Reconstruction of Palaeoglacier in the Qugaqie valley in Nyainqêntanglha Range

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Abstract: Reconstruction of palaeoglacier is important for understanding the mechanism of palaeo-climatic change and predicting water resource in Tibet. The climate and water resource are sensitive to global change in western Nyainqêntanglha Range. However, the data of how glacier changed in its area and equilibrium line, particularly its volume are still in paucity. In this study, we generated the palaeoglacier landform map by field investigation and 3S (RS, GPS and GIS) technology, reconstructed the palaeoglaciers surface by glacial landforms and glacier model, accordingly estimated the ice volume and equilibrium line altitude (ELA), and then discussed the palaeo-climate during the last glacial maximum (LGM) in the Qugaqie valley. During the LGM, the Qugaqie glacier was about 18.5 km long and 102.1 m thick in average. It covered an area of 59.1 km² and had a volume of 6.05 km³, which were 8.34 times of the area and 18.33 times of the ice volume of the modern glacier. The 75.3% of Qugaqie valley was covered by glacier. The palaeo-ELA was 5405~5496 m with a depression of 400 to 300 m, which confirms Shi Yafeng’s point that an even global ELA lowering value of about 1000 m didn’t virtually exist.

1. Introduction
Numerous glaciers existed in the Tibetan Plateau and left abundant glacial remnants in the Quaternary period. Glacial landforms, which are the products of palaeoglacier activities, are important for reconstructing palaeo-glaciation and palaeo-climate. In the early days, scientists got geometry information based on glacial landforms by the traditional fieldwork investigation, which is a hard work and spends a lot of time. With the development of geographic information science (GIS), remote sensing (RS) and Global Positioning System (GPS), some scholars used GIS and RS to identify glacial landforms [1-3]. This greatly reduced fieldwork, and made the mapping large-scaled glacial landforms much easier [4-6]. Some scholars also have used high-precision differential GPS for topography measurements to accurately study the macroscopic characteristics of moraine landscapes [7,8].

With the intensification of recent glacier retreatment in the Tibetan Plateau [9,10], water resources become more and more much concerned [11]. And the water resource is a focus of scientific research. Therefore, it is very significant to obtain palaeoglacial ice volume to estimate water resources in the past. In the early days, scientists used the extent of palaeoglacier to estimate water resource [12]. Later, scientist estimated water resource based on the relationship between glacier volume and area [13]. However, these methods just estimate some crude results, so some scientists have reconstructed...
palaeoglacier to get more accurate palaeoglacier volume.

Traditionally, many researchers participate in traditionally fieldworks to find geomorphologic evidences of former glaciation, and utilize aerial photographs and field mapping to plot geomorphologic evidence on topographic map, from which the lateral extent of glaciers can be identified from locations of ice marginal landforms and till limits [14-17]. This approach relies heavily on geomorphologic evidences and not explicitly on glacier physics, and the results depend on the practitioner’s experience about glaciers. Numerical models formulated from physics are routinely used to reconstruct palaeoglacier [18-22], and respect geomorphologic evidences and glacier mechanism. But some models are more complex in theory and mechanism, and need input many parameters, which leads to the application of numerical models not widely.

Another purpose of reconstruction of palaeoglacier is to estimate its ELA [19, 23]. The ELA could be used to deduce palaeoclimatic conditions [24,25]. Several empirical studies have showed the correlation between temperature and precipitation at the ELA in present-day glaciers. Therefore we can infer the temperature or precipitation when knowing any one of them [26,27]. So this method is used to deduce palaeoclimate.

During the Quaternary, there were massive palaeoglacial activities in the Nyainqêntanglha Range, and much palaeoglacial geomorphology could be found nowadays. In this paper, firstly, we produced the palaeoglacier geomorphologic map by investigation in field and extracting palaeogeomorphology information with 3S technology. Secondly, based on the palaeoglacier geomorphologic map and the ‘perfect plasticity’ model, we reconstructed the surface of palaeoglacier during the LGM. Thirdly, we calculated the palaeo-ice volume and palaeo-ELA during the LGM based on the surface of palaeoglacier and palaeogeomorphology information. Finally, we discussed the palaeo-climate during the LGM.

2. Study area
Nyainqêntanglha Range crosses the Tibet Plateau, nearly 1000 km in length extending in East-West direction. The peak of Nyainqêntanglha Range is 7162 m, and the altitude of snow line is about 5800 m. There existed numerous glaciers and snow in Nyainqêntanglha Range. Nyainqêntanglha Range is divided into eastern and western sectors. The western part is formed since the Pliocene Block Mountains and its extension direction is North-East. The main ridge is above 6000m in altitude, and there developed typical modern continental mountain glaciers. Western mountain barriers the Northwest cold and Indian Currents, which makes this place have a semi-arid continental climate with annual precipitation between 300 ~ 400 mm.

The Qugaqie valley is located on the northeast slope of the main peak and the western part of Nyainqêntanglha Range (Fig. 1). It is to the southwest of the Namco Lake. The Qugaqie watershed is 78.48 km² in area, 19.00 km in length. There are five branches in upstream. The watershed develops lakes, rivers and modern glaciers with 7.09 km² in area. All the rivers flow into the Namco Lake. There are lots of tall lateral moraines and terminal moraines, and most of them are granite and metamorphic rocks. The valley is wider than other place and keeps terminal moraine in the mouth of the valley. These moraine forms piedmont alluvial fan sediments, where the vegetation is good. The Qugaqie valley has an annual average temperature of - 3.4°C, an annual average wind speed of 4.1 m/s and an annual amount of radiation 229.6W/m² [28].
3. Data and Methods

In this section, we introduce all the data we used and three methods we applied in this study. The data include DEM, remote sensing image and DGPS points. Three methods we applied are indentifying palaeoglacial landform by investigating in field and 3S technology, the ‘perfect plasticity’ glacier model and palaeo-ELA estimation.

3.1. Data

3.1.1. Digital elevation model
SRTM is made by the US National Aeronautics and Space Administration (NASA) and the National Geospatial-Intelligence Agency (NGA) to map the world in three dimensions in February 2000. The horizontal resolution is 3″ (SRTM3, approximately 90m). In this study, we used the latest version of the SRTM3 (ver.4.1).

3.1.2. Remote sensing image
ETM+ (Enhanced Thematic Capper Plus) data is the product of Landsat by NASA. It includes 8 bands, in which 1~7 bands have spatial resolution of 30 m, the 8th band has spatial resolution of 15 m. The data had acquired in August 1, 2007.

3.1.3. DGPS point
DGPS (Differential Global Positioning System) points were obtained using two portable THALES MobileMapper units. One was used as the mobile station to collect GPS points; the other was the base station that provided differential correction information. The vertical accuracy of these DGPS points falls within 10 m.

3.2. Identifying palaeoglacial landform

3.2.1. Investigating palaeoglacial landforms in field
We have investigated geomorphology to collect palaeoglacial landform information and have taken the photos of the landforms in the field. The Qugaqie valley has five branches in upstream. The main valley is 1.6 km in average width, 19 km in length. There are glaciers in the high area. We have found a set of moraines with height of 10 ~ 40 m in the mouth of the valley. These moraines consists of two
parts, one is terminal moraines (Fig. 2a), and another is lateral moraines (Fig. 2b). These two moraines together around the palaeoglacier tongue, forming a horseshoe shaped moraine. At about 6 km and 9 km distance from the mouth of the valley, we found two sets of clear lateral moraine ridges, one is about 300 m in length and 65 m in height (Fig. 2c), and the other is about 2.7 km in length and 60 m in height (Fig. 2d).

Fig.2. Photo of moraines in the Qugaqie Valley

From space and relative topography method, we deduce these three moraines should be generated at the same period. Cheng (2012) got the $^{10}$Be exposure age result (18.0±1.7~30.6±2.8 ka) of the terminal moraines in Payuwhang valley [29], which is 22 km distance from the Qugaqie valley in the east direction. Thus we determine that these moraines should be generated during the LGM basing on the relative topography method.

In addition, we have used differential GPS to measure topography, in order to provide positioning information for extracting the palaeoglacial landforms. The GPS data can be overlaid on DEM, remote sensing images and Google Earth, which is convenient to display the locations of the glacial landforms.

3.2.2. Identifying palaeoglacial landform by 3S technology

We have used remote sensing images, Google Earth, DEM, GPS survey lines, and geomorphologic evidence obtained in field to identify two kinds of palaeoglacial landforms: moraine and glacial valley. We also extracted the rivers, lakes and glaciers and other landform information.

Glacial valleys are valleys with a clear U-shaped cross-section and valleys with a trough-like shape, which often characterised by steep sides and a flat bottom, resulting primarily from erosion by strongly channelled ice. Marginal Moraines are deposited at the margin of a glacier and formed by valley or outlet glaciers, and therefore mark the former position of its terminus. They are ridge-shaped features formed along the margins of glaciers and typically are ridges with a gentle relief.

Glacial valleys have primarily been identified using the DEM and Google Earth 3D terrain. Marginal moraines have primarily been identified using the DEM and satellite imagery. The method of identifying palaeoglacial landscape describes as follows: firstly, in the ArcGIS software, use DEM data to generate the slope and shaded relief data. Secondly, in the ENVI software, composite Landsat Enhanced Thematic Mapper Plus (ETM+) image with bands 5, 4, 2 and 4, 3, 2. In order to improve the spatial resolution of the ETM+ image, the data is draped with a semi-transparent gray-scale image of band 8. Thirdly, colored DEM draped by a semi-transparent grey-scale slope image to identify glacial valleys; colored DEM draped by a semi-transparent grey-scale shaded relief to identify moraines. Finally, we refer to remote sensing images, Google Earth 3D terrain, GPS survey line and geomorphologic evidence obtained in field to identify the palaeoglacial landscape.
3.3. Reconstruction of palaeoglacier
Schilling and Hollin based on Nye’s theory for the flow mechanics of glacier Eqn(1), developed an iterative model to reconstruct palaeoglacier surface [18,30]. The model is a two-dimensional valley centre-line reconstruction calculated from a step by step integration of the Eqn (2):

\[ \tau = \rho g H \Delta h/\Delta x \]  
\[ h_{i+1} = h_i + \left( \frac{\tau}{fH} \right) \frac{\Delta x}{pg} \]  

Where \( \tau \) is the shear stress, \( f \) is the valley-shape index, \( \rho \) is the density of glacier ice (900 kg/m\(^3\)), \( g \) is the gravitational acceleration (9.81 m/s\(^2\)), \( H \) is the glacier thickness, \( h \) is the ice surface elevation, \( \Delta x \) is the constant distance steps, \( x \) is the horizontal distance from the snout, with the \( x \)-axis parallel to glacier flow. This approach takes into account topographical irregularity below the former glacier and is preferred to simpler models that assume a horizontal bed.

This model is called ‘perfect plasticity’ model, which have been available for several study [19, 23]. Benn and Hulton (2010) developed a user-friendly excel spreadsheet program to calculate the surface profiles of former glaciers basing on the ‘perfectly plastic’ glacier model [21], which facilitate the reconstruction of palaeoglacers. In this study, the palaeoglacier profiles were calculated by this spreadsheet developed by Benn and Hulton.

3.4. Equilibrium Line Altitudes
Equilibrium Line is the line or zone on a glacier’s surface where a year’s ablation balances a year’s accumulation. The Equilibrium Line Altitude (ELA) is an important indicator of palaeoclimatic, and can be used to deduce palaeoclimatic conditions. Benn and Lehmkuhl reviewed five concepts of the ELA and examined the applicability of several commonly used methods of ELA reconstruction for different glacier types [31]. Other scientists have introduced the methods of ELA reconstruction [17, 19, 25, 32]. In most time, it requires multiple methods to determinate the palaeo-ELA, and then calculates the average value as ELA. By this means a more accurate palaeo-ELA may be approached [33]. There are a number of different methods that may be utilized for ELA estimation, and only four methods are used here.

The accumulation area ration (AAR) method is based on the assumption that the accumulation area of the glacier (the area above the ELA) occupies some fixed proportion of the total glacier area. The AARs are generally 0.5–0.8 for modern mid and high-latitude glaciers [34]. The maximum elevation...
of lateral moraines (MELM) method is based on geomorphologic evidences to represent the palaeo-ELA. Glacier ablates and produces ice-marginal depositions to form lateral moraine. Thus, the palaeo-ELA must lie above the highest lateral moraines [35]. The toe to headwall altitude ratios (THAR) method is based on the assumption that the glacier ELA lies at some fixed proportion of the vertical distance between the altitude of the terminus and the head of the glacier. The toe to summit altitude method (TSAM) assumes that the glacier ELA can be approximately estimated from the arithmetical average of the altitude of the terminal moraine and the summit of the glacier catchment [36].

4. Results

4.1. Palaeoglacier landform map
We collect the palaeoglacial landform information based on the traditional fieldwork investigation and identify geomorphologic features by 3S technology. We have figured out the glaciation during the LGM in the Qugaqie valley and have made a glacial geomorphological map of the Qugaqie valley, on which we have mapped glacial valleys, terminal moraines, lateral moraines and other glacial landform information. This glacial geomorphological map is a base for reconstructing the palaeoglacier of the Qugaqie valley during the LGM and indicates the former presence of glaciation (Fig. 4).

![Fig.4. Mapped glacial landforms of the Qugaqie](image)

4.2. Simulation of the palaeoglacier surface
We divide the Qugaqie valley into 10 longitudinal profiles, and get the long profile of the bed, a series of points along a flowline in the form of \((x, z)\) from DEM. The \(\Delta x\) (step) is 20 m. The target elevations are from the heights of the lateral moraines that we found in the field. We choose some representative cross-section to calculate the shape factors, and then extend them along the flowline.

The palaeoglacier long profile is constrained by lateral moraines and the shear stress is varied until the reconstructed glacier surface matches the lateral moraines. In the absence of geomorphological (lateral moraines) control, an arbitrary shear stress is assigned. Varying the shear stress until the
reconstructed glacier surface matches the lateral moraines. However, lateral moraines are found at only a few locations below the ELA. Above the ELA, the shear stresses take the constant value of 100 kPa (Fig. 5).

![Fig.5. Glacier simulation parameters (a, shear stress; b, ice thickness; c, shape index)](image)

After simulating the 10 longitudinal profiles, we obtain the palaeoglacier topography, a DEM of the palaeoglacier surface with a cell size of 5 m (Fig. 6a), which is got by spatial interpolation. We use the DEM of the palaeoglacier surface minus the DEM of free ice to calculate ice thickness (Fig. 6b). We also calculate the other scale parameters of the palaeoglacier, such as area, volume, average thickness, the largest thickness and length. The Qugaqie glacier was 18.50 km in length, 102.10 m thick on average in the LGM. It covered an area of 59.10 km², had a volume of 6.05 km³, which were 8.34 times of the area and 18.33 times of the ice volume of the modern glacier. The 75.3% of Qugaqie valley was covered by glacier.
4.3. Equilibrium Line Altitudes

4.3.1. AAR
The AARs are generally 0.5–0.8. The AAR is 0.6 when glaciers are in the steady state, and generally less than 0.6 when glaciers are piedmont glaciers [37]. Therefore, in this study, the AAR is 0.6. We have calculated the palaeo-ELA based on the reconstructed palaeoglacier surface. The results is about 5455 m.

4.3.2. MELM
We have collected the geomorphologic evidence by fieldwork investigation and have found that the large lateral moraines are well preserved and the maximum elevation of lateral moraine is 5405 m. So the most minimum palaeo-ELA is about 5405 m.

4.3.3. THAR
We have gotten the height of the glacier backwalls and terminus based on the DEM data. The average height of backwalls is 5960 m, and the height of glacier terminus is 4770 m. The THAR is often chosen as 0.4 in the Tibet Plateau [38]. Therefore, in this study, the THAR also was taken as 0.4, and the final palaeo-ELA is 5496 m.

4.3.4. TSAM
We have gotten the summit altitude of the glacier catchment from DEM, which is 6082 m. The height of glacier terminus is 4770 m. so the palaeo-ELA is 5426 m by the TSAM method.

Finally, we estimated the palaeo-ELAs with four methods (Table 1). In most time, it needs to calculate the average value of ELAs estimating by multiple methods to determinate the final palaeo-ELA [17]. The mean value of these palaeo-ELAs is 5446 m. So we think the palaeo-ELA is about 5446 m in Qugaqie valley during the LGM.

| Table 1. ELA of the palaeoglacier estimated with four methods |
|------------------|---|---|---|---|
| method           | AAR | MELM | THAR | TSAM |
| ELA (m)          | 5455 | 5405 | 5496 | 5426 |
5. Discussions

The traditional fieldwork investigation is a hard work and spends a lot of time and efforts, but it can get more detail glacial landforms that RS and GIS technology can’t. This inversely confirms the mapped geomorphology by RS and GIS technology. Meanwhile, although RS and GIS technology can be easier and quicker to extract landform information, the resolutions of the DEM and satellite imagery limit the size of detectable landforms. So that those landforms too small to be identified have not been mapped. So it is a good way to combine investigation in the field and 3S technology to map palaeoglacial landforms.

The ‘perfect plasticity’ model needs sample input parameters and can be used easily to reconstruct palaeoglacier. But the shear stress is a vital parameter, which influences the ice thinness. Because of lacking of geomorphological control, shear stress arbitrarily assigns. Although, lateral moraines well preserved, the height of lateral moraines can’t exhaustively stand the height of the palaeoglacier in flowline.

During the LGM, the Qugaqie glacier covered an area of 59.10 km$^2$, which is 8.34 times of the area of the modern glacier and is close with the point that LGM glaciers were 8.34 times of the area of the modern glacier in Nyainqêntanglha Range [39]. The 75.3% of Qugaqie valley was covered by glacier, which probably indicates that there is not an ice sheet in the Tibet Plateau. During the LGM, the ELA of Qugaqie glacier was 5405~ 5496 m, which were lower 400 to 300 m than that of modern glacier and confirms the point that an even global ELA lowering value of about 1000 m didn’t virtually exist [39].

Once reconstructed, empirical relationships derived from present-day glaciers, may be applied to glacier palaeo-ELAs to derive palaeo-climate information. Two commonly used relationships relating temperature and precipitation at the ELA are given below:

(1) from a global data set, Ohmura et al. (1992):

$$P_a = 465 + 296T_{s-a} + 9T_{s-a}^2$$  \hspace{1cm} (3)

(2) and from glaciers data in western of China, Shi et al. (1997):

$$T_{s-a} = -15.4 + 2.48 \ln P_a$$  \hspace{1cm} (4)

Where, at the ELA, $P_a$ is the annual precipitation in millimeters (mm) and $T_{s-a}$ is the mean summer (June–August) temperature in centigrade.

In order to assess climate associated with the reconstructed palaeo-ELA, present-day climate data are required. Temperature records are obtained from Namco weather stations (5400 m). From 2006 to 2011 years, the average summer temperature is 4.05 °C, the lapse rates is 1.01 °C per 100 m [28], so the mean summer temperature is 3.64°C at the 5446 m. The mean summer temperature decreased about 5 °C during the LGM period [39]. So the mean summer temperature is about -1.3°C during the LGM period at the palaeo-ELA (5446 m).

We have used the mean summer temperature of LGM at the palaeo-ELA to calculate the annual precipitation, based on Eqn (3) and Eqn (4). The annual precipitation at the palaeo-ELA is 288 mm and 259 mm respectively. We choose the result calculated by the Eqn (4), which is more appropriate for palaeoclimate reconstructions in the Tibet Plateau as it is derived from glaciers data in western of China. The present-day annual precipitation is about 445 mm in the Qugaqie valley [40]. So, during the LGM, the annual precipitation is about 60% of the modern precipitation at the ELA in the Qugaqie valley.

6. Conclusions

Through the above palaeoglacier reconstruction in Qugaqie valley during the LGM, we obtained the following conclusions:

The Qugaqie glacier was 18.50 km long, 102.10 m thick in average during the LGM. It covered an area of 59.10 km$^2$, had a volume of 6.05 km$^3$, which were 8.34 times of the area and 18.33 times of the ice volume of the modern glacier. The 75.3% of Qugaqie valley was covered by glacier.

During the LGM, the ELA of Qugaqie glacier was 5405 m in minimum, 5496 m in maximum and
5446 m in average, which were lower 400 to 300 m than that of modern glacier. This confirms Shi Yafeng’s point that an even global ELA lowering value of about 1000 m didn’t virtually exist.

This case study shows that reconstruction of ‘perfect plasticity’ model can be used to rebuild the glaciers in the area with well preserved palaeoglacial landform in the Tibet Plateau.

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