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Features of permafrost in the West Kunlun Mountains

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Abstract

Permafrost is distributed both along the Xinjiang-Xizang Highway and wide areas between Tianshuihai and Keriya Pass. The lower limit of scattered permafrost is at around 4300 m a.s.l. Thickness of permafrost varies greatly, from less than 5 m at the lower limit to around 100 m at Tianshuihai. Mean annual ground temperature ranges from 0.0°C to −3.2°C. Along the steep shore of Tianshuihai Lake, ground ice including small ice wedges have been observed. The vertical range within which the periglacial processes occur is around 3000 m: from 3800 m to more than 6000 m. Almost all types of periglacial landforms are distributed in permafrost areas.

1. Introduction

This paper describes the main features of permafrost in the West Kunlun Mountains, with a great deal of data obtained in the Sino-Japanese joint comprehensive investigations carried out in 1985 and 1987. Before these investigations, only brief descriptions on permafrost and periglacial phenomena in this region were given in geomorphological books (Geomorphology Group in the Comprehensive Expedition Team to Xin Jiang, 1978; Yang *et al.*, 1983). A preliminary report by one of the present authors has been published already based on the 1985's investigation (Li, 1987).

2. Geological and geographical environments

Facing the Qinghai-Xizang Plateau on the south, and bordering the Taklimakan Desert on the north, the West Kunlun Mountains have a great elevation difference, over 5000 m. Upper parts of the mountains are covered either by glaciers and permanent snow, or by permafrost. In the mountains, glacial deposits developed in the alpine cold desert zone at elevations of over 4000-5000 m. Below 3500 m, the slope is generally covered by silty clay, preserving desert features: intensive wind actions in cold climate occur subsequently, wide pediment and diluvial fan were formed at the feet of the inter-montane basins. The ridges are usually covered with Pre-cambrian crystalline rocks and granite and Hercynian granite (Yang *et al.*, 1983).

Because of the location of the West Kunlun Mountains, the precipitation in this region is much less than that in the Tien Shan and Altai Mountain regions. It is beyond the reach of the warm-moist air mass from the Mediterranean Sea and the monsoon from the Indian Ocean is blocked by the Himalaya and Karakoram Mountains, therefore the West Kunlun Mountains are one of the most arid mountain ranges in Asia. The snowlines of the Kunlun Mountains at about 79 E are 5200 m and 6000 m on the north-facing slopes and south-facing slopes respectively (Li *et al.*, 1986). Southeast of Kangxiwar, the moist air mass is blocked by higher mountains on the north and west sides, the climate is much more arid, with less than 50 mm of annual precipitation (Table 1), and the snow lines on north and south slopes are at 5900 m and 6000 m, respectively: these are the highest in the Kunlun Mountains. According to incomplete statistics, the 0°C mean annual isotherm is generally at an elevation of about 3800 m. The mean annual air temperature at

Table 1. Mean annual temperature and precipitation around the West Kunlun Mountains and on the Tibetan Plateau.

Locality	Long.°E	Lat.°N	Altitude (m)	Mean annual air temp. (°C)	Mean annual precipitation (mm)	air temp. in July (°C)	Observing period
North slope							
Hotan	79°56′	37°04′	1326	12.1	35.0	25.3	1954−1970
Minfeng	82 43	37 04	1409.1	10.9	28.9	24.7	1957−1970
Gangguziluoke	79 55	36 49	1650		64.7		1964−1970
Hydro-Station of Pishan	77 46	37 13	2460	11.8	116.6	25.4	1972−1975
Hydro-Station Nuer River	80 59	36 15	2300		221.6		1964−1967
South slope							
Kangxiwar	78 36	36 12	3986.4	− 0.6	36.6	9.8	1963−1970
Tianshuihai	79 33	35 16	4840	− 6.3	23.8	6.0	1965−1970
Gozha Co	80 55	35 00	5250	− 6.7	200−250	0.4	1987
Tibetan Plateau							
Shiquanhe	80 06	32 30	4278	− 0.6	105	12.7	1984−1986
Gerze County	84 30	32 09	4414.9	0.1	117.5	10.9	1984−1986
Tianwendian	78 11	35 18	5243	− 9.8	46.7	3.0	1963−1964

Kangxiwar is -0.6°C, and that at Tianwendian is -6.3°C (Table 1). The temperature lapse rate is about 0.6-0.7 °C/100 m. Calculated with a lapse rate of 0.65°C/100 m, the average annual air temperature at the snow line at 5600-5800 m, on north slopes, south of Yutian, should be -13.0- -15.0°C. The average annual air temperature around the snow line at 5900 m on south slopes above in Kangxiwar is about -13°C, which is 4-7°C lower than the average temperature at the snow line in the Everest Area and about 10 °C lower than that at the snowline in the maritime glacial region in southeast Xizang.

3. Distribution of permafrost

The permafrost in the West Kunlun Mountains is the high-altitude permafrost in middle latitudes, so that the distribution depends on elevation.

It was proved that the permafrost is distributed along the Xinjiang-Xizang Highway, from Yecheng, Xinjiang to Ali (or Shiquanhe), Xizang, with a total length of about 1070 km. The north lower limit of scattered permafrost is on the mountain slope and ridge near Mazar Pass, where the elevation is about 4600 m and the mean annual air temperature is about -5.0°C (Fig. 1). Permafrost occurs on the river terrace, 4450 m a.s.l., three kilometers south of Dahongliutan beside the Xinjiang-Xizang Highway, where the thickness estimated with electrical exploration method is 2.9 m, the average annual air temperature is about -4.0°C, and the thaw layer depth is more than 2.0 m. On the south side of the river terrace, nine rock glaciers with various shapes are developed (see *6.3.*c). The existence of rock glaciers can be used as an auxiliary evidence indicating the existence of permafrost there. The south lower limit of scattered permafrost is in marsh land one kilometer west of the Duoma region, where the elevation is 4430 m, the thaw layer depth on June 20, 1987 was 0.6 m and the permafrost thickness was 2.0 m.

In the area between Tianshuihai and Keriya Pass, there are several lakes, such as Aksayqin Lake, Gozha Co Lake and Bangdag Co Lake. The elevation of the plateau areas is 4900 m to 5600 m generally, and 6100 m in maximum. On this wide plateau, permafrost is widespread (Fig. 1). According to the data obtained from a test pit on the terminal moraine of the Guliya Ice Cap, where the elevation is 5600 m, the thaw depth and ground temperature on August 19 were 1.3 m and 0.0°C, respectively. In this permafrost, conglomerate structures occur. Permafrost also exists under modern glaciers. Around Bangdag Co Lake, at 5020 m elevation and 21.6 m in depth, the shore is formed by halomorphic soil which contains calcareous cement of pipe-like structure. A probing pit, 1.8 m deep and 8 m distant from the lake water, shows that the thaw depth of the permafrost was 1.3 m on August 25 with -3.8°C ground temperature. In the pit profile, sandy clay, silty clay and silty soil are found in yellow, red

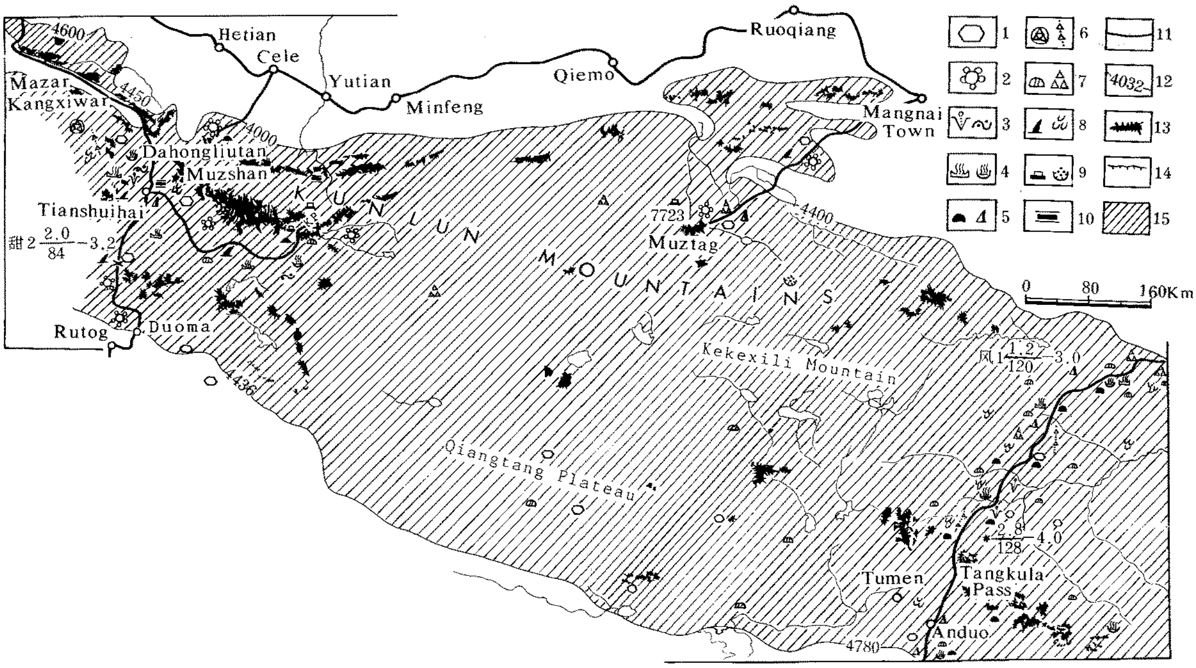

Fig. 1. Distribution of permafrost and periglacial phenomena in the Kunlun Mountains, and locations of boreholes indicating Borehole No.; Active layer thickness (cm)/Thickness of permafrost (m); Temperature of permafrost (°C). 1: Polygonal patterned ground, 2: Sorted circles, 3: Ice wedges and involutions, 4: Thermokarst lake and thermokarst depression, 5: Frost heaved mounds and icing, 6: Rock glacier and stone stripes, 7: Peat mound and blockfield, 8: Upfreezing stone and mud flows, 9: Cryoplanation terraces and nivation depressions, 10: Massive ground ice (more than thickness of 20 cm), 11: Investigation route, 12: The lower limit of alpine permafrost, 13: Snow and glaciers, 14: The upper table of permafrost, 15: Alpine permafrost, KP: Keriya Pass.

and other colors. This is a reflection of different climatic environments when such lacustrine deposits were formed.

Three kilometers from the north shore of Gozha Co Lake, several gray-white sand-covered mounds 1 to 1.5 m high and 10 to 20 m in diameter were found along the mountain valley. Pit probing in the mound centers shows that they all consist of medium silt from the surface to 2.4 m deep, but debris and sandy gravel below 2.4 m. Sulfurous steam smells stronger and stronger with increasing depth. The sub-surface temperatures in the pit were 11°C at 0.2 m, 14.2°C at 1.0 m, 16.0°C at 1.6 m, 17.0°C at 2.0 m and 17.6°C at 2.4 m. This suggests existence of a hot spring, so that permafrost is interrupted and geothermic talik forms.

4. Thickness and temperature of permafrost

According to permafrost data on the Qinghai-Xizang Plateau (Li, 1982; Tong and Li, 1983), the ground temperature decreases about one degree as the latitude increases one degree northward, with the increase of permafrost thickness 20-30 m/degree of latitude. It is also found in the plateau that the ground temperature decreases 0.4° to 0.8°C and the permafrost thickness increases about 20 m, with 100 m increase of the elevation. This shows obvious altitude zonation of permafrost in the area. Assuming the same altitude zonation and latiutde dependence on permafrost along the Xinjiang-Xizang Highway in the West Kunlun Mountains, the permafrost thickness at the lower limit is obtained as less than 5 m, its temperature is about 0.0°C and the active layer depth is 1.5 to 2.5 m.

Tianshuihai Lake Basin, ranging from 4840 to 4900 m in elevation, is the district where the continuous permafrost is the most widespread in the West Kunlun Mountain region. In the basin, the active layer thickness is 1.0 to 1.5 m, mean annual ground temperature is -3.2°C, and the depth of zero annual temperature amplitude is 13-15 m. Estimated from the geothermal gradient, the permafrost thickness is 119.7 m, while from geophysical method (seismic prospecting), the permafrost thickness is 77.0 m. This thickness and

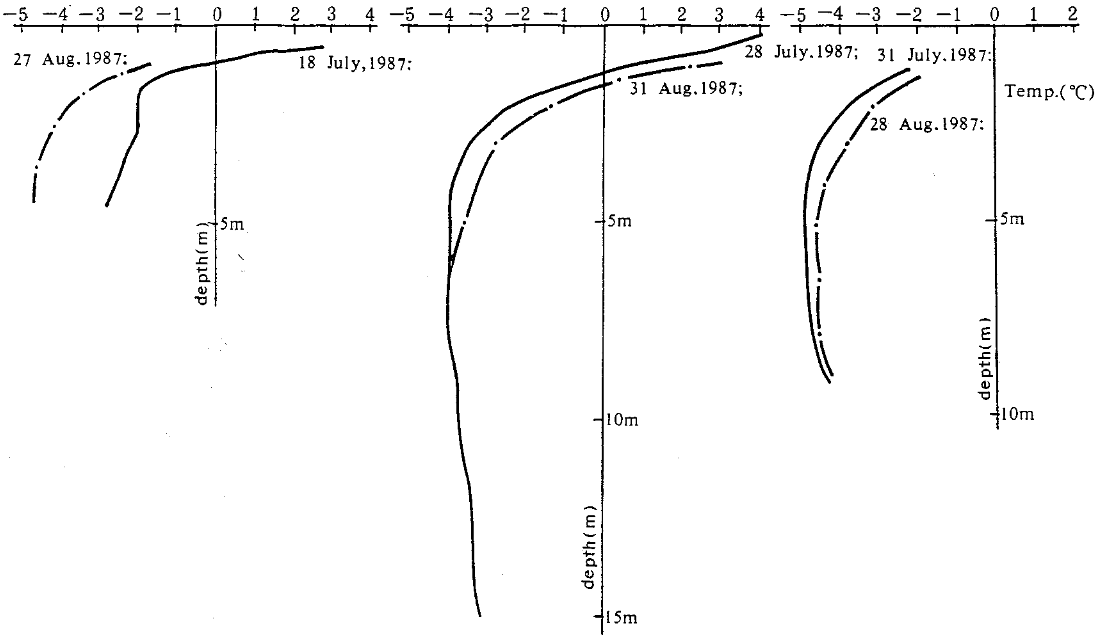

Fig. 2. Temperature profiles of boreholes in Tianshuihai in the West Kunlun Mountains.

ground temperature approximate those in the Fenghuoshan Mountains along the Qinghai-Xizang Highway. Because of low temperature and great thickness, the permafrost in the basin is considered stable permafrost (Fig. 2).

5. Permafrost structure and ground ice

Permafrost on the south slope of the West Kunlun Mountains contain thick horizontal ice-rich layers and ice masses near the permafrost table. Sometimes, very large blocks of ice were found. For example, the one exposed on a slumping cliff had thickness of 6 m. Average ice content in this block was more than 50%, and its maximum appeared at a depth between 1.2 to 2.5 m from the top. There was about 20 cm of milky white pure ice with a large number of round and oval bubbles. This block of ice is considered as ground ice formed by the action of repeated segregation in water-saturated lacustrine deposits. Furthermore, ice wedge and ice vein, more than one and a half meters high, were first found by the barrack builders of Tianshuihai Station. As told by them, they saw many pure ice blocks in several places during excavation.

In 1987, several small ice wedges were found on the steep shore cliff of Tianshuihai Lake, buried in the soil-containing ice layer about 100 cm below the ground surface (Figs. 3 and 4). One of them developed a clear outline, tapering in 150 cm height from top to bottom: 70 to 80 cm wide on the top, and 20 cm wide at the bottom. In this ice wedge, the vertical joints and round and oval bubbles can be observed with naked eyes. Block-shaped sandy clay, lying vertically and obliquely, was also found on the side of middle part of the ice wedge. This suggests that the ice wedge was formed by imposed frost heave force on its both sides. Above the ice wedge in the active layer, no fissure was found, so that it is inactive at present and shows a relic feature. Presumably, the ice wedges were formed in frost cracks which were filled with water in summer, because of sudden cooling of the ground in winter.

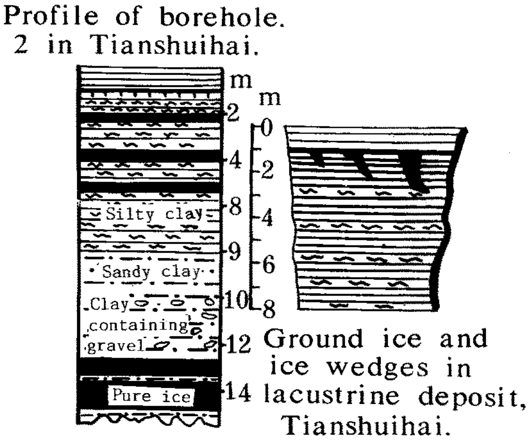

Fig. 3. Profile and section of permafrost in Tianshuihai.

Buried glacial ice was discovered in the terminal moraine of the Zhongfeng Glacier, and Dr. Wan Jintai considered this kind of ice as ice-core in till. It is seldom found that thick-layered ground ice can develop and persist in an extremely arid continental climate; therefore the authors consider that the buried glacial ice may have been formed in the last glaciation.

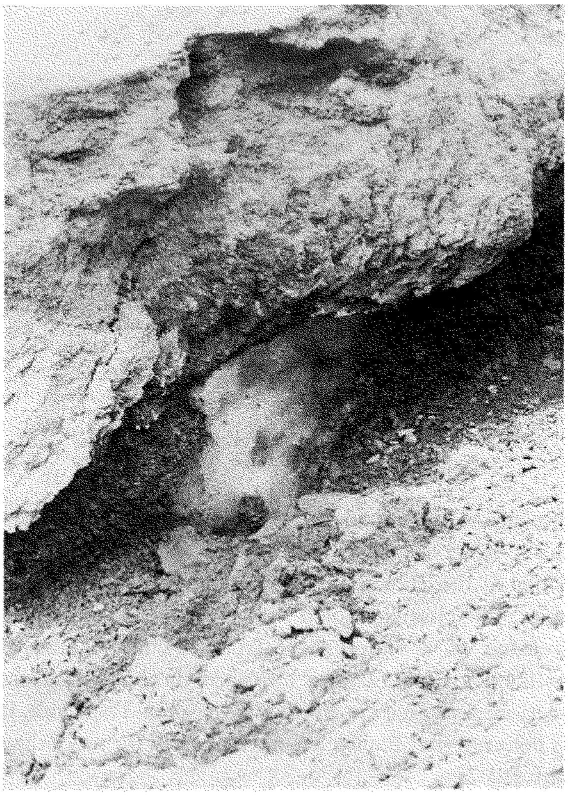
Fig. 4. Ice wedge in lacustrine deposit, Tianshuihai.

6. Periglacial phenomena and landforms

Various periglacial phenomena are found in the West Kunlun Mountain area which locates in the middle-latitude alpine periglacial zone. The lower limit of the periglacial zone may reach 3800 m a.s.l. so that the extent is as wide as 3000 m. Many periglacial phenomena in the study area were described by Li (1987).

6.1. Landforms formed by frost heaving

a. *Frost mounds*: Frost mounds are main topographic features in permafrost regions. They are classified into seasonal frost mounds and ice-cored mound. In this article, ice-cored mound which exists for at least two consecutive winters is called pingo. Soil and stony pingos are distinguished by their composition. Soil-pingos occur widely in Tianshuihai lacustrine deposits; they are about 1 m high and have fissured summits. The fissures at the top are 20 to 40 cm deep. The upper part is composed of dry soil covered with thin coarse-grained soil, while their lower part is composed of ground ice with frozen soil. The seasonally thawed layer here ranges from 1.0 to 1.2 m. Stony frost mounds were found in the pediment (4900 to 5200 m a.s.l.) between Aksayqin Lake and the Litian River, ranging between 50 and 100 cm in height. Stones on the top of mounds had their long axis vertical or oblique. Pingos with heights of 1 to 2 m and basal diameters of 3 to 5 m are also located in the glacio-fluvial fan bordering the moraine ridge of the Chongce Glacier. A remnant pingo with a basal diameter of about 100 m exists here with developed thaw slumping around it.

b. *Frost-heaved bedrock*: Ejection of stones from the fines by up-freezing were often found on the permafrost ground and on moraines (Fig. 5). Frost-heaved slate, 20-40 cm in height, developed in the lateral moraine of the Chongce Ice Cap. There was an undisturbed layer (including ice) 30 cm thick above the permafrost table, which indicated that the frost-heaved stones were generated in saturated fines by seasonal freezing. Frost-heaved stones were also widespread in yellow lacustrine sediments, ranging from 5 to 10 cm in height.

c. *Icings*: Icings were often encountered in the routing

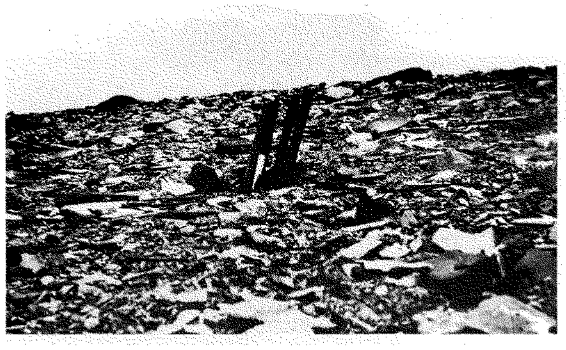

Fig. 5. Vertical stones by upfreezing on the lateral moraine, the Gozha Glacier.

Fig. 6. Micro-stone circle in the wide valley, upstream the Litian River.

expedition on the south slope of the Kunlun Mountains. River ice, with several square kilometer, was found at the Zhongfeng Glacier tongue. On top of the river, an icing 1 m high was formed by successive freezing of a water sheet from the river. Several polluted ice layers were observed through the cross section of the ice cut by fluvial erosion. Therefore, it is believed that the ice has accumulated for more than one year.

Seasonal spring icings were also recognized in a thaw lake at 5400 m a.s.l. The temperature of the springs was 4℃ on July 18 and the water was slightly saline. A broad ice sheet formed here in winter (0.4-1.2 m thick), with icings (40-60 cm high) on its top. Radial fissures were also found on icings.

6.2. Patterned ground

a. *Sorted circles*: Small circles 10 to,40 cm in diameter occurred in the flat valley (5200 m a.s.l.) along the upper reach of the Litian River (Fig. 6). They were fine-grain centered and stone bounded. Center of each circle was frozen in the morning in middle-July, but in the afternoon, it thawed and thin layer of melt water deposited there. When a man stood on the circles, he sank down by 10 cm.

Large circles, bounded with stones 2-10 cm long, were found in the moraine of the Chonce Ice Cap and on the cryoplanation terraces of Guliya Pass. Diameters of the circles generally range from 2 to 4 m, up to 8 m in maximum. Stones were granite, sandstone and limestone; and polygonal structures could be seen within the circles. When seen from a far, a large number of circles constituted an attractive landscape.

b. *Fissure polygons*: They were widespread in groups on the gentle slope of the Tianshuihai Basin and on the glaciofluvial fan of Guliya Pass (Fig. 7). Polygons were quadrilateral and hexagonal, 15-10 cm in diameter, sharing rims mutually. In the lacustrine deposits of Aksayqin Lake, large polygons 3-5 m in dia-

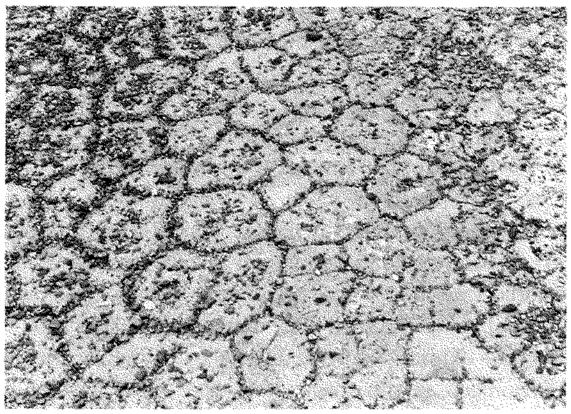

Fig. 7. Fissure polygons on the cryoplanation terrace, Keriya Pass.

Fig. 8. Patterned ground in Aksayqin Lake.

meter developed; their rims were filled with snow, which made the polygonal pattern more apparent (Fig. 8).

6.3. *Mass-wasting forms*

a. *Solifluction sheet*: Beside the terminal moraine of the Chongce Ice Cap, a small solifluction sheet was located on a slope of 30° at 5800 m a.s.l. It is one of the highest solifluctions yet observed in the world.

b. Talus: Debris of fractured rocks caused by frost wedging and cracking from bare rockwalls produce many talus slopes in arid and cold climatic conditions in the West Kunlun Mountains.

c. *Rock Glaciers*: Rock glaciers in and around Tibet have been reported by Cui (1983) and Li and Yao (1987): there are sixteen rock glaciers in the Kunlun Mountains, and twenty-six in the Gongga Mountains. During our expedition, nine rock glaciers with different forms were recognized: one was 400 m long and 30-50 m wide, near Dahongliutan, lying on a slope of 30°. The rock glacier rampart was about 4 m high, and composed of shale and sandstone. Emerging elevations of rock glaciers range between 4800 and 4500 m a.s.l. in this region. Debris from slopes and nivation hollows are the material sources of the rock glaciers.

d. *Cryoplanation terraces*: Cryoplanation terraces were found at 5800-6000 m a.s.l. near Guliya Pass on south facing slopes of the West Kunlun Mountains; circles, stripes and block fields occur on the surface.

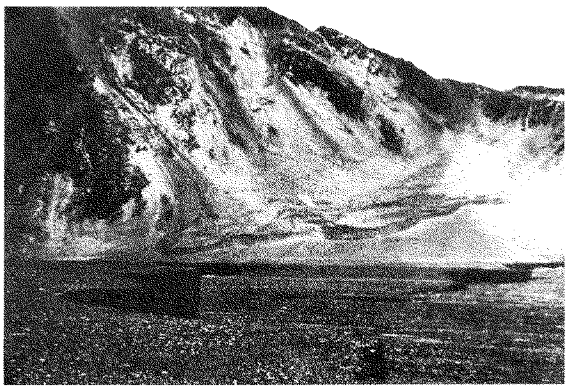

Fig. 9. Rock glacier on the slope, west side, near Dahongliutan.

6.4. *Thermokarst*

Thermokarst lakes were found at Tianshuihai. Ground ice was widespread in lacustrine deposits in Tianshuihai Lake on the south side of the West Kunlun Mountains. Ground ice 6-8 m was thick exposed beneath the ground surface in cross section. Several layers of ground ice could be seen in a borehole while pure ground ice appeared at the following depths: 2.0-2.2 m; 3.6-3.8 m; 5.0-5.3 m; 13.0-13.3 m; 13.4-14.7 m. A thaw lake several square kilometers in area was produced by melting of ground ice; in it water was 3.5 m deep. One meter away from the lake the ground surface was underlain by permafrost. A hot spring at the end of the Zhongfeng Glacier thawed the glacier and permafrost, and that produced thaw lakes in the modern moraine.

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