Late Cenozoic Sedimentary Evolution of Pagri-Duoqing Co graben, Southern End of Yadong-Gulu Rift, Southern Tibet

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Abstract: The north trending rifts in southern Tibet represent the E–W extension of the plateau and confirming the initial rifting age is key to the study of mechanics of these rifts. Pagri–Duoqing Co graben is located at southern end of Yadong–Gulu rift, where the late Cenozoic sediments is predominately composed of fluvio-lacustrine and moraine. Based on the sedimentary composition and structures, the fluvio-lacustrine could be divided into three facies, namely, lacustrine, lacustrine fan delta and alluvial fan. The presence of paleo-currents and conglomerate components and the provenance of the strata around the graben indicate that it was Tethys Himalaya and High Himalaya. Electron spin resonance (ESR) dating and paleo-magnetic dating suggest that the age of the strata ranges from ca. 1.2 Ma to ca. 8 Ma. Optically stimulated luminescence (OSL) dating showed that moraine in the graben mainly developed from around 181–109 ka (late Middle Pleistocene). Combining previous data about the Late Cenozoic strata in other basins, it is suggested that 8–15 Ma may be the initial rifting time. Together with sediment distribution and drainage system, the sedimentary evolution of Pagri could be divided into four stages. The graben rifted at around 15–8 Ma due to the eastern graben-boundary fault resulting in the appearance of a paleolake. Following by a geologically quiet period about 8–2.5 Ma, the paleolake expanded from east to west at around 8–6 Ma reaching its maximum at ca. 6 Ma. Then, the graben was broken at about 2.5 Ma. At last, the development of the glacier separated the graben into two parts that were Pagri and Duoqing Co since the later stages of the Middle Pleistocene. The evolution process suggested that the former three stages were related to the tectonic movement, which determined the basement of the graben, while the last stage may have been influenced by glacial activity caused by climate change.

Key words: north trending rifts, initial rifting age, Late Cenozoic strata, sedimentary evolution, OSL, ESR and paleomagnetic dating, Tibet, China

1 Introduction

The Tibetan plateau is one of the strongest active collision orogenies caused by the continuous penetration of India under and into the Eurasian plate (Armijo et al., 1986; Peltzer et al., 1988; Tapponnier et al., 1986). The nearly north-trending rifts, one of the distinct active structures especially since the Late Cenozoic, are mainly distributed in the Lhasa and Himalaya block (Fig. 1). These rifts are related to the shallow-focus earthquakes, the Cenozoic magmatic activity and the uplift of the Tibetan plateau (Hou et al., 2004; Molnar et al., 1978, 1993); the initial rifting time and mechanics are contested areas of research in studies of Tibet (Armijo et al., 1986; Harrison et al., 1995; Kapp et al., 2008; Molnar et al., 1978, 1993; Styron et al., 2011, 2015; Wu Zhenhan et al., 2016; Wu Zhonghai et al., 2008). The nearly north-trending rifts mostly consist of a series of graben or half-graben basins, part of which developed with late Cenozoic strata. Research on these strata is helpful in comprehending the deformation history of these grabens due to the close relationship between the strata and the graben-boundary faults. Therefore, studies of graben sedimentary evolution of these rifts are the key to understand the initial rifting time and mechanics of these rifts. However, most previous studies focused on the

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bedrocks at the footwall of rift-boundary fault (Cogan et al., 1998; Cooper et al., 2015; Harrison et al., 1995; Lee et al., 2011; Leloup et al., 2009; Li et al., 2015; Lin Bin et al., 2017; Mahe et al., 2007; Meng Yuanku et al., 2016; Mitsuishi et al., 2012; Styron et al., 2013; Sundell et al., 2013; Zhang et al., 2007, 2012).

Currently, the sedimentary studies are involved in the research of a small number of these grabens, such as Gyirong graben (Chen Fenning et al., 2013; Shen et al., 2016; Wang Dechao et al., 2009; Yue Leiping et al., 2004), Thakhkola graben (Garzione et al., 2000), Dati basin (Deng Tao et al., 2015) and Zanda basin (Wang Shifeng et al., 2008) in the Himalaya block (Fig. 1), as well as the Oiyug basin (Chen Hehai et al., 2008; Zhu Yingtang et al., 2006) and Lunggar basin (Woodruff et al., 2013) in the Lhasa block (Fig. 1). These studies are confined to the central and western plateaus while the eastern grabens are rarely covered.

Pagri–Duoqing Co graben is at the southern end of Yadong–Gulu rift and located in the Tethys and High Himalaya terrace cutting across the southern Tibet detachment (Wu et al., 1998). The Cenozoic strata had been discovered in previous research expeditions, however there is no consensus about their age (Academia Sinica Scientific Expedition to the Qinghai-Xizang Plateau, 1983; Zhu Zhiwen et al., 1981) due to the lack of exact dating. In this study, the Cenozoic strata was dated by paleomagnetic geochronology, Electron Spin Resonance (ESR) and Optically Stimulated Luminescence (OSL).

Also, the sedimentary evolution is discussed along with simple analysis of sediment facies.

# 2 Geological Setting

By interpretation of satellite images and DEM, the north trending rifts comprise 10 rifts—from east to west, Cona–Oiga rift, Yadong–Gulu rift, Dinggye–Xainza rift, Gangga–Tangra Yumco rift, Gyirong–Zhari Namco rift, Zhongba (Thakhkola)–Coqên rift, Lunggar rift, Burang–Yagra rift, Geygai rift and Zanda–Chem Co rift (Fig. 1). Yadong–Gulu rift is the eastern second one with the length of 500km and striking NE, which cuts through the Himalaya block and Indus–Yarlung Zangbo suture at the south and ends in the northern part of the Lhasa block (Armijo et al., 1986; Wu Zhonghai et al., 2015). Based on the spatial distribution characteristics of the boundary normal faults, the rift could be divided into three parts—southern part, consisting of Pagri–Duoqing Co graben, Nieru graben and Relong graben; central part consisting of Angang graben, Yangyi graben, Pabu graben, Penggang graben and Panggang graben; and, the northern part consisting of Geda graben, Damxung–Yangbajain graben and Gulu graben. The boundary normal fault of the southern part extends along the eastern margin of the grabens dipping to W–WNW; the grabens of the central part are relatively smaller in scale without a significant regular distribution of boundary faults; while, the northern part traces along the western margin dipping to the E–NE.
Pagri–Duoqing Co graben lies at the southern end of the Yadong–Gulu rift that extends into the High Himalaya and cuts off the Southern Tibet Detachment System (STDS) (Wu et al., 1998). The graben is located at the dividing mountain ridge of south-north Himalaya and strikes NE with relatively high elevation. The eastern margin normal fault controls the evolution of the graben. This boundary fault strikes NE for a length of about 100 km from south of Pagri to east of Kangmar County crossing Chomolhari Peak and Lake Duoqing Co (Fig. 2). This normal fault displaced the late Quaternary moraine showing it to be a strong active fault, which is also supported by high fault triangular facets (Fig. 3d).

Strata in and around the Pagri–Duoqing Co graben are Precambrian to Quaternary as per descending age (Fig. 2). The lithology of Precambrian and Cambrian are mainly quartz schist. While the Ordovician, Silurian, Devonian Carboniferous, Permian and Triassic formations mainly consist of limestone, sandstone and shale, along with intrusions of Caledonian and Himalayan granites (Fig. 2). The Cenozoic to Quaternary formations are a series of lacustrine, fluvial and moraine deposits (Fig. 2). Zhao

Fig. 2. Simple geological map of Pagri-Duoqing Co graben modified from regional geological map (revised from China University of Geosciences (Beijing), 2004; STDS- Southern Tibetan Detachment system).
Xitao (1976), who was the first to report that the fluvio-lacustrine strata in Pagri graben, suggested that the age of this sediment could be early Pleistocene. However, other researchers consider that these fluvio-lacustrine strata could be Pliocene in origin (Academia Sinica Scientific Expedition to the Qinghai-Xizang Plateau, 1983; Zhu Zhiwen et al., 1981). The late Quaternary moraine is mainly distributed along the eastern margin of the graben and may be divided into 4 groups with different ages: Nyalam glaciation (Middle Pleistocene), Jilongsi glaciation (early Late Pleistocene), Rongbusi glaciation (most recent of the Late Pleistocene) and Holocene glaciation (Academia Sinica Scientific Expedition to the Qinghai-Xizang Plateau, 1983; Shi Yafeng et al., 2006).

3 Sedimentary Facies

Sedimentary facies are the material manifestation of the sedimentary environment, and the summation of sedimentary characteristics such as rock composition, tectonics, structure and biological fossils. The formation and evolution of basins are coupled with regional tectonic
activities, and the strata in these basins are the response to tectonic activities. Thus, studies of the strata, sedimentary facies, paleocurrents and provenance all help to understand the formation and deformation history (Chen Jianqiang et al., 2004).

Late Cenozoic strata in Pagri-Duoqing Co graben mainly consists of late Miocene to early Pleistocene fluvo-lacustrine and late Quaternary moraine and alluvium. The fluvo-lacustrine strata are covered by the late Quaternary moraine and alluvium except to the northwest of Pagri Town (Academia Sinica Scientific Expedition to the Qinghai-Xizang Plateau, 1983).

3.1 Measured section of fluvo-lacustrine

Detailed measurements of the Late Cenozoic fluvo-lacustrine strata were conducted, and it was found that total thickness is >110 m, being divided into 22 layers. Based on the characteristics of rocks, the section could be segmented into 3 units from bottom to top. There may be a sedimentary unconformity between the Unit 1 and Unit 2 due to the immediately change from sand, mud to conglomerates (Fig. 4).

Unit 1: Layers 1–7 with thickness of approximately 29 m (Fig. 4). This unit primarily consists of cinerous, off-white silt and clay with a small amount of medium-fine sand layers with calcium cementation. The structure mainly developed with horizontal beddings (F1), massive beddings (Fm) and lenticular beddings (SI).

Unit 2: Layers 8–17 with thickness of approximately 42 m (Fig. 4). The unit is mainly conglomerate intercalated sand and contains a small amount of clay locally. Layers 8–13 are primarily composed of gravel and sand interbedded by a small amount of clay, where the diameter is <5 cm, which exhibit good grinding, poor sorting and calcium cementation with sand lens. Cross-bedding and fossils were found in the sandstone layers. Layers 14–17 are mostly pebble, with a little amount of sand and clay, where the diameter is larger than the layers above and are grain-supported.

Unit 3: Layers 18–22 with thickness of >40 m (Fig. 4). This unit consists of pebbles with local deposits of gravel-sand lens. The diameter of pebble is greater than 5 cm in most cases and cobbles >20 cm is common. The conglomerate is grain-supported and is characterized by good grinding and low cementation.

3.2 Sedimentary structures

Sedimentary structures are the macroscopic manifestation of the compositions, structure, colour, and other features of sediments in rocks; they could be divided into three types based on origin, i.e., physical, chemical and biogenic. The physical origin sedimentary structures could be divided into plane, bedding and reaction surface structures (Chen Jianqiang et al., 2004). In the studied section, plane structures are mainly present as erosion surface between two different compositions with different diameters (Figs. 5a, 5b), while beddings are the predominant structures.

(1) Horizontal beddings (F1): Horizontal beddings are distributed broadly in the studied section and are found in layers 1, 2, 4, 5, 7 and 17 (Figs. 4, 5d). The lithology mainly consists of alternate layers of silt and fine sand. The silt layers and fine-sand layers alternate, and are of different thickness, ranging from tens of millimeters to centimeters. This type of bedding represents the calm or weak dynamic low-density gravity flow alternating water environment of suspended sediments that are usually present in deep-water.

(2) Massive beddings (Fm, Fm): Massive beddings are usually formed by the rapid accumulation of sediments; hence the sediments are not fully differentiated, or are formed by high turbidity deposits (Wang Zhengying, 1988); these could appear in conglomerate, sandstone or mudstone. In the studied section, the massive beddings are distributed in layers 2, 3, 4, 7, 14, and 17 (Figs. 4, 5c, 5f).

(3) Parallel beddings (Sb): Parallel beddings are similar to the horizontal bedding in appearance. They are characterized by the parallel relationship between the thin layers and the bedding and are often accompanied by cross-beddings. In the studied section, the parallel beddings are typically developed in layer 9 (Fig. 5g). This bedding presents as medium to coarse sand reflecting the strong hydrodynamic conditions.

(4) Lenticular beddings (SI): Lenticular beddings, which have mainly developed in layer 4 (Fig. 4), mostly consist of mud and sand, in which mud and silt account for a large portion. Formed from weak dynamic and wave action, these beddings are characterized by horizontal discontinuity and primarily develop in the sedimentary environments of lakesides and delta fronts (Chen Jianqiang et al., 2004).

(5) Weave beddings (Sw): Weave beddings mainly appear in layers 4 and 17 (Figs. 4, 5e). This bedding consists of mud and sand, which reveal the strong and weak hydrodynamic alteration environment. The weave bedding is characterized by alternation of horizontal layers of sand and mud.

(6) Flaser beddings (SF): Flaser beddings mainly appear in layers 4, 9 and 17 (Figs. 4, 5h). The flaser beddings consist of mud and sand with a large portion of the sand reflecting a strong hydrodynamic environment. These beddings are characterized by thick and horizontal continuous sand and thin and horizontal discontinuous
Fig. 4. Sedimentary column of Late Cenozoic strata in Pagri graben
Gr: granite; L: Limestone; S: sandstone; Qz: quartz. The black star shows the sampling position and its age of ESR.
Fig. 5. Pictures of sedimentary structures in late Cenozoic strata in Pugri graben.
(a), Scour mold in layer 6; (b), scour channel in layer 7; (c), Massive beddings interacted with a maddy lenticular in layer 17; (d), Horizontal beddings in layer 4; (e), Weave beddings in layer 17; (f), Massive beddings developed in conglomerate in layer 14; (g), Trough cross beddings and parallel beddings in layer 9; (h), Flaser beddings in layer 17.
mud.

(7) Trough cross-beddings (Gt, St): Trough cross-beddings are mainly distributed in layers 7, 9 and 17 in the studied section (Figs. 4, 5g). This bedding is characterized by the arc-shape in the bottom of the lamina with thickness verified by lithology as changing from fine sand to coarse, reflecting a lowered flow regime.

(8) Plate cross-beddings (Gp, Sp): Plate cross-beddings mainly developed in sand layer 5 and conglomerate layers 14, 16 and 19 (Figs. 4, 6b). They are characterized by the plate-shape of the bottom and top boundary of the bedding with invariant thickness (Wang Zhengying, 1988).

(9) Graded beddings (Sn): The significant characteristic of graded beddings is the change in particle size gradually from coarse to fine without bedding surface (Chen Jianqiang et al., 2004). In the studied section, this kind of bedding mainly appears in layer 15 with the change from coarse sand to silt reflecting the turbidity current (Figs. 4, 6a).

(10) Biogenic sedimentary structures: Biosedimentary structures appear as a variety of traces formed and preserved in sediments by biological growth and behaviour/activity patterns. These include biological trace structures, biological growth structures, plant root traces and so on (Chen Jianqiang et al., 2004). In the studied section, many biosedimentary structures were found in layers 15 and 17 which were mainly presented as rusty yellow vertical or near vertical plant roots with diameter of 5 mm (Figs. 6c, 6d).

3.3 Sedimentary facies

Combined with lithology and sedimentary structures, the sedimentary facies of Pagri-Duoqing Co graben can be divided into three facies, namely, lacustrine, lacustrine delta and alluvial fan.

(1) Lacustrine facies: Lithology of lacustrine facies mainly consists of silt, sand and mud. These facies appear in layers 1–9 of this section. Based on the difference of lithology and sedimentary structures, it is also divided into deep lake, shallow lake and lake shore subfacies (Fig. 4). Deep lake subfacies are typically developed in layer 4. The lithology is mainly composed of gray and brownish black mud with organic matter, along with fine-sand and silt. The thicker mud layers are large, hard, with calcitic cementation; massive bedding, horizontal bedding and lenticular bedding also develop in these mud subfacies. Shallow lake subfacies are typically developed in layer 7. They mainly consist of gray mud and fine sand with calcitic cementation that is generally present as interbedding of sand and mud. Horizontal bedding and

Fig. 6. Pictures of sedimentary structures in late Cenozoic strata in Pagri graben.
(a), Graded beddings in layer 15; (b), Plate cross-beddings in layer 5; (c), Dark yellow plant root remains in layer 15; (d), Shell of a shellfish in layer 16.
massive bedding develops in this subfacies. 
Shore lake subfacies are typically developed in layer 9. They mainly consist of brownish black, gray silt, sand and mud with calcitic cementation.

(2) Lacustrine fan delta: Lacustrine fan delta is a kind of alluvial fan advancing into a stable water body, which mainly develops around the lakeside with greatly undulating terrain. Based on the lithological characteristics and structural association, the lacustrine fan delta in the studied area could be divided into delta front and delta plain subfacies (Fig. 4).

Delta plain subfacies typically developed in layer 13 and mainly consist of gravel and sand with some silt layers. The components of gravel are granite, sandstone and limestone with calcitic cementation and are grain-supported. The diameter of the gravel mostly lies in the range of 0.5 cm to 3 cm, followed by 3–5 cm, while that of the largest pieces is at around 20 cm. Massive bedding and large cross-bedding also developed in these layers. The delta front typically developed in layer 10 that mainly consists of conglomerate and sand with some mud and silt sand. Cross-bedding develops in these layers.

(3) Alluvial fan: Alluvial fan has a large amount of detrital matter that is presented in a fan shape in the outlet of valleys due to the broadening of terrain and slowing of velocity of water flow (Chen Jianqiang et al., 2004). The main characteristic is coarse grain and poor sorting. In the studied section, it occurs mainly in the form of fluvial deposits and can be divided into roof fan and inner-middle fan.

The roof fan typically developed in layer 18 that mainly consists of gray fluvial imbricate conglomerate. Massive and imbricate structures develop in the layers. Inner-middle fan were typically found to have developed in layer 20 that consists of fluvial deposits. The lithology is mainly conglomerate, the components of which are limestone and sandstone with some granite. The rate of sand and conglomerate is greater than the roof fan, but the diameter of the conglomerate is smaller. Cross-bedding (Gm, Gp) was developed in these layers (Fig. 4).

3.4 Late Quaternary moraines
As suggested, the manifestations of four glaciations can be divided into three groups based on their development time, namely, Holocene moraine, Late Pleistocene moraine and Middle Pleistocene moraine (Fig. 2). The moraine from the Holocene glaciation is mainly distributed in the valleys around the main peaks such as Chomolhari Peak (Fig. 2). Late Pleistocene moraine is distributed around the Jiujula Pass and Paohanli Peak (Fig. 2), some of which are overlaid on the late Cenozoic strata (Fig. 3a). Boulders and conglomerates of this glaciation consist of migmatite, augen gneiss, sandstone and granite with intensive weathering. The Middle Pleistocene moraine largely extends into the central graben. Boulders of moraines are composed of granite and sandstone that come from the Tethys Himalaya sequence and possibly the high Himalaya. In addition, these moraines divide the graben into two basins: Pagri and Duqing Co, indicating the significant influence of glaciation on the evolution of the graben. In this case, the age of Middle Pleistocene moraine represents an important change in the late stage of the evolution process of Pagri–Duqing Co graben. Therefore, four samples were collected from the Middle Pleistocene moraine in the eastern graben.

4 Paleocurrent and Conglomerate Components

4.1 Paleocurrents
Measurements of the flat surface of conglomerates at around 49–53 m, 57–60 m, 76–80 m, 85–92 m and 95–108 m that were projected on the rose-map, were conducted. The results show that the paleocurrent directions are at around 310°, 260°, 310° and 30°, respectively at the former four measurement locations, which are distributed in the range of NW-NNE (Fig. 4). While, the paleocurrent direction is approximately 110° at 92–108 m (Fig. 4), indicating that the paleocurrent had changed from NW to SE.

4.2 Components statistics of conglomerates
Components and content of conglomerates could be used to reflect the sources of sediments in basins. Statistics of conglomerates in the upper part of the studied section on a square with the length about 1m were analysed. The results show that the conglomerates mainly consisted of sandstone and limestone with some quartz and granite (Table 1). Generally, the content of sandstone could reach to approximately 30% and the limestone is 50% or more, while quartz could appear in all layers in small amounts (Table 1). There is slight difference between the 49.5–86 m and 93–108 m due to the relatively high sandstone rate and low limestone. This difference suggests a slight change of provenance between the upper and the lower portions of the section, which indicates that

<table>
<thead>
<tr>
<th>Number</th>
<th>Location (m)</th>
<th>Amount</th>
<th>Sandstone (%)</th>
<th>Quartz (%)</th>
<th>Limestone (%)</th>
<th>Granite (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>49.5</td>
<td>94</td>
<td>49</td>
<td>3</td>
<td>23</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>59</td>
<td>125</td>
<td>58</td>
<td>1</td>
<td>60</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>78</td>
<td>109</td>
<td>37</td>
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<td>86</td>
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<tr>
<td>5</td>
<td>93</td>
<td>106</td>
<td>40</td>
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<tr>
<td>6</td>
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<td>105</td>
<td>43</td>
<td>3</td>
<td>47</td>
<td>7</td>
</tr>
</tbody>
</table>
the upper portion is sourced from the Tethys Himalaya sequence more than the lower portion. This is consistent with the pattern of recorded palaeocurrent directions.

5 Sedimentary Chronology

5.1 ESR and OSL dating

For sandy and muddy sediments which are older than 200,000 years, especially those without constituents of volcanic origin, ESR is the default choice for dating due to lack of other reliable methods to date their age. First used in geology in 1975, ESR has since been widely used to date Late Cenozoic sediments (Liu et al., 2010, 2014; Rink et al., 2007; Voinchet et al., 2004; Yin et al., 2007). Two media to coarse sand samples were collected on the upper section at approximately 87 m and 83 m. The samples were analysed at Chengdu University of Technology. The ages of the 2 samples ranged from 1.11 Ma to 1.28 Ma (Table 2), which was a reference point for confirming the section’s age.

To date the age of moraine around the graben, 4 samples were collected for OSL dating along the eastern margin (Fig. 2). The samples were dated by the Daybreak 2200 (U.S.) OSL measuring system. The equivalent dose (D.E.) was determined by Simplified Multiple Aliquot Regenerative-dose (SMAR) protocol for fine-grain samples and Single-aliquot Regenerative-dose (SAR) protocol for coarse-grain samples. The U, Th and K contents in the environment dose rate (D) were measured by neutron activation analysis. The contribution of cosmic rays was estimated based on the method suggested by Prescott and Hutton (1994). The age of sample was confirmed by the equation Age (A)=D.E./D. (Aitken, 1998). The results showed that the age changed in the range of 181 ka to 109 ka (Table 3), which was consistent with previous research.

5.2 Collecting and measurements of paleomagnetic samples

Magnetostratigraphy is a reliable method to date the Late Cenozoic strata that was sampled on the lacustrine strata in this study. All samples were collected in the sand and mud layers using a portable drilling apparatus, with a diameter of 2.5 cm. The average space between two samples was approximately 0.25 m and there were no samples collected in some of the conglomerate layers. A total of 233 samples were obtained for analysis. All 233 samples were processed into a cylinder with diameter of 2.5 cm and height of 2.2 cm in the Key Laboratory of Paleomagnetic and Reconstruction of the Ministry of Natural Resources. Gradual thermal demagnetization of these samples was carried out inside a magnetic shielding house with near-zero magnetic fields. The samples were heated using the T48 thermal demagnetization furnace with the stepped temperature of 80°C, 160°C, 200°C, 240°C, 280°C, 320°C, 360°C, 400°C, 440°C, 480°C, 520°C, 550°C, 585°C, 620°C, 640°C, 655°C, 665°C, 675°C, 680°C, and 695°C. The residual magnetism of samples was measured using the 2G–755 vertical superconducting magnetometer (USA).

The demagnetization results were analysed using the orthographic projection diagram method (Zijderveld, 2013), and the choice of characteristic remanence direction was decided by principal component analysis (Kirschvink, 1980). Demagnetization line that is close or through the original point represents the firm remanence direction and the average paleomagnetic direction of samples were calculated by using Fisher’s (1953) statistical analysis (Fig. 7).

5.3 Results

Stable characteristic residual magnetism readings could be obtained from 142 of the 233 samples, most of whose natural remanence strength ranged from 10⁻³ A/m to 10⁻⁴ A/m. The remanence direction is divided into two groups – low temperature (<360°C) and high temperature (>360°C). Remanence strength attenuation curve of some of samples dropped to zero at 585°C (Curie temperature of titanite magnetite) and the others at 675°C (Curie temperature of hematite) (Fig. 7).

Finally, 22 polarity zones were created, including 11

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Location (m)</th>
<th>Paramagnetic center concentration (10¹⁵ spin/gram)</th>
<th>Uranium equivalent (ppm)</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K (%)</th>
<th>Age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE14-6</td>
<td>87</td>
<td>1.38</td>
<td>5.98</td>
<td>2.88±0.28</td>
<td>8.77±0.80</td>
<td>2.51±0.25</td>
<td>1.28±0.10</td>
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<tr>
<td>PE14-7</td>
<td>83</td>
<td>0.65</td>
<td>5.27</td>
<td>2.54±0.25</td>
<td>7.80±0.70</td>
<td>2.17±0.20</td>
<td>1.11±0.10</td>
</tr>
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</table>

Table 3 OSL dating results of moraine

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Location (m)</th>
<th>Paramagnetic center concentration (10¹⁵ spin/gram)</th>
<th>Uranium equivalent (ppm)</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K (%)</th>
<th>E.D. (Gy)</th>
<th>Dy (Gy/ka)</th>
<th>Water content (%)</th>
<th>Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2261-1</td>
<td>27°58'03.6&quot;</td>
<td>89°20'35.6&quot;</td>
<td>458</td>
<td>3.6</td>
<td>12.6</td>
<td>2.77</td>
<td>602</td>
<td>3.35</td>
<td>0</td>
<td>181±25.4</td>
</tr>
<tr>
<td>S2261-2</td>
<td>27°58'07.2&quot;</td>
<td>89°22'17.0&quot;</td>
<td>4598</td>
<td>2.4</td>
<td>13.8</td>
<td>2.18</td>
<td>383</td>
<td>2.84</td>
<td>0</td>
<td>135±21.1</td>
</tr>
<tr>
<td>S2267-1</td>
<td>27°58'03.5&quot;</td>
<td>89°22'29.5&quot;</td>
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<td>2.4</td>
<td>15.9</td>
<td>2.41</td>
<td>361</td>
<td>2.8</td>
<td>0.1</td>
<td>129±20.9</td>
</tr>
<tr>
<td>S2267-3</td>
<td>28°07'49.6&quot;</td>
<td>89°25'21.6&quot;</td>
<td>4501</td>
<td>4.3</td>
<td>13.2</td>
<td>1.3</td>
<td>281</td>
<td>2.58</td>
<td>0.1</td>
<td>109±10.6</td>
</tr>
</tbody>
</table>
positive polarities and 11 negative polarities based on the inclination and declination of characteristic remanence of samples and virtual geomagnetic pole (VGP) latitude. Based on the ESR results, a comparison with the standard polarity (Hilgen et al., 2012) was conducted, and the results showed that the studied section was likely to be older than 8 Ma (Fig. 8). Studies on Gyirong basin in central Himalaya suggested that the sedimentary era was older than 7.2 Ma; this was supported by Hipparion fossil research and the sedimentary end time of this basin was at circa 3.2–2.6 Ma (Qiu Zhangxiang, 1988; Wang Fubao et al., 1996; Yue Leping et al., 2004). The evolution of Gyirong basin could be compared regionally and related to the tectonic movement of the Himalayas (Wang Fubao et al., 1996). Recent research shows that the initial rifting age of Gyirong basin was ca. 10 Ma (Chen Fening et al., 2013; Shen et al., 2016). Similarly, the age of sediments in Dati basin located in the Himalayas is ca. 7 Ma (Deng Tao et al., 2015; Zhu Zhiwen et al., 1981), and Thakkhola is ca. 11 Ma (Garzione et al., 2000). Due to the similar tectonic locations and geodynamic setting in Himalaya of these basins (Fig. 1), it is suggested that 8–11 Ma is the lower age of the sediments in Pagri graben.

6 Discussion

Based on this study, the initial rifting age is around 8–11 Ma, which is consistent with the early researches on Daxunng–Yangbajain graben (Ha et al., 2017; Harrison et al., 1995; Wu Zhenhan et al., 2001). However, other researchers have suggested that regional E-W extension could start at around 15 Ma (Bilsnick et al., 2001; Coleman et al., 1995). Recent studies on Linshi fault east of Chormohari showed that the initial faulting time of Pagri could be after ca. 14 Ma (Cooper et al., 2015). Therefore, in combination with these studies, it is suggested that the opening time of Pagri–Duoqing Co graben could be 15–8 Ma. After the appearance of graben, a geologically quiet time followed till about 8–2.5 Ma, mostly with formation of continuous
deposits showing as an inflow lake (Fig. 9b). In this stage, the sedimentary facies were lake and lacustrine delta. At about 8–6 Ma, the sediments were mainly composed of silt, fine-sand and mud, developed horizontal bedding and massive bedding and formed biological remains-based structures locally. However, after 6 Ma, there was a series of conglomerates created indicating that the environment had changed from lake to lacustrine delta. Above layer 10 (Fig. 4), the sediments showed as sand, mud and gravel indicating that the paleolake reached the maximum surface range at around 6 Ma. From the section location and statistics of gravel composition, it is inferred that the sediments mainly come from the west of the graben and that the sedimentary centre was located in the east. This is

![Graph](image)

Fig. 8. Magnetostratigraphy of the studied section in Pagri graben and its correlations with GPTS2012 (Hilgen et al., 2012).
also consistent with the paleocurrents and the changes of sediment thickness revealed by geophysical research (Cogan et al., 1998). Thus, in this stage the paleo-lake developed from east to west. After 2.5 Ma, the change from lacustrine delta to alluvial fan indicated that the graben was broken, and the water flowed outside, which was consistent with the typical evolution of Late Cenozoic lakes in southern Tibet (He Lin et al., 2016). Besides, the paleocurrents changed from NW to SE during the Early Pleistocene in the section (Fig. 4). Due to the location of the studied section in Pagri, it is difficult to determine the paleocurrent in the Duqing Co part with the same age, and the reason for change in paleocurrent is unclear.

Academia Sinica Scientific Expedition to the Qinghai–Xizang Plateau (1983) suggested that a strong tectonic movement of the Himalaya since the Pleistocene caused the southern graben uplift with the appearance of sediments while the northern graben moved downwards. But the average elevation of Duqing Co is higher than Pagri, so that Pleistocene tectonic movement may not be the reason. The water system of the graben shows that streams in Pagri flow to Ganges River across the Himalaya, and others in Duqing Co flow to Lake Duqing Co and Gala Co, which hints that the paleocurrent change in early Pleistocene may be related to the headward erosion of transverse rivers across the Himalayan range. If so, the lake water flowed outside in two different directions from the northern and southern parts of the graben in this stage. In this study, the age of the oldest moraine around the graben was obtained to be 186 ka (late Middle Pleistocene) corresponding with the Nienie Xiongla moraine. The boundary between the Duoqing Co and Pagri also consists of this moraine (Fig. 2), and the modern Duoqing Co has also been surrounded by moraines since the Late Pleistocene. Thus, it is inferred that the development of moraines caused the separation of Duqing Co and Pagri, leaving the closed lake Duqing Co (together with Gala Co) and exposing the Late Cenozoic strata at the end of Pagri graben since the later stages of the Middle Pleistocene (Fig. 9). Therefore, the evolution in later periods of the graben may be more influenced by the development of glaciers caused by climate change.

The Late Cenozoic evolution of Pagri–Duoqing Co graben can be divided into four stages. At around 15–8 Ma, the graben appeared in a paleolake which resulted from the activity of the boundary fault along the eastern margin (Fig. 9a). Followed by a quiet period at around 8–2.5 Ma, the paleolake expanded from east to west and was deposited with fine-grained lacustrine (Fig. 9b). Then, the graben was broken, and the sedimentary facies changed from lacustrine delta to alluvial fan at about 2.5 Ma (Fig. 9c). During the Early Pleistocene the paleocurrent changed from NW to SE possibly due to the headward erosion of transverse rivers across Himalayas. Finally, the development of a glacier separated the graben into two parts, namely, Pagri and Duoqing Co, since the late stages of the Middle Pleistocene (Fig. 9d). The evolution process of the graben suggested

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**Fig. 9. Diagram of sedimentary evolution of Pagri-Duoqing Co graben.**

H: High Himalaya; TTH: Tethys Himalaya sequence; STDS: Southern Tibetan Detachment Systems; N: Neogene strata. The red lines show the normal faults.
that the former three stages were related to tectonic activity, which determined the basement of the graben, while the last stage may have been influenced by the glacial activity caused due to climate change.

7 Conclusion

(1) The Late Cenozoic strata in Pagri-Duoqing Co graben mainly consists of fluvial-lacustrine strata, Late Quaternary moraine and alluvial conglomerates. Combining the lithology and sedimentary structures, the Late Cenozoic fluvial-lacustrine strata in Pagri could be divided into three sedimentary facies that are lacustrine, lacustrine fan delta and alluvial fan. Palaeocurrent directions and composition of conglomerates indicate that the sediments come from Tethys Himalaya and High Himalaya surrounding the graben.

(2) Two ESR samples at the upper part of the section give a date of 1.11–1.28 Ma, and paleomagnetic measurements of the lacustrine strata suggest that the age could be ca. 8 Ma. Together with previous research, it is suggested that ca. 15–8 Ma as the age of the Late Cenozoic strata. The dates of four samples of moraine along the eastern margin of the graben range from 109 ka to 181 ka and are representative of early glacial deposits illustrating the climate change since Middle Pleistocene of this region.

(3) Based on the sedimentary division, provenance and sedimentary chronology, the sedimentary evolution of Pagri-Duoqing Co graben could be divided into four stages since the Late Cenozoic. At around 15–8 Ma, the graben appeared into a paleoake resulting from the activity of boundary fault along the eastern margin. Followed by a quiet period at around 8–2.5 Ma, the paleoake expanded from east to west. Then, the graben was broken, and the sedimentary facies changed from lacustrine delta to alluvial fan at about 2.5 Ma. Finally, the development of a glacier separated the graben into two parts, namely, Pagri and Duoqing Co, during the later stages of the Middle Pleistocene. The evolution process suggests that the former three stages were related to tectonic movement, which determined the basement of the graben, while the last stage may have been due to glacial action influenced by climate change.

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