically, the Zardkuh Mountain is located in the High Zagros Zone (Falcon, 1974). The High Zagros Zone is a topographic high and a relatively narrow zone (up to 80 km) of imbricated thrust faults. The High Zagros is bounded by the Main Zagros Thrust to the north and High Zagros Fault to the south. This belt includes exposures of Lower Palaeozoic rocks thrust south-westward over Mesozoic and Tertiary sedimentary rocks along the High Zagros Fault. The occurrence of numerous main faults such as Bazoft, Haftanan, Panbekal and Chamal indicates a strong tectonic activity in the area. The most exposed geological formations are Cretaceous and Oligo-miocene limestone, marlstone and marly limestone whose general trends are NW-SE. Geomorphology of the region is directly related to its geological and structural features. It is characterized by a high mountain range whose southern slopes are steeper than the northern slopes. The high relief region is composed of Cretaceous Limestone which is the most resistant formation in the region. Geologic maps of the study area with a geologic section across the main summit of Zardkuh are presented in Fig. 3.

The same as other parts of Zagros, various types of karst features, e.g. surface karrens, dolines, vertical shafts and krastic springs (Fig. 4) are common in these limestone formations (Ebrahimi 2015). All sub basins around the Zardkuh Mountains are drained by main streams flowing through the mountain valleys during flood periods, although some of the surface water infiltrate to the karstic aquifers through the karstic dolines (Fig. 4).

The upstream of all tributary valleys have a fairly U-shape cross section while the downstream of valleys has a clear V-shape cross section. The cross sections of some valleys in downstream (e.g. Pursunan and Khersan) are deep and narrow.

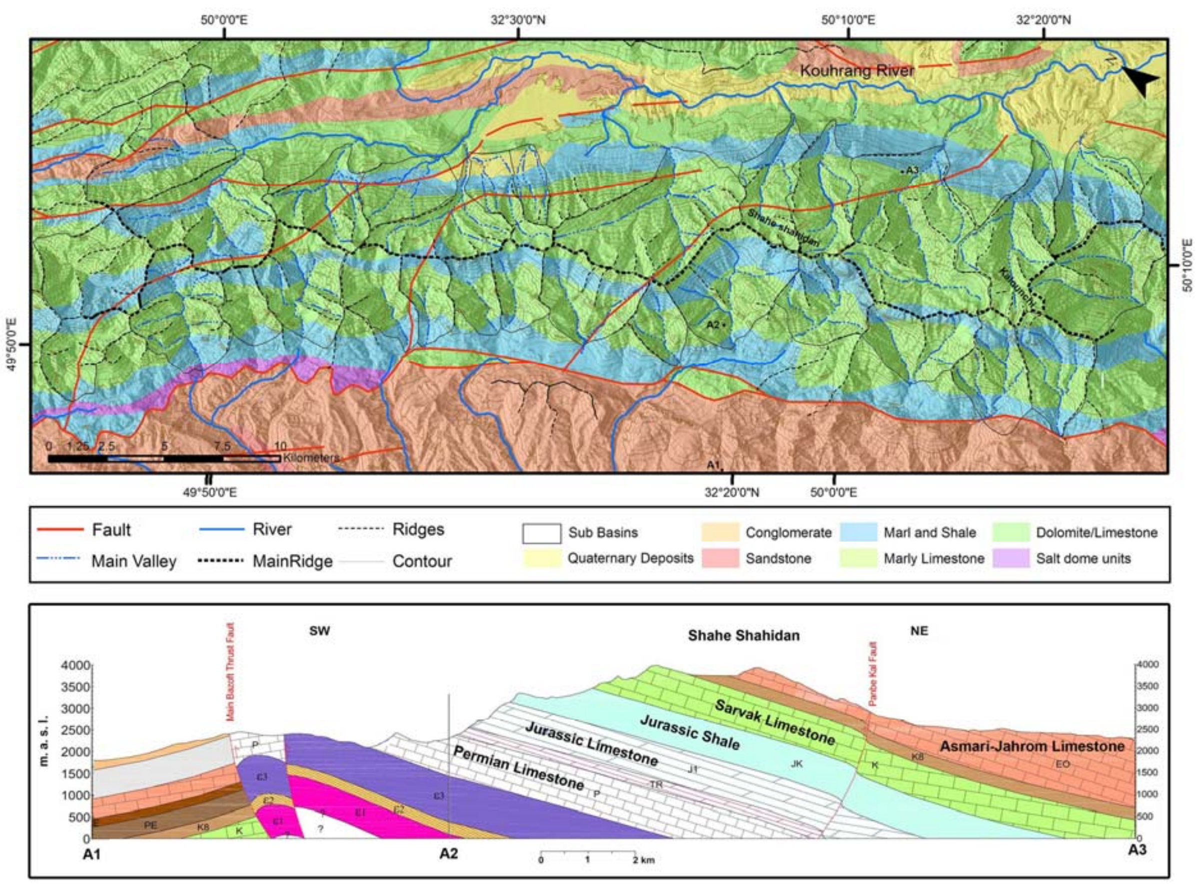

Figure 3. General geologic map of the study are with a geologic cross-section perpendicular to Zardkuh axis and pass through Shahe Shahidan summit (A1 to A3).

Figure 4. Various types of karstic landforms in the study area such as karstic spring (Kuhrang spring ▲) and karstic sinkhole (■)

Material and Methods

In this study, all sub-basins around Zardkuh Mountain were extracted using ArcGIS 10 (Spatial Analyst Tools - Hydrology) from the 1:25 000 topographical map and the DEM with 10 m spatial resolution published by National Cartographic Center (2010) of Iran. In this research, we focused on Joftzarde (No.14) and Kuhrang (No.16) sub-basins in the NW of Zardkuh (Fig. 5). The longitudinal profiles of main tributary valleys of the studied basin were extracted using ArcGIS 10 (3D Analyst) from the DEM with 10 m resolution. 3D models of the basins with combination of DEM (10 m resolution) and satellite images (Google Earth) were produced. In fact, the spatial resolution of the satellite image of Google Earth is relatively enough for our study, but its elevation data has some serious error especially in mountainous area. Thus a combination of DEM with 10 m spatial resolution and Google images were produced in our study. These models are useful tools in the identification of landforms and preparation of the glacio-geomorphological map.

Measured temperature and precipitation data are important to evaluate present day ELA in the study. For an accurate estimate of ELA depression (ΔELA), modern ELA should be calculated based on the measured temperature and precipitation of meteorological stations data. In order to calculate modern ELA, 20 meteorological stations (Synoptic and Climatological stations belong to Meteorological Organization of IRAN) for estimation of temperature (with 25 years data) and 12 stations for estimation of precipitation (with 25 years data) were selected in and around the study area (Table 1). Lack of data in some stations is reconstructed according to regression correlation of desired station and other near stations.

For the purpose of glacier reconstruction the only method is Quaternary-geological method. By means of glaciogenic key forms in the area of denudation and accumulation and their arrangement of the positions to each other it registers the maximum past glacier extension and its stages of retreat (Penck & Bruckner 1909; Klebelsberg, 1948; Flint, 1971; Kuhle, 1991; Kuhle, 2013). The importance of the arrangement of the positions with regard to the geomorphological proof of a past glacier extent is discussed in Kuhle (2013). According to glacigenic key forms and their locations relative to each other, several techniques for ELA reconstruction are developed. Standard methods applied to reconstruct the former ELAs have been described in the glaciological literature (e.g. Meierding, 1982; Kuhle, 1988a, 2013; Porter, 2001, 2005; Gross *et al.,* 1976).

The concepts of the former ELAs reconstruction methods vary significantly, as do their reliability and ease of use (Porter, 1981, Furbish & Andrews, 1984, Benn & Evans, 1998, Benn & Gemmel, 1997, Benn & Lehmkuhl, 2000, Holmlund, 1991, Richardson & Holmlund, 1996, Kuhle, 2007). Some approaches for reconstruction of the former ELAs are based on detailed evaluation of mass balance and glacier hypsometry (such as accumulation-area ratio (AAR) or balance ratio (BR) methods). The others are based on large-scale morphology (the glacier catchment, altitude of marginal moraines, and cirque floor).

Table 2. List of selected meteorological stations in Zardkuh area

NO	Stations	X	Y	Z	Station Type	1	2	3
1	Abaspoor Dam	49.60	32.07	820.00	Precipitation / Evaporation	**	*	*
2	Adalat Oregan	50.93	31.88	2323.00	Climatology	*		*
3	Adl Dezak	51.05	32.07	2280.00	Climatology	*		*
4	Beheshtabad	50.62	32.03	1686.00	Precipitation / Evaporation	**		*
5	Broojen	51.30	31.95	2197.00	Synoptic	*		*
6	Chadegan	50.63	32.77	2100.00	Climatology	*		*
7	Chamangoli	32.20	50.03	1500.00	Precipitation / Evaporation	**	*	*
8	Damaneh Freydan	50.48	33.02	2300.00	Climatology	*		*
9	Dezakabad	50.32	32.26	2232.00	Precipitation / Evaporation	**		*
10	Freydoonshahr	50.10	32.93	2490.00	Climatology	*		*
11	Ghaleshahrokh	50.45	32.66	2109.00	Precipitation / Evaporation	**		*
12	Godar Landar	49.38	32.33	260.00	Precipitation / Evaporation	**	*	*
13	Izeh	49.87	31.85	767.00	Synoptic	*	*	*
14	Koohrang	50.12	32.43	2285.00	Synoptic	*	*	*
15	Lordegan	50.82	31.52	1580.00	Synoptic	*		*
16	Marghak Bazoft	31.65	50.47	860.00	Precipitation / Evaporation	**		*
17	Masjed Soleyman	49.28	31.93	320.00	Synoptic	*		*
18	Shahrekord	50.85	32.33	2061.40	Synoptic	*		*
19	Soosan Dehsheykh	49.87	31.98	600.00	Precipitation / Evaporation	**	*	*
21	Zayandehrood	50.75	32.73	2173.00	Precipitation / Evaporation	**		*
22	Andika	49.40	32.05	500.00	Precipitation / Evaporation	**	*	
23	GoshePol	49.56	32.22	1700.00	Precipitation / Evaporation	**	*	
24	Chelgerd	50.08	32.27	2400.00	Precipitation / Evaporation	**	*	
25	DoabSamsami	50.17	32.10	1997.00	Precipitation / Evaporation	**	*	
26	GhalehTak	50.07	32.30	2380.00	Precipitation / Evaporation	**	*	
27	DezakAbad	50.20	32.15	2320.00	Precipitation / Evaporation	**	*	

1: Meteorological Station Reference : * I. R. I. Meteorological Organization and ** I.R.I. Ministry of Energy 2: Station used for precipitation analysis 3: Station used for temperatures analysis

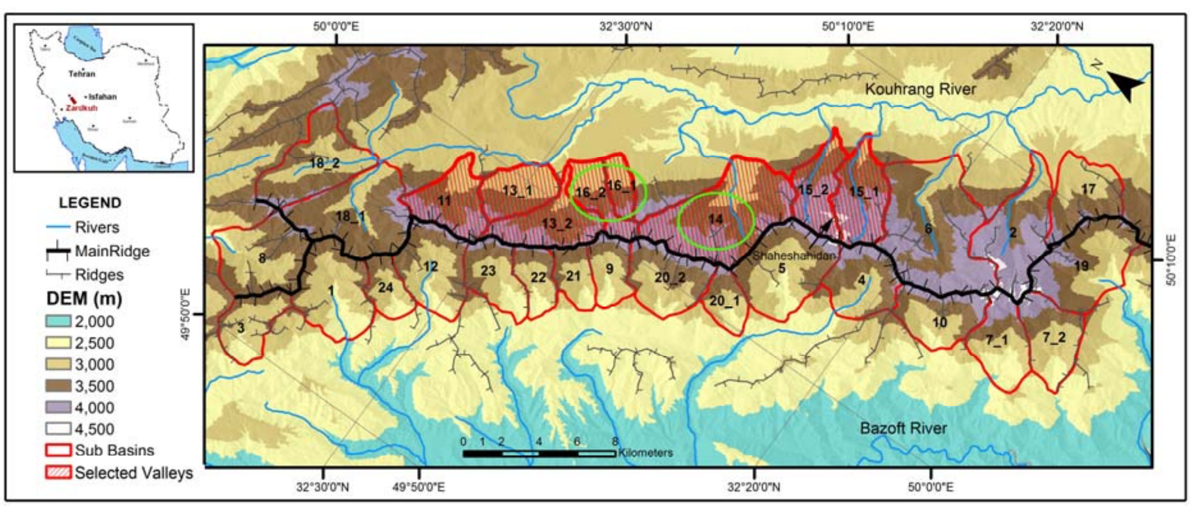

Figure 5. Location map of the main hydrological sub-basins around the Zardkuh Mountain with the location of selected sub-basins (Joftzarde and Kuhrangs).

Advantages and disadvantages of various methods have been described in the Seif (2015). In following paragraphs a summary of important methods will be discussed.

The method terminus to headwall altitude ratio or median elevation of a glacier MEG (THAR method) is commonly used because of the relative ease with which ELAs can be determined using map data. The terminus to headwall altitude ratio method is based on the observation that the ELA on modern glaciers lays approximately half-way (median) between the altitude of the upper reaches of the glacier and altitude of the terminus. In this method, ELA is reconstructed based on the altitudes of terminus and headwall of glaciers and is calculated from the following equation:

$$ELA = A_t + THAR\ (A_h - A_t) \quad (1)$$

In this formula, A_h is altitude of the head of the glacier; A_t is altitude of the terminus and THAR is a constant value (i.e. THAR = 0.45 (Klein et al. 1999, Ramage et al., 2005) or THAR = 0.35-0.40 (Meierding 1982)). In this method, determination of the lower limit of a glacier based on end moraines or outwash heads may be relatively straightforward but assigning an upper altitudinal limit to the former glacier is generally subjective and arbitrary (Porter 2001). Away to overcome the problem of defining the upper limit of a former glacier is to use the maximum altitude of the glacier catchment. This means that in Toe to Summit Altitude Method (TSAM or method by Louis 1955), THAR value is considered equal to 0.5 and maximum altitude of the glacier catchment is considered as upper altitudinal limit. Hofer (1879) used a variation of this approach by computing the arithmetic mean of the altitude of a glacier's terminus and the average altitude of the mountain crest at the glacier's head (This means that THAR = 0.5). Based on Hofer method, the ELA could be estimated by:

$$ELA = A_t + 0.5\ (A_h - A_t) \quad (2)$$

In this method, the medium altitude of the crest fringe as height of the glacier feeding area (Ah) is problematic with regard to past glaciers. Here, the averaging is only allowed with heights that are situated above the ELA, because they alone belong to the glacier feeding area. At first, however, the ELA has to be determined. This vicious circle that with regard to past glaciers is inevitable, can be avoided insofar, as first a rough approximation as base value (bv) were be determined (Kuhle 1988a). It is mediated from the highest height of the catchment area (greatest summit height in the fringing crest) of the glacier and its lowest ice margin position:

$$Bv = 0.5\ (A_m - A_t) + A_t \quad (3)$$

Where Bv is base value (Kuhle, 2013); A_m is highest backwall elevation and A_t is terminus of glacier tongue. Thus based on the Kuhle suggestion, medium altitude of the crest fringe (Ah) is equal to average altitude of the mountain ridge at the glacier's head (mean of summits and cols) above base value.

In summary, terminus to headwall altitude ratio method fails to take into account variations in valley morphology and topographic situation, which strongly affects the area-elevation distribution of a glacier. Based on the new researches, topography is an important factor in regulating moraine distribution and deposition (Barr and Lovell, 2014). In the case of cirque glaciers, topographic factors control the accumulation of redistributed snow and ice and the availability of surface debris.

Kuhle (1988) developed a version of terminus to headwall altitude ratio method to reconstruct equilibrium line of former glaciation. The method by the Kuhle (1988) is developed based on the study of the position of the toe and head wall altitudes of more than 200 recent glaciers with considering their topographic situations. The improved method by Kuhle (1988a), consider glaciers as dynamic systems whose variables, climatic environment and topography, are linked through feedback. In fact, in this method variations in valley morphology and topographic situation and their effect on the ELA is considered. In this method, THAR value was calculated based on the regression relationship of glacier morphology and ELA. In addition, the problem of upper altitudinal limit is solved by introducing the base value parameter (Eq. 3). Application of this method needs a detailed geomorphic map which should be prepared based on the field geomorphologic data, digital elevation models and remote sensing interpretations

Based on the method by Kuhle, the calculation of ELA of paleo-glaciers must involve the reconstruction of three values: (a) elevation of glacier terminus (A_t), (b) average summit elevation above base value (Bv), and (c) glacier level in zone of the mathematical index (Im). The method of determining mathematical index (Im) is based on the average summit elevation above base value and elevation of glacier terminus:

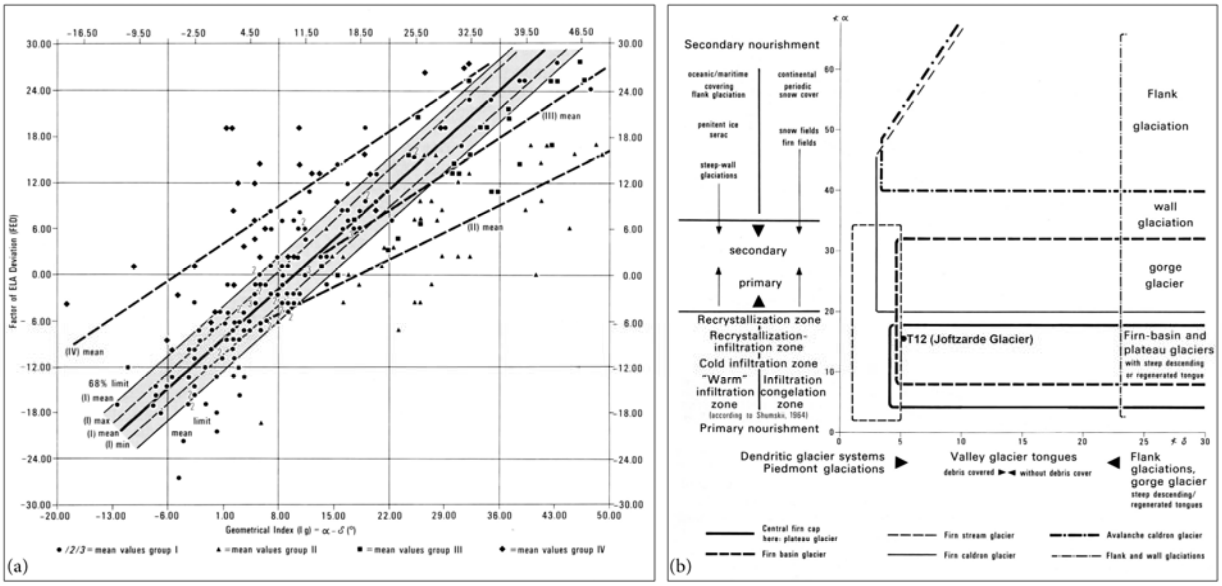

Figure 6. Diagram of Geometrical index (Ig) and equilibrium line deviations (FED) of modern glaciers (a). The position of the studied basin on the Idealized Glacier-typological diagram based on the angles α and δ (Kuhle 1988) shows that the former glaciers in maximum extension were mostly firn-basin glacier with valley glacier tongue and primary nourishment (b).

$$\mathrm{Im} = 0.5\,(A_p - A_t) + A_t \quad (4)$$

Where Im is mathematical index and A_p is the average summit elevation above base value.

Geometrical index (Ig) is another index introduced by Kuhle (1988a). The geometrical index (Ig) of a glacier is the difference between mean slope of the basin in accumulation zone (above the Im (α)) and ablation zone (below the Im (δ)) with considering some criteria given in Kuhle (1988a). Factor of equilibrium line deviation (FED) is a necessary index for calculation of the amount of ELA deviation from the mathematical index (Im-ELA) which could be extracted from Figure 6 a. Considering value of the FED and the glacier groups (Kuhle, 1988a), former ELA can be calculated by:

$$\mathrm{ELA} = \mathrm{Im} - (\mathrm{FED}.\ \mathrm{Vd} / 100) \quad (5)$$

Where Vd is vertical distance and FED is factor of equilibrium line deviation.

Kuhle (1988a) used the distribution of glaciers on a α/δ diagram (Figure 6 b) and also used terminology of Schneider (1962) for the classification of glaciers: (1) Central firn cap which continental glaciations also belong to this type; (2) Firn basin type; (3) Firn stream; (4) Firn caldron; (5) Avalanche caldron; (6) Flank glaciation/wall glaciation and (7) Schneider's ice stream system. Kuhle (1988a) also showed that the type of glacier nourishment has a relationship to the absolute values of α and δ angles. Based on his idea, up to an angle of α = 20° primary glacier nourishment can be regarded as predominant. Between 20°, and 35°, a proportionally increasing mixture with secondary nourishment is characteristic. Above 35°, the former decreases to the advantage of the latter.

Subtracting estimates of modern ELA from estimates of corresponding ELA of LGM provides an estimate of change in equilibrium-line (or ELA depression, ΔELA). Modern ELA is an important parameter that effect on the accuracy of ELA depression. According to the literatures, modern ELA is calculated based on the relationship of the ELA in the present glaciers and precipitation - temperatures data. A theoretical approach to calculate present ELA based on observed winter precipitation and ablation-season temperature is formulated by Lie *et al.* (2003) based on the Dahl and Nesje's works (Dahl & Nesje, 1992). They introduced the terms temperature-precipitation equilibrium line altitude (TP-ELA) and temperature-precipitation-wind equilibrium line altitude (TPW-ELA) to distinguish between glacier ELAs reflecting the general winter precipitation and ablation season temperature in a region and glacier ELAs that are influenced by either snow deflation or accumulation (such as on cirque glaciers). Lie *et al.* (2003) have shown that AIG (altitude of instantaneous glacierization) could be calculated by the following expressions:

AIG (or TP-ELA) = $H_0 + (100*h)$ (6)

and

$h = [\ln(0.915) + 0.339T_0 - \ln(P_0)] / [\ln(1 + \Delta P) + 0.339\Delta T]$ (7)

Where P_0 and T_0 are the winter precipitation (1 October to 30 April) and the ablation-season temperature (1 May to 30 September) at a known altitude (H_0, or altitude of climate station) and h is the height of the AIG above the H0 in hundred meters. ΔT is adiabatic lapse rate and ΔP is precipitation-elevation gradient. It must be noted that the above calculations do not take into account the effect of wind deflation and/or accumulation and thus the AIG will be the same altitude as any measured TP-ELA.

A literature survey indicates that the ELA depressions from the modern values during the LGM are typically in the range of 1000-1200 m worldwide and locally 1300-1500 m (Kuhle, 2011). Kuhle (1982, 1988b, 1998, 2001, 2013) offers a very clear documentation and detailed description of the glacial history in the High Asia (and east of Zagros) including calculation of the ELA depressions. Based on his works, the mean ELA depression of the Riß (pre-Last Glacial Maximum) is about 1400 m, the mean ELA depression of the Würm (Last Glacial Maximum) is about 1300 m, mean of ELAs depression during Late Glacial is about 700 m to 1100 m and mean of ELAs depression during Neo-Glacial stages is less than 300 m.

Discussion

In this study, the toe to summit altitude method (Louis 1955, Porter 2001), terminus to headwall altitude ratio method (THAR = 0.5 (Hofer 1879); THAR = 0.45 (Klein *et al.,* 1999, Ramage *et al.,* 2005); THAR = 0.40 (Meierding 1982, Porter 2001)), Cirque floor method with comparison of the method by Kuhle (1988a) were applied for estimation of the former ELAs in Zardkuh. As the accurate reconstruction of the equilibrium line of paleo-glaciers is dependent on the accurate glacio-geomorphologic evidences, the locations of various glacier indicators has mapped with the help of numerous signatures. In the study area, the glacial cirque, remnants of ground moraine, lateral and end moraines is founded as glacigenic forms. The maximum glacier extent is indicated by end moraines and ice marginal outwash ramps (e.g. outwash fans) in the mountain forelands.

The glacio-geomorphological data obtained from field and satellite image observations establish the sequence of the past mountain glaciations in Joftzarde basin (basin no. 14, Figure 5 and 7). The area of the basin is equal to 26.8 km^2 with mean altitude of 3381 and maximum elevation of 3995 m a.s.l.. The Kuhrang basin is another basin which has been studied. The area of the basin is equal to 11.3 km^2 and maximum elevation of 3947 m a.s.l.. The mean altitudes of the basin is 3100 m a.s.l.. The main downstream valley of the basin is a narrow and deep valley with nine main tributaries that Chalmishan and Joftzarde cirques have been developed in their uplands valleys (Figures 8, 9 and 10). The hypsometric curve of the basin shows downward concave curve which represents the young topography (Figures 8a,b,c).

An outwashed fan with 5.6 Km^2 formed by braided streams from melting of the former glaciers, are observed in the outlet of the Joftzarde basin (Figures 9, 11 and 17). The lowest terminus of former glacier is estimated at 2390 m a.s.l. based on position of the outwash fan. In the outlet of the Kuhrang basin two outwashed fans with the total area of 2.3 Km^2 can be observed, too (Fig. 12 and 17).

In the investigation area, several terminuses as indicators of glacier terminus with related lateral moraines were identified at elevation ranges from 2740 to 3650 m a.s.l. (Figures 13, 14, 15 and 16). Remnants of ground moraine, lateral morainic ramps are observed in the study area, too (Figure 9 and 10).

Figure 7. Photo mosaic of Zardkuh shows Joftzarde paleo-Glacier (▲) and Kuhrang Paleo-glaciers (■).

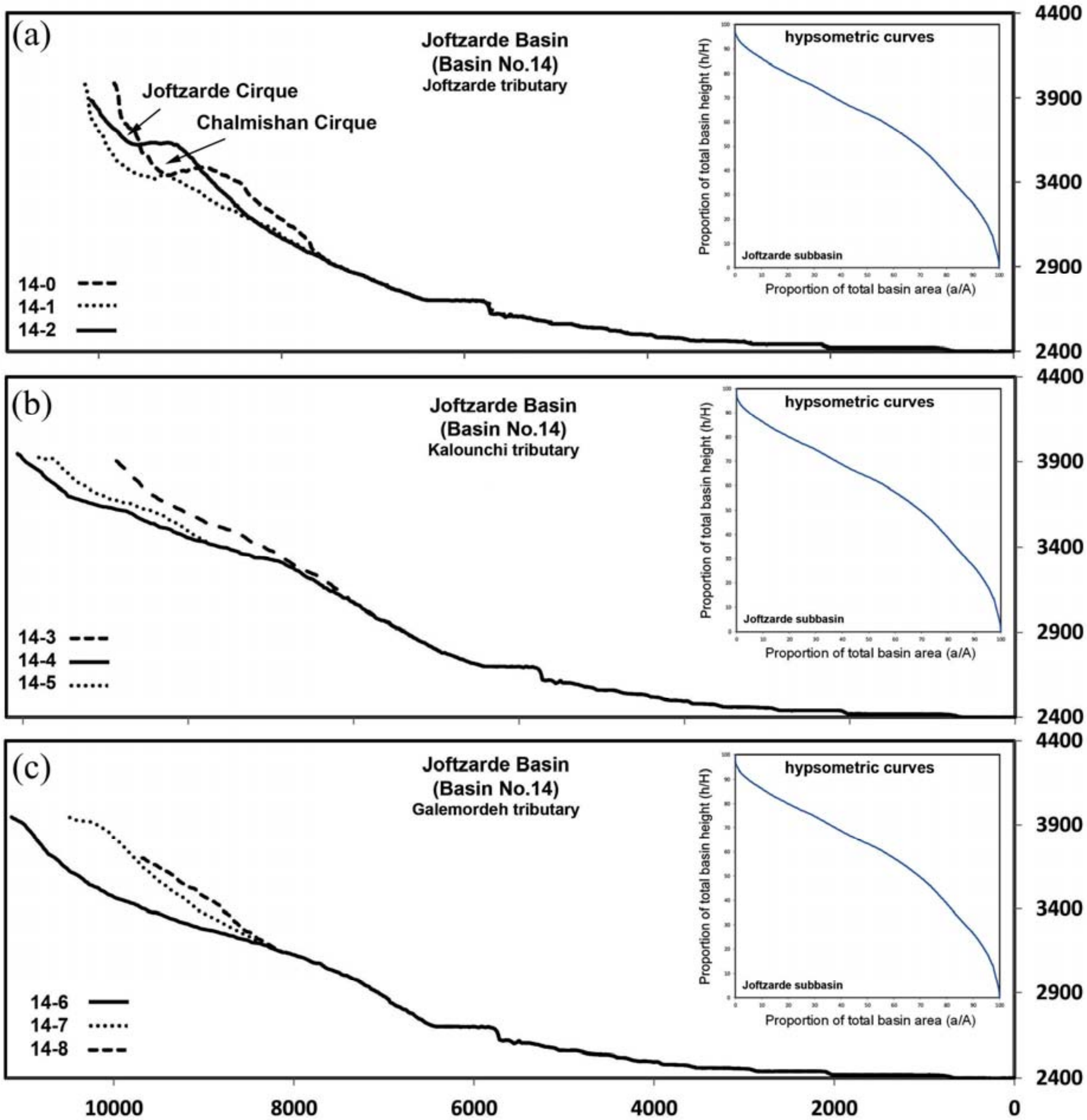

Figure 8. The longitudinal profiles of main tributary valleys of Joftzarde sub-basins with their hypsometric curves.

The subglacial ravines have been shaped by subglacial melt water erosion, are another indication of former glaciations in the study area. Normally these erosional forms are found 100 m to 300 m below the equilibrium line (Kuhle 1976) and in the basin they are observed at elevation below 3300 m a.s.l. (Fig. 10 e, f). At elevation above 3400 m a.s.l., several glacial cirques are identified (Seif & Ebrahimi, 2014). The Chalmishan and Joftzarde glaciers (Moussavi *et al.,* 2009), are small relict glaciers preserved in the glacial cirques of Joftzarde Basin.

The floor elevations of the Chalmishan and Joftzarde cirques are about 3600 and 3400 m a.s.l., respectively (Figure 10, 13 and 14).

Remnants of ground moraine, lateral morainic ramps are observed in the study area, too (Figure 9 and 10). The mean of floor elevations of the glacial cirques in Joftzarde basin is about 3578 m a.s.l. At elevations above 3300 m a.s.l., several glacial cirques containing the Kuhrang-2 and the Kuhrang-3 glaciers were observed (Seif & Ebrahimi, 2014; Moussavi *et al.,* 2009) in Kuhrang Basin (Figure 12, 15 and 16).

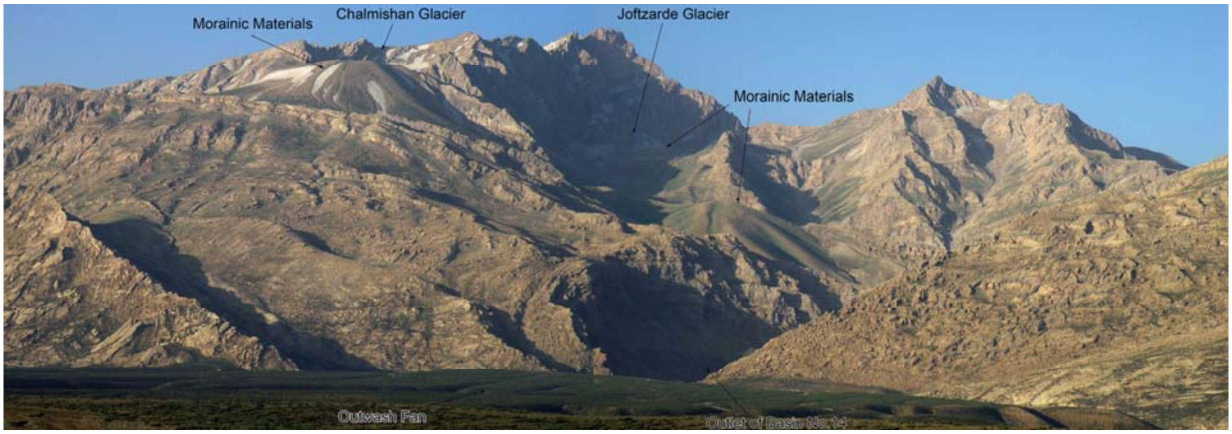

Figure 9. Photo shows the position of Chalmishan and Joftzarde cirque glaciers and related morainic materials.

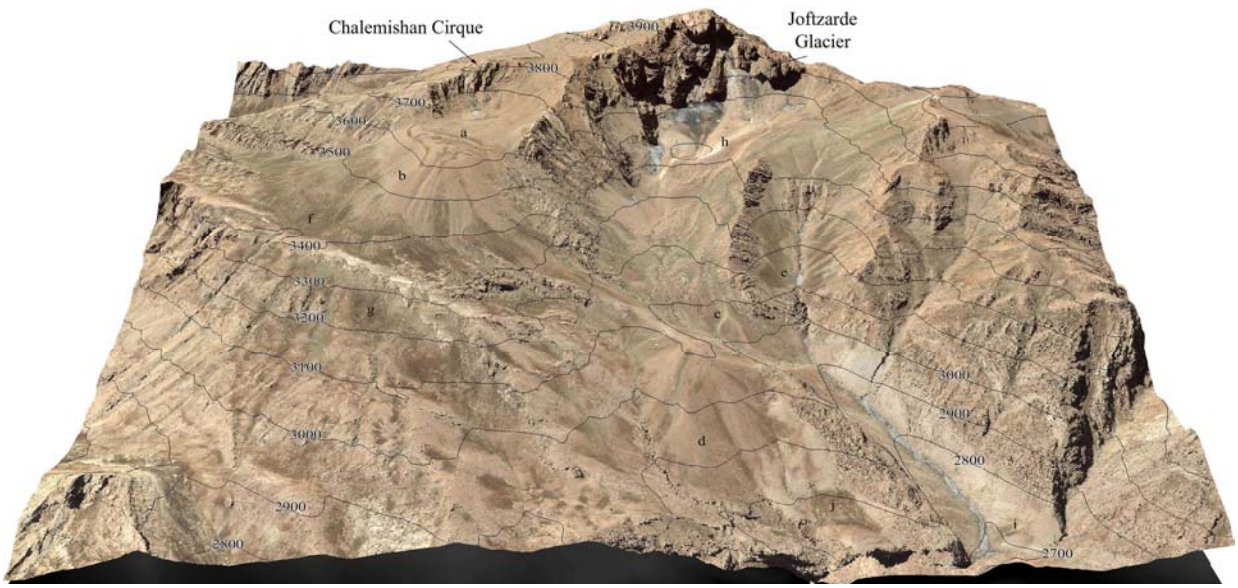

Figure 10. The position of Chalmishan and Joftzarde Glaciers in 3D model of the basin no. 14 and the position of recessional moraines ramp (a, b, c, h), ground moraines remnants (d, e, f) and subglacial channels lower than 2800 m a.s.l. (near to f and e) with some relict moraines preserved of the oldest stage (j and i).

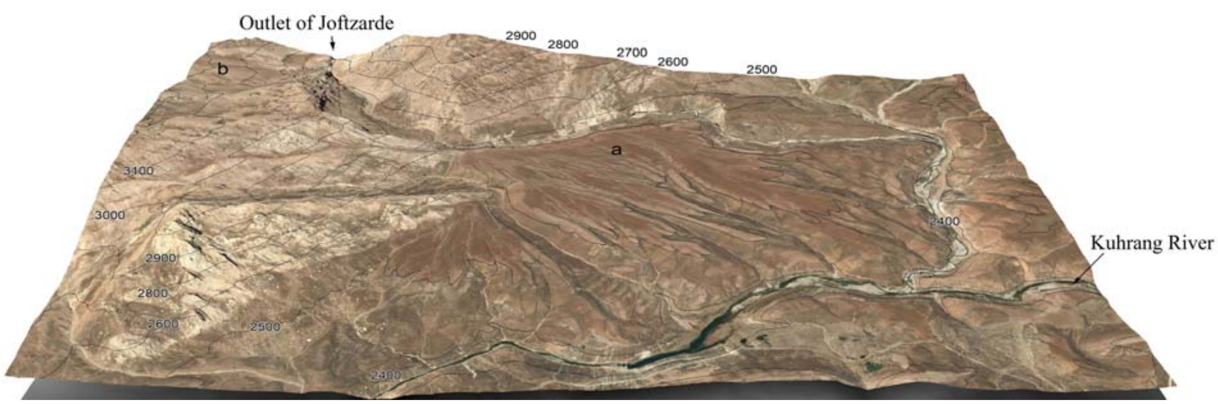

Figure 11. The position of the glacial outwash fan (a) with morainic material (b) in the outlet of the Joftzarde basin.

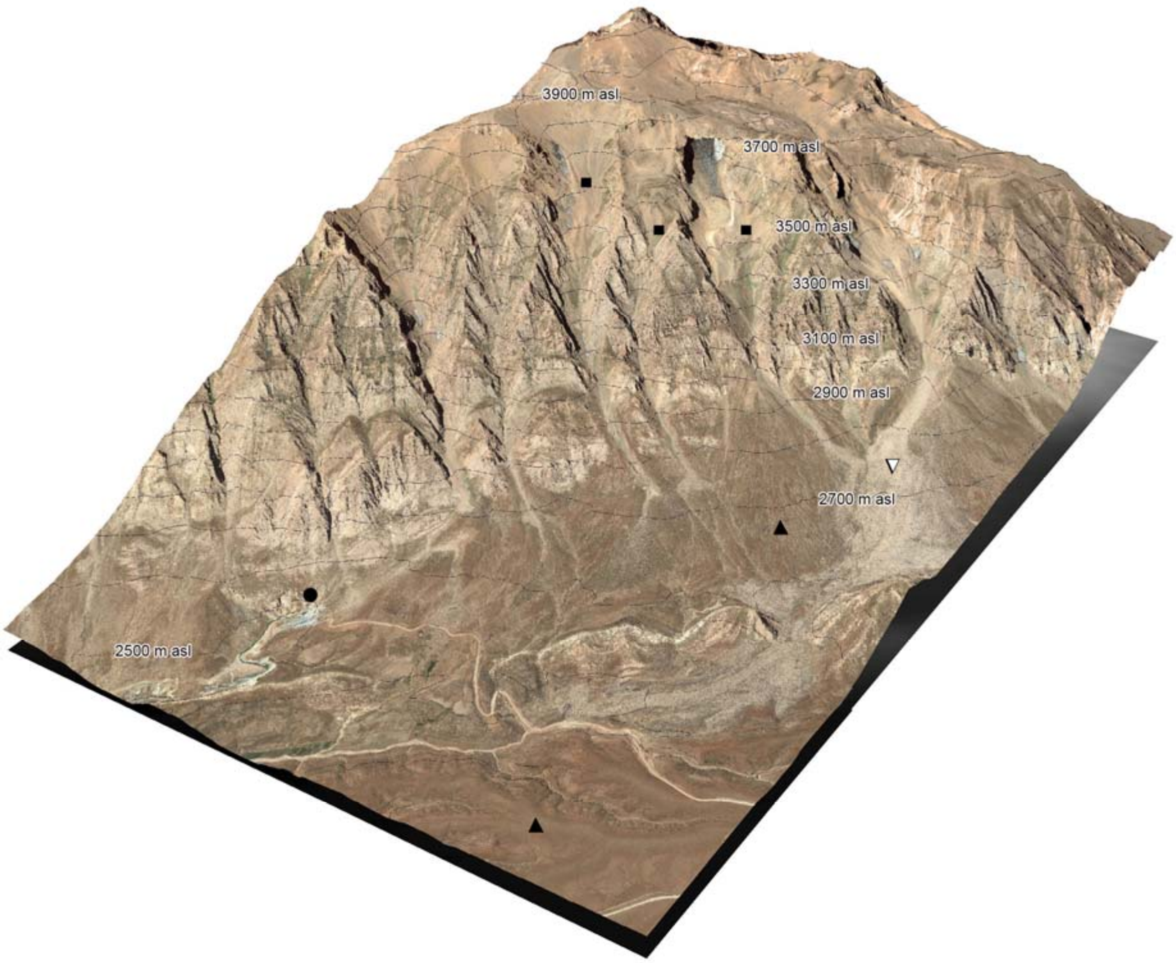

Figure 12. 3D model of Kuhrang glaciers with several glacial cirques contain relict glaciers. The position of recessional moraines ramp (■), glacial outwash fans (▲), debris flow materials (∇) and Kuhrang karstic spring (●) are marked in figure.

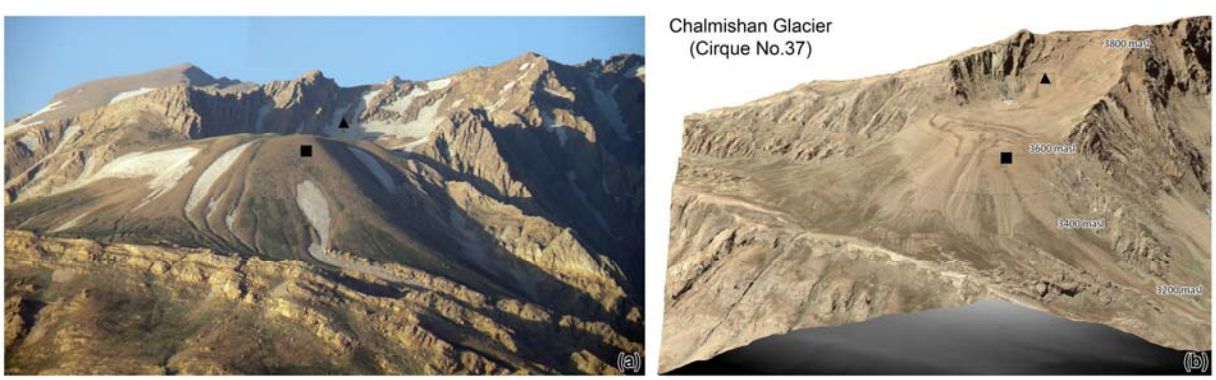

Figure 13. Photo shows position of Chalmishan cirque (▲) and related morainic materials (■) in north face of the Zardkuh (a); 3D model shows the position of Chalmishan relict glacier in the cirque glacier (▲) of the Joftzarde basin and the position of recessional and end moraines (■) (Imagery August 2013) (b).

The mean of floor elevations of the glacial cirques in Kuhrang basin is about 3500 m a.s.l. (Figures 17). In adjacent of the Kuhrang basin, Kuhrang-4 glacier are preserved in a perfect glacier cirques (No. 23) with floor elevation above 3500 m a.s.l., too (Figure 17).

Some perfect moreinic ramps belong to the youngest glacial activities (Late Glacial and Neo-

Glacial stages) are deposited within the glacial cirques (especially in cirque no. 36, 37 and 27 (Figs. 13, 14, 15 and 17)). The result of findings in the both study area are mapped on detailed glacio-geomorphological maps and are shown in Fig. 17.

Beside various methods for ELAs reconstruction, the methods by Kuhle (1988a) has shown its capability for reconstruction of the former ELA in Siberia and High Asia and thus this method in comparison of cirque-floor altitude and terminus to headwall altitude ratio methods, were used to calculate the former ELA's related to the distinguished terminuses in Zardkuh. The method by Kuhle in comparison of toe to summit altitude, terminus to headwall altitude ratio and Cirque floor methods. In this study base level which is defined by Kuhle is considered for all types of terminus to headwall altitude ratio method, too (Seif, 2015). Results of the methods are presented in Table 1.

Based on the toe to summit altitude method, lowest ELA (probably during the LGM) in Joftzarde basin was 3193 m a.s.l.

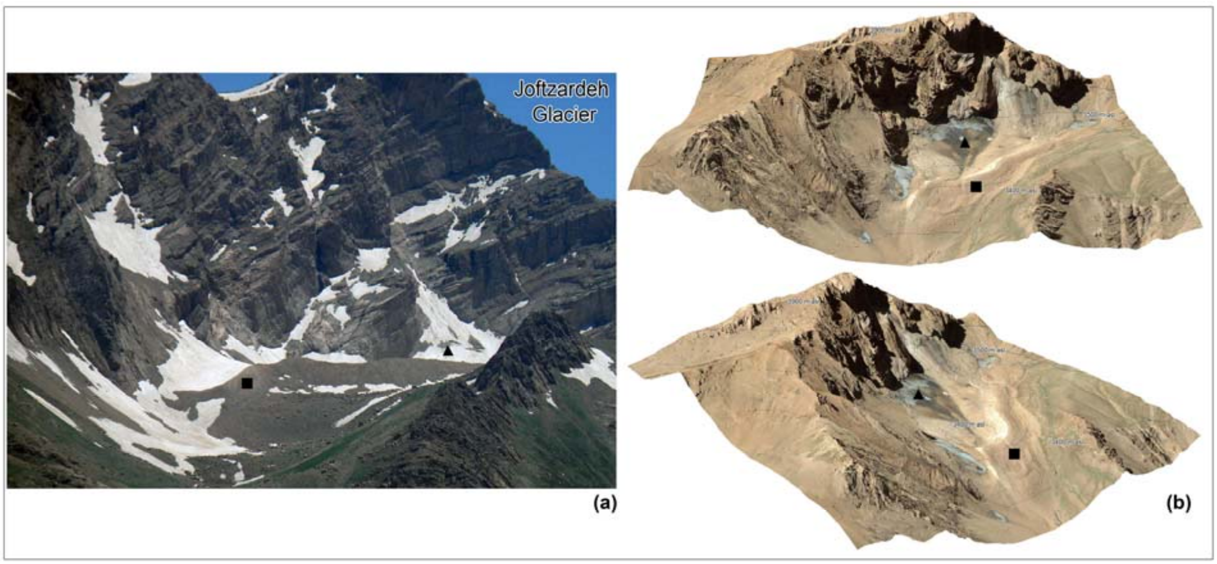

Figure 14. Photo shows position of Joftzarde relict Glacier (▲) and related morainic ramp (■) in north face of the Zardkuh (a); 3D models shows the position of Joftzarde relict glacier (▲) in the cirque glacier of the Joftzarde basin and the position of recessional and end moraines (■) (Imagery August 2013) (b).

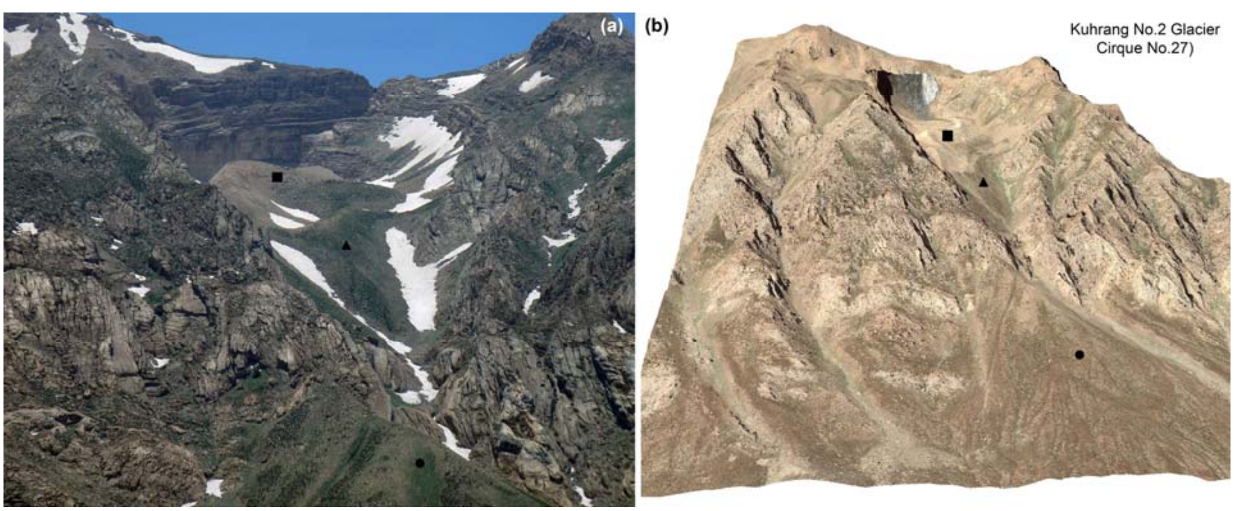

Figure 15. Photo shows position of Kuhrang 2 relict Glacier and related morainic ramp (▲■) in Kuhrang basin (a); 3D models shows the position of Kuhrang 2 relict glacier in the cirque glacier no. 27 and the position of young (■) and older morainic ramps (▲) with related outwash fan (●) (Imagery August 2013) (b).

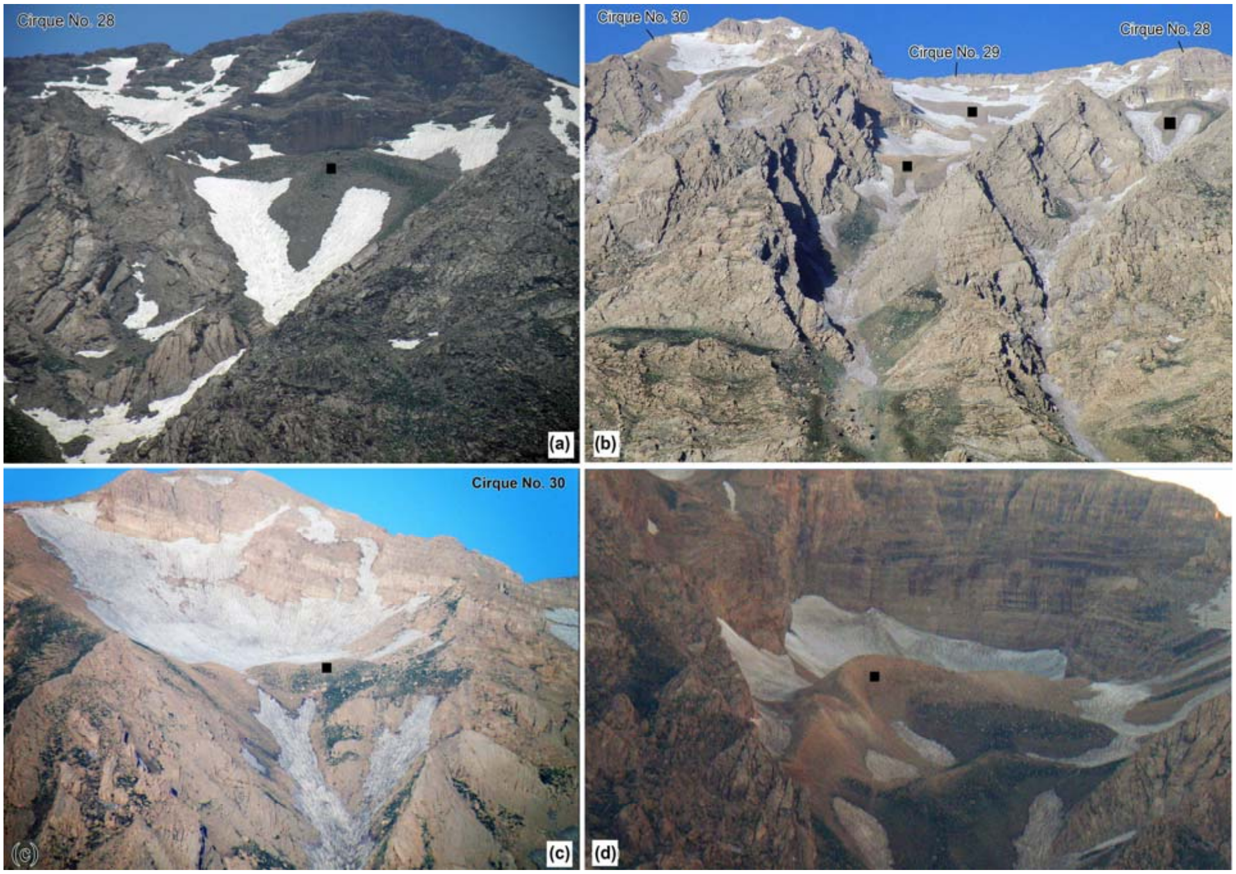

Figure 16. Photos show position of cirque no. 28 (a), cirques no. 28, 29 and 30 (b), cirques no. 30 (c) and cirques No. 30 (d). Morainic ramps (Late Glacial) are clearly seen in these photos (marked by ■ symbol).

The lowest ELA based on the terminus to headwall altitude ratio method was between 3017 m a.s.l. (THAR=0.4) to 3043 m a.s.l. (THAR=0.5 or Hofer method). Based on the Kuhle's method, lowest ELA was equal to 3067 m a.s.l. (2996 to 3126 m a.s.l. in 68% confidence limit). Fig. 18 presents upper margin of glacier accumulation and the lowest ELA with difference angle of accumulation and ablation zones that is plotted on longitudinal profiles of valleys in Joftzarde basin. The lowest ELA in Kuhrang basin based on the toe to summit altitude method was 3335 m a.s.l and based on the terminus to headwall altitude ratio method was between 3165 m a.s.l. (THAR=0.4) to 3183 m a.s.l. (Hofer method). The lowest ELA based on the Kuhle's method was equal to 3411 m a.s.l. (3365 to 3453 m a.s.l. in 68% confidence limit).

In the Joftzarde basin, glacial cirques are located on the headwall of the basin with average elevation about 3578 m a.s.l.. The average of cirque floor elevation in Kuhrang basin is about 3500 m a.s.l.. If it is considered that glacial cirques are the work of glaciers and considering 'glacial buzzsaw' propose (Mitchell and Montgomery 2006), the positions of the cirques (between 3500 to 3600 m a.s.l.) could be an indication of the average Quaternary glacial equilibrium line.

The Late Glaciations phases of Pleistocene and Neo-Glaciations are represented by morainic ramps (terminal and lateral moraines) and small relict glaciers in the Joftzarde basin. The elevation of these features from 3120 reaches to 3640 m a.s.l. The former ELAs related to Late Glaciations are calculated based on the mentioned methods and shown in Table 1. Based on the Kuhle's method, the ELAs during the Late Glaciations phases of Pleistocene and Neo-Glaciations were 3331 to 3800 m a.s.l.. The highest elevation of ELA during Late and Neo-Glaciations phases in Kuhrang basin was 3767 m a.s.l. (Kuhle's method).

Fig. 6 (b) shows positions of glacier in Joftzarde Glacier on the idealized glacier-typological diagram (Kuhle 1988a). Diagram shows that the glaciers in

Joftzarde Glacier (in maximum extension) were mostly firn-basin glacier with valley glacier tongue. Based on the diagram, nourishment of glaciers could be as primary type (glacier was fed by direct snow on the basin). For a more accurate estimate of ELA-depression (ΔELA), modern ELA was calculated, too.

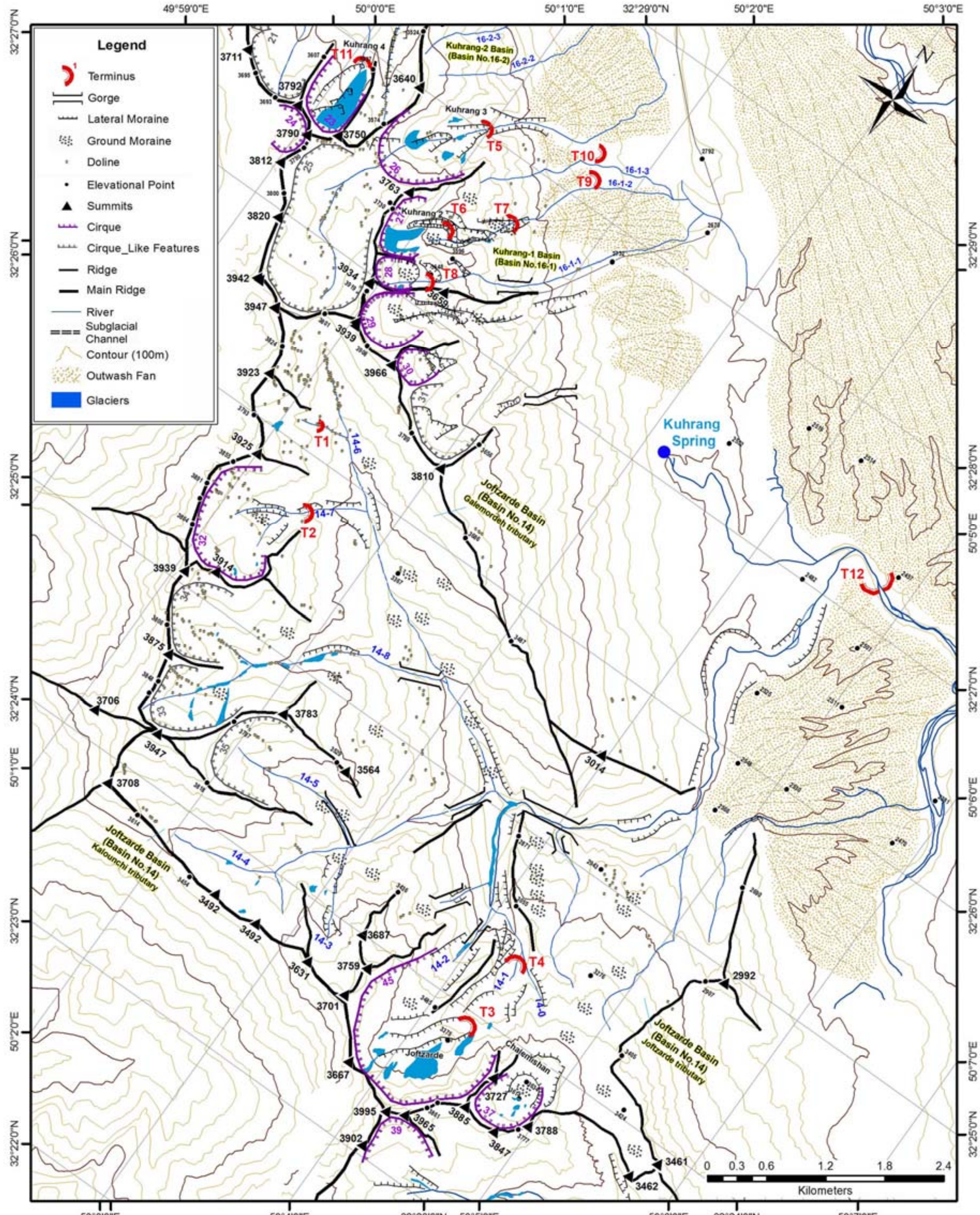

Figure 17. Map showing glaciogeomorphological findings in the study area.

Table 3. Calculated former ELA and related parameters for all terminuses

Terminus		Base value (m a.s.l.)	Mathematical Index (IM) (m a.s.l.)	Alpha (deg.)	Delta (deg.)	Geometrical Index (Ig) (m a.s.l.)	Cirque floor M (m a.s.l.)	Former ELA (Kuhle Method) (m a.s.l.)			ELA (TSAM M.) (m a.s.l.)	ELA (Terminus to Headwall Altitude Ratio Method.) (m a.s.l.) THAR Value:		
No.	Elevation (m a.s.l.)							Max (68%)	Mean	Min (68%)		0.5	0.45	0.4
Joftzarde (Basin No.14)														
T1	3640	3803	3790	23.7	17.0	6.7	3578	3810	3800	3787	3783	3761	3749	3756
T2	3590	3765	3755	16.5	10.9	5.7		3783	3770	3754	3765	3729	3715	3723
T3	3350	3673	3587	57.5	13.3	44.2		3409	3386	3354	3674	3575	3553	3566
T4	3120	3558	3472	41.1	13.2	27.9		3363	3331	3289	3558	3450	3417	3437
T12	2390	3193	3073	16.0	5.3	11		3126	3067	2996	3193	3043	2978	3017
Kuhrang (Basin No.16)														
T5	3150	3549	3485	12.5	19.6	-7.1	3500	3644	3612	3578	3549	3462	3431	3450
T6	3450	3690	3648	31.5	15.8	15.7		3642	3624	3602	3690	3622	3605	3615
T7	3150	3540	3467	22.8	22.9	-0.1		3572	3542	3507	3540	3437	3408	3426
T8	3650	3790	3790	35.0	15.7	19.4		3777	3767	3754	3790	3755	3745	3751
T9	2740	3335	3262	18.6	23.5	-4.9		3453	3411	3365	3335	3183	3139	3165
T10	2740	3344	3275	14.0	19.6	-5.7		3500	3453	3400	3344	3242	3192	3222
Kuhrang 4 Glacier														
T11	3450	3621	3597	23.5	13.7	9.8	3500	3611	3598	3583	3621	3568	3556	3563

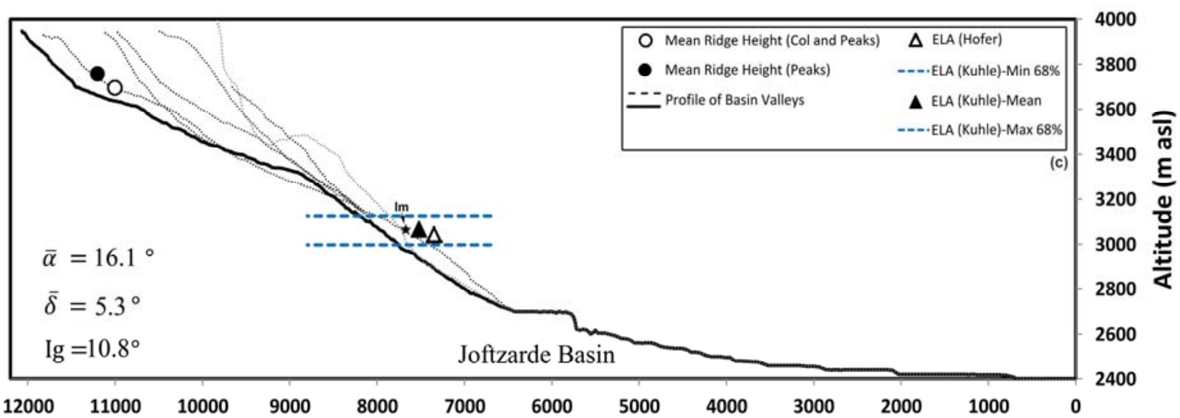

Figure 18. Upper margin of glacier accumulation and average of ELA during the LGM based on the Höfer (1879) and Kuhle (1988) methods with difference angle of accumulation and ablation zones, plotted on the longitudinal profiles of valleys in Joftzarde basin.

The mean annual temperature of the selected stations is between 9.6 °C (in Kuhrang station) and 25.5 °C (in Godarlandar station). In Table 4, the coefficients values of linear regression relationships between altitude and temperature parameters (T=aH+b) are presented. Based on the regression equations, it is estimated that the mean of annual temperature is less than 0 °C in the areas with altitudes about 3700 m. Based on the equation, the mean of annual temperature is -3.6 °C in the highest summit of Zardkuh (4220 m a.s.l.). In addition, it is estimated that the mean of temperature in ablation-season, mean of summer temperatures and the warmest month of the years are below 0 °C for the altitudes above 5015 m a.s.l., 5100 and 5430 m a.s.l., respectively (Figure 19). Based on the precipitation data, the northeast of Zardkuh receives 1468 mm precipitation per year in its piedmont area (at Chelgerd station with 2400 m a.s.l. altitude). In winter, several meters of snow cover is normal in mountainous area of Zardkuh. The maximum and minimum annual precipitations recorded at Chelgerd station are equal to 2555 mm and 925 mm, respectively (SD = 355 and the Coef. of Var. is 24). Figure 19 shows the mean annual precipitation plotted against altitude; the linear correlation coefficient ignoring Dezakabad station is 0.937 and with considering Dezakabad is 0.839. Based on the regression equations, it is estimated that the mean annual precipitation in the peak of Zardkuh (4220 m a.s.l.) is about 2100 mm (between 2026 mm and 2244 mm). Following the method by Lie et al. (2003) and considering the meteorological data, the modern AIG or TP-ELA are 4512, 4514 and 4626 m a.s.l. based on Kuhrang, Chelgerd and Dezakabad meteorological stations, respectively (Table 5). The analysis shows that the modern ELA (above 4500 m a.s.l.) in Zardkuh area is upper than the highest summit of the area. The mean annual temperature, the ablation-season temperature, the temperature of winter precipitation period, the warmest and coldest month temperatures at the ELA ELA altitude are -5.6 °C, 3.5 °C, -11.9 °C, 6.6 °C and -20.6 °C respectively.

In this study, ΔELAs are calculated based on the reconstructed ELAs related to various identified terminuses and amount of the modern ELA (~4500 m a.s.l., considering Chelgerd station). As presented in the Table 4, the mean of ΔELAs in Joftzarde basin range from -1433 to -700 m and in Kuhrang range from -1089 to -733 m.

Table 4. Relationship of altitude (H) and Temperatures (T) parameters in the study area.

T=aH+b (T: Temperatures (°C), H: Altitude (m a.s.l.))			
Parameters	a	b	r^2
Mean of annual temperature - °C	-0.0070	25.893	0.977
Mean of summer temperature - °C	-0.0072	36.715	0.963
Mean of temperature in coldest month - °C	-0.0079	14.991	0.969
Mean of temperature in warmest month - °C	-0.0070	38.046	0.962
Mean of temperature in ablation season - °C	-0.0068	34.100	0.956
Mean of temperature during winter precipitation season - °C	-0.0071	20.032	0.982

Table 5. Present TP-ELA (AIG) based on meteorological parameters of Kuhrang, Dezakabad and Chelgerd stations.

Parameters	**Kuhrang**	**Dezakabad**	**Chelgerd**
T0 : (°C)	19	18.2	18.2
P0 : (mm)	1420	876	1468
H0 : (m a.s.l.)	2285	2320	2400
ΔP : (%)	3.66 to 4.29	3.66 to 4.29	3.66 to 4.29
ΔT : (°C / 100 m)	0.68	0.68	0.68
TP-ELA (AIG) : (m a.s.l.)	4512 (4537-4487)	4626 (4651-4600)	4514 (4491-4538)

Table 6. Lowest and highest reconstructed ELAs based on the various methods with related ΔELAs.

Terminus No.	**Kuhle Method**	**Toe to Summit Altitude Method**	**Terminus to Headwall Altitude Ratio Method**		
			THAR=0.5	**0.45**	**0.4**
Joftzarde (Basin No.14)					
Lowest ELA (m a.s.l.)	3067	3193	3043	2978	3017
ΔELA (m)	-1433	-1307	-1457	-1522	-1483
Minimum ELA above the Lowest ELA	3331	3558	3450	3417	3437
ΔELA (m)	-1169	-942	-1050	-1083	-1063
Highest ELA (m a.s.l.)	3800	3783	3761	3749	3756
ΔELA (m)	-700	-717	-739	-751	-744
Kuhrang (Basin No.16) and Kuhrang 4 Glacier					
Lowest ELA (m a.s.l.)	3411	3335	3183	3139	3165
ΔELA (m)	-1089	-1165	-1317	-1361	-1335
Minimum ELA above the Lowest ELA	3453	3344	3242	3192	3222
ΔELA (m)	-1047	-1156	-1258	-1308	-1278
Highest ELA (m a.s.l.)	3767	3790	3755	3745	3751
ΔELA (m)	-733	-710	-745	-755	-749

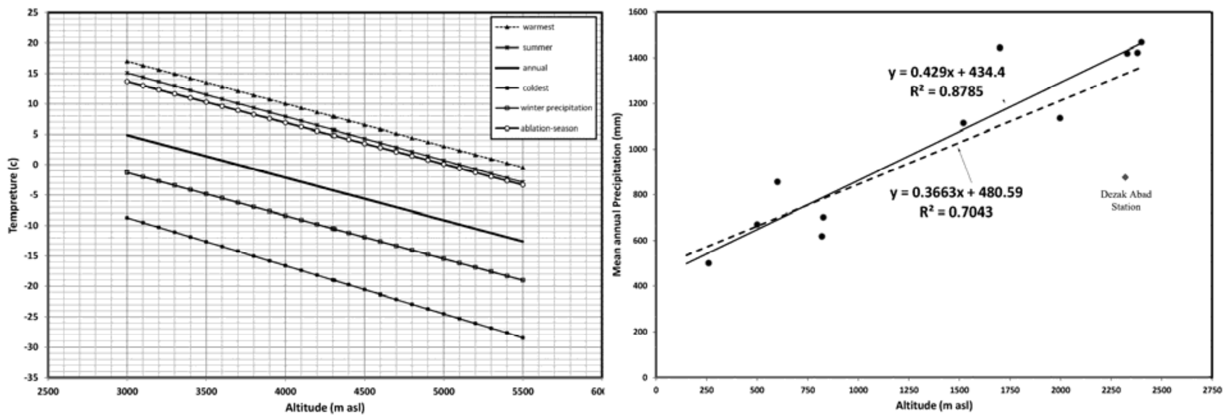

Figure 19. The relationship between altitude and temperature parameters (left) and regression plots of altitudes (H) against mean annual precipitation (P).

Based on the lowest reconstructed ELA (3067 m a.s.l. for Joftzarde basin), the value of ΔELA is -1433 m. Above the lowest reconstructed ELA in Joftzarde, minimum ELA related to the recessional moraine was 3331 m a.s.l. which shows about -1169 m depression in ELA. The amount of ΔELA of the highest ELA is presented in Table 4, too. Based on the highest reconstructed ELA (3800 m a.s.l. for Joftzarde basin), the value of ΔELA is about -700 m. In Kuhrang basin, lowest ELA (3411 m a.s.l.) with -1089 m depression is more correlated with minimum ELA above the lowest ELA of Joftzarde basin. The highest reconstructed ELA in Kuhrang basin (3767 m a.s.l.) with -733 m depression is more correlated to highest reconstructed ELA of Joftzarde basin (ELA=3800 m a.s.l. and ΔELA=-733).

Conclusion

Zardkuh in the central part of Zagros is one of the best places in Iran to find traces of Pleistocene mountain glaciers. Various founded glacial landforms in the Zardkuh (such as outwash fans, glacial cirques and glacial moraines) are best evidences of glacial activity during last Quaternary in Zagros Mountains. The developed glacial cirques in upland valley of the study area contain obvious exposed Pleistocene morainic ramps. The resulting pattern of spatial distribution of founded glacial landforms belongs to former glaciations made possible to reconstruct the glacial history of the study area. The glacio-geomorphological analysis with the calculation of former and modern ELA and ΔELA show various phases of Late and Neo-glaciations activity.

The oldest Pleistocene deposits in form of outwash fans are observable in the foot of the northern flanks of Zardkuh Mountain. There are large and perfect recessional moraine above the oldest Pleistocene deposits of the area at elevation about 2740 m a.s.l. which could be correlated with oldest phases of Late Glacial. The last glacial phase of the Pleistocene in Zardkuh is represented by small relict glaciers on well-developed glacial cirques (Chalmishan, Joftzarde, Kuhrang 2) and related morainic ramps at elevations above 3500 m a.s.l.

The amount of ELAs during the former glaciations across the north flanks of Zardkuh region was evaluated using the toe to summit altitude method, terminus to headwall altitude ratio, cirque floor and method by Kuhle (1988a). Based on the toe to summit altitude method method, the mean of lowest ELA in the north flanks of Zardkuh was about 3193 m a.s.l.. Application of the Höfer (THAR=0.5) method showed an ELA about 3043 m a.s.l.. Based on the method by Kuhle, the mean of lowest ELA was about 3067 m a.s.l. (2996 to 3126 m a.s.l. in 68% confidence limit). The application of cirque floor altitude showed an ELA above 3500 m a.s.l. which is higher than of the other methods (more than ~400 m). If we accept the idea of Mitchell and Montgomery (2006), then positions of the cirques above 3500 m a.s.l. are indications of the average Quaternary glacial equilibrium line (not LGM or Wurm Glaciation) of Zardkuh mountain.

According to the method by Lie *et al* (2003), the modern ELA (AIG or TP-ELA) of the study area is about 4500 m a.s.l.. Considering the modern ELA and the reconstructed former ELAs, amount of ΔELAs ranges from 1433 m (maximum depression) to 733 m (minimum depression). It means that, the ELA in Zardkuh Mountain was depressed in the Pleistocene approximately 1433 m to an elevation of 3067 m, and the glaciers extended down at least as low as 2390 m a.s.l. By comparison of the calculated ΔELA (~1400 m) and the amount of the ELA depression around the world (1000-1200 m worldwide, locally 1300-1500 m), in Kuh-i-Jupar massif 1500 m (Kuhle, 1982, 1988b, 1998, 2001, 2011, 2013) and in Oshtorankuh mountain 1400 m (Seif, 2015) the lowest ELA (3067 m a.s.l.) could be correlated with the LGM (Würm Glacial Period).

In Zardkuh area, during the LGM period, depression of the climatic snowline (ΔELA) amounted to 1433 m. Accordingly, with gradient of 0.68 °C/100 m, depression of the annual temperature during the LGM period was 9.74 °C. It is reminded that depression of the annual temperature during Würm glaciations was calculated 10.5 °C for Jupar Mountain by Kuhle (1976) and 9.8 °C in Oshtorankuh by Seif (2015).

Above the lowest Pleistocene deposits of the area recessional moraine are observed at elevations about 2740 (in Kuhrang basin) to 3650 m a.s.l (in Kuhrang basin) which can be formed in the younger glaciation phases. Based on the method by Kuhle, the ELAs related to morainic deposits at higher elevation were between 3331 to 3800 m a.s.l.. Considering the modern ELA (4500 m a.s.l.) and the reconstructed ELAs, amount of ΔELA for lower ELA is 1169 m. By comparison of the calculated ΔELA (1169 m) and the amount of the ELA depression around the world, ELA equal to 3331 m a.s.l. could be correlated with the early phases of Late Glaciations periods. Clarification exact date of these sediments requires isotopic study (e.g. OSL, 14C, or cosmogenic isotopes dating) and it is necessary to be considered in future studies. The ELA related to youngest deposits in the study area was about 3800 m a.s.l. (based on the method by Kuhle). Considering the modern ELA (4500 m a.s.l.) and the reconstructed ELA related to the youngest glacial deposits, amount of ΔELA is 700 m which with considering the leeward accumulation of wind-blown snow (TPW-ELA) for Neo glaciation, is more comparable to the latest phases of Late Glaciations or first phases of Neo-glaciations. It means that, during the latest phases of glaciations in Zardkuh area, depression of the climatic snowline (ΔELA) amounted to 700 m. Accordingly, with gradient of 0.68 °C/100 m, depression of the annual temperature during the latest phases of glaciations was 4.76 °C (4.98 °C warmer than the LGM). In addition, the average annual temperature at the LGM snowline (3067 m) was -5.2 °C. This is an indication for temperate glaciers with wet base, similar to the current glaciers in the European Alps.

Finally, Application of the method by Kuhle also shows that the former glaciers in maximum extension were mostly firn-basin glacier with valley glacier tongue and direct nourishment which their tongues had reached to elevation about 2400 m a.s.l., during the LGM.

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