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Surface Geotechnical Weathering and denudation in the Northeast Margin of Tarim

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Abstract. The research region is located in the northeast margin of Tarim, which is characterized by a typical continental arid desert climate, with a scanty rainfall and large difference in temperature between day and night. The research region is relatively stable in geology and exposed to the long-term weathering and serious erosion of seasonal surface water, which lead to the typical landform of "planation surface" and Yadan. In order to investigate the long-term stability of superficial facilities in this region, a series of methods have been conducted to study the erosion characteristics of soil and rocks in some representative positions, i.e., soil erosion monitoring in different places, modelling analysis of soil erosion, terrestrial cosmogenic nuclides concentration measurement, denudation amount measurement of stone relics, and estimation of regional strata denudation. The results demonstrate that erosion rate is less than 0.3m/10^4a for sandstone in flat surface, 0.8 m/10^4a in seasonal gully. The erosion rate of soil is averagely 0.16～0.19cm/a for palaeo-lacustrine deposition area since late pleistocene epoch, 0.42cm/a for monitoring platform, 3.97cm/a for erosional depression. The denudation rate is estimated to be 0.9 mm/10^4a for siliceous stone relics, 9.5～11.6 mm/10^4a for sandstone and granite relics, and 4.0mm/a for ancient architecture made of soil in research area. By the method of tectonic trend of missing strata, it is estimated that the erosion rate is less than 0.35 m/10^4a since the tertiary period when a steady stage of uplift and denudation begin in the research region.

1.Introduction

As the change of landforms is generally very slow, speculation and conjecture are used to explain the origin and formation process for geomorphic phenomena in the early stage. In the past, geomorphologists mainly focused on analyzing the influence of one aspect or factor of weathering and erosion of rocks or soils. In reality, especially for arid areas, weathering erosion of rocks and soils is generally the comprehensive result of multi-factors. With the emergence and improvement of new methods, along with correlative equipment for monitoring environmental parameters (such as temperature, humidity, etc.)[1], there's an urgency to study the characteristics of weathering and denudation from multiple influencing factors.

The northeastern margin of Tarim is one of the most arid regions in Asia. The rock and soil near surface have been weathered and denuded for a long time, soil region is usually characterized by gullies, but in bedrock area the effect of rock and water erosion is weak, forming the"planation surface" phenomenon [2]. The main surface erosions in study area are water and weathering erosion. Water erosion is mainly characterized by seasonal or abrupt water erosion, such as flaky erosion, linear erosion and planar erosion on sloping plains and palaeo-lacustrine sedimentary plains. The near-surface soil is scoured or washed away by runoff or flaky water flow, which forming gullies of various size. The weathering and erosion is mainly affected by rock types, structures, material composition, terrain and climate, physical rupture and chemical decomposition of minerals and rocks, etc., it's a comprehensive effect of complex processes of multiple factors.

In order to evaluate the effect of surface geotechnical denudation on the long-term stability of surface engineering in this area, the study on denudation degree and amount has been conducted. Several steps have been taken to figure out the impacts and mechanisms of weathering and denudation of bedrock: First, the observations and analysis on denudation characteristics of different lithology in the field is implemeted; Secondly, the current techniques and methods in the world of weathering and denudation has been investigated; Finally, a series of methods benefited from above preparations have been put into effect to study multi-scale and comprehensive denudation in this area, i.e., derivation the total denudation of regional rock and soil, local monitoring and sampling tests in representative areas. The method for measuring rock erosion rate was cosmogenic nuclide method, with this method the sand erosion amount in alluvial plain area can be regularly measured, and then a comparison and analysis on the erosion amount of special characteristics formed in different periods can be obtained, meanwhile the erosion amount of stone relics around the study area and sedimentation rate through tectonic trend method can be also obtained, as a result, the comprehensive data on surface geotechnical erosion in the northeastern margin of Tarim Basin can be achieved.

In the study of geotechnical weathering and denudation, the cosmogenic nuclide method has been used to obtain quantitative or semi-quantitative data of long-term denudation of rocks. Its basic principle is to generate other radionuclides by bombarding the nuclei of specific minerals in near-surface rocks with cosmic rays. When cosmic rays enter the rock interior through its surface, the nuclear reaction and ionization loss are produced. The nuclide production rate decreases exponentially with the increase of rock thickness. Thus, rock minerals can record the variation of cosmic nuclide concentration, which correspondingly reflects the amount and time of denudation of rock surface. Nowadays this method is a technical method for directly measuring erosion rate and formation erosion.

In the study of surface geotechnical denudation, the measured data are affected by many factors, such as environmental conditions, complexity of geological evolution process, representativeness of measuring points and limitation of measuring methods, etc., therefor there are unavoidable deviations . But for the analysis and evaluation of the long-term safety on surface geotechnical engineering, it can be used as a reference.

2.Geographical environment and regional geology

The research area of this survey is located in the piedmont area of northeastern Tarim Basin (Fig. 1). It belongs to the extremely arid continental climate. The annual rainfall is as low as 25 mm, while annual evaporation is as high as 3000 mm, but the precipitation period is relatively concentrated, which usually forms seasonal or temporary floods on the ground. The temperature difference between day and night can reach 25 degrees. The relative humidity is low, sometimes even close to zero, which is easy to cause rising dust on the ground. The annual wind speed can reach 5.5m/s averagely and the maximum wind speed can reach more than 28m/s (the above data are from annual observation data through our meteorological station). The study area is geomorphologically located between the southern piedmont of the Kuruktag Mountains and a dry lake. From north to south, the study area is divided into middle and low mountains, hilly platforms and inclined plains, and the southernmost part is lacustrine alluvial plain. The topographic slope inclines to a dry lake on the southeast side. The highest altitude in the northwest mountainous area is 2100 m, while the lowest altitude in the southeast lake is only 780 m.

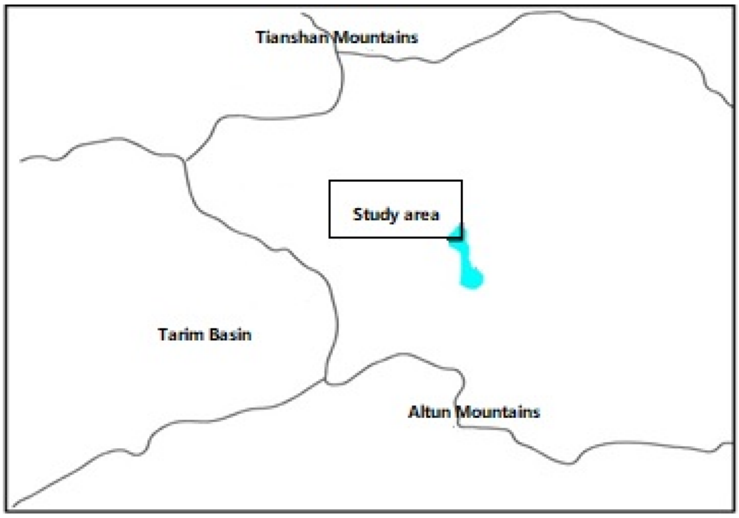

Fig. 1 Sketch map of the location of the study area

The stratigraphy in this study area are mainly from the late Proterozoic to Mesozoic and Mesozoic Quaternary. In most areas, the exposed bedrock is sandstone and limestone, with a small amount of sand on the surface. From the main evolution process of the geotectonics in the study area, the long-term denudation period has begun from the late Paleozoic or early Tertiary, and been in a relatively stable period of crustal tectonic activity. The folded mountain system of Tianshan in the Paleozoic has been gradually denuded and been in a quasi-plain state [3]; From the late Tertiary to the present, although it has been weakly and continuously compressed, the evolution of geomorphology in the area is basically in the stage of denudation and deplanation.

3.denudational landforms and its origins

Based on ETM remote sensing image data and 1:50000 topographic elevation data in the study area, the field topographic sketch map has been drawn by ERDAS 8.5 remote sensing data processing software, as shown in Fig.2. It can be seen from Fig.2 that the evolution trend of denudation plain is from North to south, as a whole it is in the stage of denudation and deplanation. In comparison with the missing strata, the stratigraphic lithology in the field indicates that the early stage of denudation and deplanation in the area should be later than that in the Cretaceous period, probably belongs to the early Tertiary period, and is still in a trend of slowly denudation and deplanation[4]. As the study area is located in the northeastern margin of the Tarim Basin and on the northern side of a dry lake, its special regional meteorological conditions (such as the precipitation is extremely low, the precipitation period is concentrated, and the infiltration rate of the rainfall in clayey soil is low), often forms seasonal or temporary floods, therefor the study area suffers water erosion. Condensate water is 0.275 mm/d in winter, 0.159 mm/d in summer and 0.127 mm/d in autumn. The annual condensate water is larger than annual precipitation[5]. The surface bedrock of the study area is exposed, resulting in significant physical weathering.

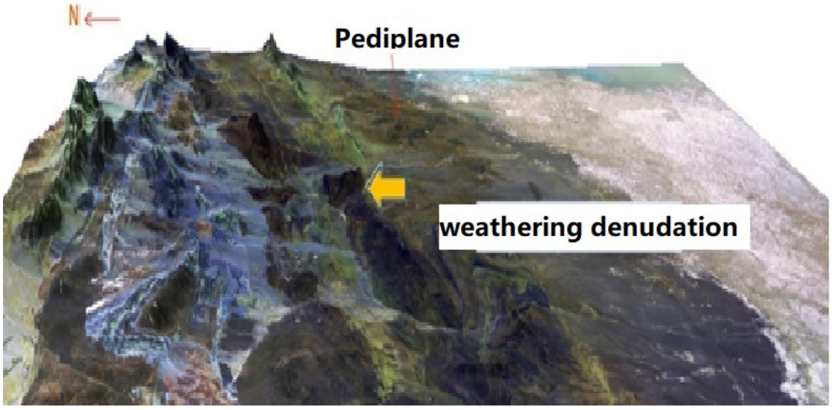

Fig.2 Sketch map of landform(electronic sand table)

The exposed rocks in the study area are mainly grey-green and fine-grained sandstone with feldspar lithic, siltstone, silty mudstone with marl and limestone. It is found that the erosion characteristics of surface rocks are obviously affected by droughty climate, large temperature difference between day and night, the erosion and abrasion of wind. Due to the structural differences in grain size, mineral composition, cements, and structural plane development, etc.，the resistance of weathering and erosion in different lithology shows obvious diversity. As a result, the main weathering in the area is physical weathering and chemical weathering. Physical weathering results in uneven thermal expansion, cold contraction and fragmentation of rocks under the influence of diurnal and seasonal temperature differences (Fig. 3-a), which enlarges the surface area of rocks subjected to weathering. At the same time, the chemical composition of surface rocks changes with the change of physical-chemical equilibrium conditions, which accelerates the physical weathering process[6]. In addition, there are dissolution phenomena occurring during hydrolysis, as shown in Fig. 3-b, and salt crystallization weathering caused by crystallization and expansion of salt minerals, which results in extrusion disintegration of rocks, as shown in Fig. 3-c

(a) **(b)** **(c)**

Fig.3Major field weathering form
(a Cylindrical shape related to differential weathering b dissolution weathering c salt crystallization)

4.research method

In order to quantitatively or semi-quantitatively describe the geotechnical denudation in the study area, the geomorphological types and weathering characteristics of denudation have been investigated in details, and the main impacts of weathering denudation have been discussed. For obtaining the denudation rate of rock and soil, the cosmogenic nuclide method, field monitoring method, stone relics estimation method, and sedimentation rate method are mainly used. Cosmogenic nuclide method mainly uses the decay characteristics of ^{10}Be (half-life 1.5 Ma) and ^{26}Al (half-life 0.705 Ma) naturally existing in rocks to analyze the weathering period of rocks[7]; Field monitoring method is completed by long-term observation of monitoring sites in lacustrine deposits; Stone relics estimation method is used to measure the stone artifacts and ancient architecture made of soil in the study area for

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denudation rate; Sedimentation rate method, which estimates the denudation rate of rock strata by using the absent period caused by unconformity interfaces and the geological age difference of the underlying and overlying strata nearby, but the accuracy of the sedimentation rate obtained is poor.

4.1 In situ investigation of weathering and erosion characteristics

The northern part of the study area has been a stable denudation plain since Cenozoic. Large area of bare bedrock shows a "planation surface" phenomenon. However, due to the different lithology, particle size and rock composition, an obvious "banded" differentiation phenomenon appears, as shown in Fig. 4. Therefore, this paper investigates the characteristics of rock weathering and erosion.

(1) Weathering and erosion characteristics of different lithology

The weathering resistance and weathering morphology of sandstones with different mineral composition, grain size composition, cements, and so on, are obviously different, i.e., different strata have different weathering denudation amount. The studied area's surface is often wavy, in which sandstone strata with strong weathering resistance forms "wave peaks" and limestone strata with weak weathering resistance forms "wave valleys", as shown in Figure 4-a.

(a) (b)

Fig.4 Weathering phenomenon of sandstone formation (a Differential weathering b Weathering of different strata in sandstone)

(2) Weathering and erosion ability of different particle sizes

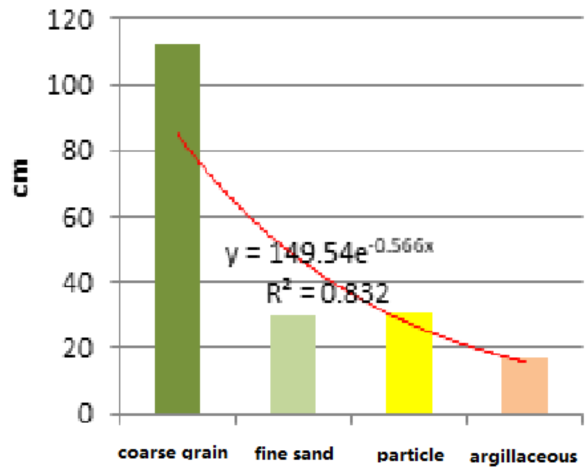


Fig.5 Contrast figure of average thickness of single layer with different particle sizes

In order to study the structure of sedimentary layer in sandstone area and the relationship on weathering resistance of sandstone, particle size and cementation composition, a 15m deep gully was selected for geotechnical weathering survey and sampling identification work. Coarse, fine, silty and argillaceous (limestone-bearing) strata, along with their thickness are classified according to particle size, shown in Fig. 5. According to the investigation, the sandstone in this area is mainly medium-coarse grained, which contains higher silt components than the general rhythmic layer curve (red curve in Fig. 5). The yellow argillaceous siltstone in Fig. 4-b is sandwiched in the gray and medium-fine grained sandstone strata, but its weathering degree is obviously higher than that of gray sandstone, and the siltstone layer in the interbedded layer is rapidly exfoliated. The weathering resistance of the whole rock mass is affected by rapid erosion of siltstone layer in the inter-bedding; Rock particles are mainly contact cementation, pore cementation is a supplement, the cementation is composed of epidote and clay, thus the diagenesis by compression and hydrochemistry has formed. Some rocks contain tuffaceous minerals, and some clay minerals in cementation have weak bonding ability, resulting in the reduce of the whole weathering resistance of rock blocks.

4.2 Cosmogenesis nuclide method

Scholars in the world generally study the surface exposure time, erosion rate and erosion amount through the content of ^{10}Be (half-life 1.5Ma) and ^{26}Al (half-life 0.705Ma) elements[8-9]. This method is suitable for the study of denudation rate of terrestrial sedimentary rocks since Tertiary geologic period, but after nuclide's formation, if the geologic time is too long, it will decay completely and can not be measured. In recent years, researchers have obtained quantitative data of rock weathering and denudation rates [10-12], as shown in Table 1 below.

Table 1 Some data of sandstone weathering rate in different region

No.	denudation rate（mm/a）	methods	reference
1	0.022～0.052	Surface retreat using false datum	Takahashi et al., 1994
2	0.013～0.066	Surface lowering using false datum	Paradise, 1995
3	0.007～0.018	Surface retreat using false datum	Paradise, 1995
4	4×10-6～ 5.5×10^{-4}	Photographic survey and surface retreat using false datum	Petuskey et al., 1995
5	0.039～0.084	Surface topography using contour-plotting frame	Sancho et al., 2003
6	0.0125～0.0506	Surface topography using contour-plotting frame	Zhang et al，2010
7	0.086	impression	Zhifa Yang，2008

Other scholars have measured the denudation rate of surface rocks (granites) in the southeastern part of Qinghai-Tibet Plateau, which is less than 60 mm/ka, the averaging value is about 27.1+10.2 mm/ka[13]. Compared with the data in Table 1, this denudation rate is higher, which may be caused by precipitation.

In order to study the denudation rate of bedrock in the area, four test samples were obtained on the surface of exposed bedrock. Because some samples contains a little amount of quartz, two samples were finally sent to the State Key Laboratory of Seismological Dynamics of the State Seismological Bureau for testing. The topography of the sampling site is shown in Figure 6 (a, b), and the specific coordinates are shown in Table 2.

After obtaining the test result of Cosmogenic Nuclide for ^{10}Be content, the geologic calculation program of cosmogenic nuclide method designed by Balco.G. has been used as the network calculator. At present, the network calculator has three main modules, which are used to calculate denudation rate, exposure age and nuclide generation correction coefficient.

In the network calculator, the erosion rate of the surface bedrock is calculated by solving the following equation (1):

$$\int_0^{\infty}[P_{sp,0}(t)\exp\left(-\frac{\varepsilon t}{\Lambda_{sp}}\right)+P_{\mu}(\varepsilon t)]\exp(-\lambda t)\,dt-N_m=0 \quad (1)$$

Where ε —the erosion rate，$g\cdot cm^{-2}\cdot yr^{-1}$

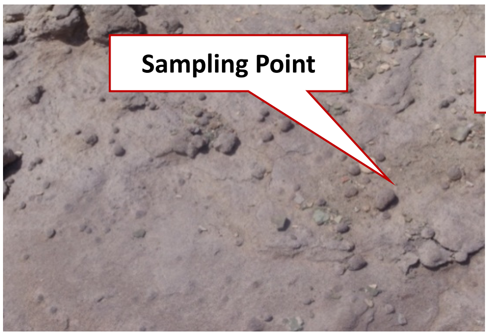
Λ_{sp}—the attenuation length，g·cm^{-2}，When the intensity and energy of the incident cosmic ray are reduced to 1/*e* of the initial incident intensity and energy, the thickness of the rock that can pass through the cosmic ray is usually taken as 160g·cm^{-2}；

λ—the attenuation constant，a^{-1}，the attenuation constant of ^{10}Be in network calculator is 4.998 ± 0.043 × 10^{-7} yr^{-1}，and that of ^{26}Al is 9.83 × 10−7 yr^{-1}；N_m—the rock nuclide concentration near surface, atomic number ·g^{-1}.

$P_{sp,0}(t)$— the nuclide production rate of neutron fission reaction, which is a function of time.

P_{μ}—The radionuclide production rate of meson reaction, which is a function of time.

Among the above parameters, parameters like $P_{sp,0}(t)$ need to be corrected according to geographic location and the variation of geomagnetic field with time. Network calculators are currently available on the basis of the calculation results of five calibration models ,i.e., Lal(1991)/Stone(2000)，Desilets(2006)，Dunai(2000)，Lifton(2005) and time-dependent Lal(1991)/Stone(2000). P_{μ} is obtained by the method recommended by Heisinger (2002)



(a) **(b)**

Fig.6 Photos of sampling location for cosmogenic nuclides concentration measurement: (a) conglomerate in denudation plain (b) sandstone in gully

Table 2 Calculated parameters of erosion rate

samples	YS-6	YS-10
altitude（m）	944	937
topography and lithology	Shangqiu conglomerate	Sandstone in riverbed
thickness（cm）	2	2
density（gens^{-3}）	2.6	2.6
terrain correction coefficient	1	0.904
the concentration of 10Be（g^{-1}）	262176	89846
the concentration of 26Al（g^{-1}）	2230750	765303

Note: the testing data are provided by the State Key Laboratory of seismological dynamics, State Seismological Bureau.

By putting the data in Table 2 into the network calculator in required format, the denudation rate have been obtained, the value at the location of YS-6 is less than 0.3m/10^{4}a and that at the location of YS-10 is less than 0.8m/10^{4}a. According to the investigation of rock denudation phenomenon in the field, the denudation rate of conglomerate is larger than that of sandstone, and the water erosion rate of rock is much higher than that of weathering denudation rate (sampling point is about 8-10m lower than the top of the gully). In addition, the location of testing sample is far from the disposal site. It is considered that the rate of weathering and erosion of bedrock should be greater than 0.8m/10^{4}a.

4.3 Denudation monitoring in lacustrine sedimentary area

The southern part of the study area is paleo-lacustrine deposits, which is mainly clay, silt and fine sand. Affected by wind direction, ground fissures and small amount of precipitation, surface runoff and other weathering factors, denudation depression appears in theacustrine depositional platform, and its long axis has a certain direction.

Basic methods of erosion monitoring: In paleo-lacustrine deposits, nearly 100 monitoring points are laid at different sites. The main reference material is steel bar with a ruler. Without destroying the surface soil, it penetrates into the soil for about 1m. The surveying and mapping instruments are used for regularly monitoring, and the measuring accuracy is ±0.5.

After years of continuous observation, the preliminary data show that the erosion rate of the paleo-lacustrine sediment layer changes obviously, the average erosion rate of the platform's surface is 0.42 cm/a, and the maximum erosion rate of the denudation depression is 3.97 cm/a.

In order to study the denudation intensity in the research area for moving the sand and dust, and to obtain the relevant soil erosion parameters, the total amount of denudation in the study area has been obtained by analyzing the amount of soil erosion and the types of erosion intensity . Referred to the denudation time since the late Holocene in the south area of paleo lacustrine (the test age of ^{14}C in the surface of lacustrine soil layer is 2190stri, tested by State Key Laboratory of seismic dynamics), the denudation rate has been calculated, in genearal, it is considered that the average denudation rate of surface soil layer in lacustrine sedimentary area is 0.16cm/a in late Holocene.

In addition, referred to the denudation time from the residual Yadan soil pillar of Late Pleistocene (At the top of the soil OSL luminescence test age is 96.7 + 4.4 ka, measured by the State Key Laboratory of Seismic Dynamics) to the bottom of the lacustrine plain of late Holocene, it is primarily considered that the denudation rate is 0.19 cm/a during the period from the early stage of late Pleistocene to the late stage of Holocene.

4.4 Investigation on weathering and erosion of cultural relics

Surface geotechnical denudation is a long-term evolution process. It is necessary to study the amount and time of geotechnical denudation for the denudation rate. In order to obtain some reference data, the denudation survey of cultural relics on the surface of the study area has been carried out, and the denudation rate of some geotechnical cultural relics has been preliminarily achieved, in which the reference time of cultural relics was assessed by experts in local cultural relics. The main objects of investigation are the stone relics left on the surface and the surface erosion of the ancient architecture, as shown in Figure 7.

(1) Fine stone relics of silicolite, including polygonal and conical stone nucleus, slender feldspar shaped into pieces, small flaky stone and other siliceous relics, which are found on the surface of the studied area and have been weathered and denuded for a long time. The measured denudation depth is about 0.26-0.28 mm, the reference denudation time of cultural relics is 3000 years, thus the initial estimated denudation rate is about 0.9 mm/10^4a.

(2) Grindstone relics of granite, later than the fine stone age, the granite is grayish-white and medium-grained, its denudation depth is about 0.66-0.8mm. According to the age assessed by experts, the denudation rate is estimated to be about 9.5 ~ 11.6mm/10^4a.

(3) Stone relics of sandstone, later than the fine stone age, which are grey-green and medium-grained, the denudation depth is less than 2 mm. The reference erosion time is 2000~3000 years, thus the initial denudation rate is <10mm/10^4a.

（a） （b） （c）

Fig.7 Erosion of stone relics（a siliceous rock b granite c siliceous rock and sandstone)

The denudation rate of stone relics ranges from 0.09 mm/ka to 1.16 mm/ka, which is smaller than the average denudation rate of 16.97 mm/ka measured by domestic experts in the southeastern part of the Qinghai-Tibet Plateau, which may due to the drought and rainless climate, moreover the altitude (about 780 m) is much lower than that of the Qinghai-Tibet Plateau (about 4000m).

(4) Erosion of surface sand in ancient architecture

The ancient architecture existed in the Han and Jin Dynasties (about 201 B.C. to 420 A.D.), and perished in the fourth century A.D. (The data show that the ancient architecture was abandoned in 330 A.D.). Houses, pagodas and the bottom of the residual platforms during the early times have been used as the reference plane. Compared with the bottom of eroded gully, the reference denudation time is 1600a, the height difference between the reference plane and the denudation bottom is about 6-7 m, and the denudation rate is preliminarily estimated about 4.0 mm/a [14].

4.5 Estimation of deposition rate of absent strata

The basic method for estimating the sedimentary rate of absent strata is as follows: The normal sedimentary rate of the adjacent area is used as a reference, during the same period the absent strata section has the same sedimentary rate as that in the adjacent area [15], and according to the method of tectonic trend (i.e. supposing that only tectonic deformation exists in the study area, meanwhile the sedimentary rate does not change abruptly), the stratigraphic interface extends outwards according to the extensional trend on the tectonic profile map, therefor the denuded strata can be speculated[16].

The denudation period in this area has begun in the early Tertiary period and has lasted about 65 million years. According to the normal sedimentary thickness between the top and bottom interfaces of unconformity denudation, the thickness loss in the structural axis is 2289m, therefor the denudation rate is estimated to be about 0.35 m/10^4a.

5.Conclusion

The study area is located in the plain area which has been eroded for a long time. Physical weathering and chemical weathering denudation are the main causes of surface erosion, along with the interaction of hydrolytic dissolution, salt crystallization weathering, and so on, among the multiple impacts, soil erosion is dominated by wind erosion and water erosion. Due to the long-time erosion and multiple impacts, it is difficult to accurately obtain the denudation rate, at present the reliable way is to use a variety of testing methods comprehensively in order to complement each other, thus a relatively reasonable denudation amount can be preliminary obtained. Generally speaking, the natural weathering denudation rate of rocks in sandstone plain is less than 0.3m/10^4a, and the denudation rate in seasonal gullies is more than 0.8m/10^4a due to the water erosion. The monitoring data preliminarily show that the surface erosion rate is about 0.16-0.19 cm/a since the late Pleistocene, in which wind erosion dominates the plain surface since the late Holocene, and the erosion rate is 0.42 cm/a. Surface water erosion occurs in the eroded strip depression, and the erosion rate can reach 3.97 cm/a. The denudation rate of siliceous rocks is about 0.9 mm/10^4a, granite and sandstone is about 9.5-11.6 mm/10^4a, and that of ancient building is about 4.0 mm/a. The denudation rate calculated by stratum profile estimation method is less than $0.35m/10^4a$, which is consistent with the geologically stable evolution and slow denudation of regional crust.

The quartz content of the rock samples obtained in the field is relatively high, which is basically equivalent to the average denudation rate of 27.1 +10.2mm/ka measured by domestic experts in the southeastern part of the Qinghai-Tibet Plateau. The low denudation rate of surface stone cultural relics around the study area may be due to the a certain degree of intactness of stone relics, the hardness of rock material, and siliceous cementation, which attribute to strong weathering resistance, thus it is weakly eroded by surface precipitation or runoff.

Geotechnical denudation is a long-term research problem, which requires systematic cooperation of different research methods to obtain relatively reasonable data. The surface rock denudation rate is slow and can not be monitored directly. It needs testing and deduction under specific conditions, and analogical analysis with reference objects which are visual and intuitive. As the soil denudation rate is greatly affected by climate, water environment, the denudation divergence at different sites is remarkable, it is necessary to analyze macroscopically the change of geological environment in the working area, and objectively study its denudation characteristics and denudation amount.

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