J. Mt. Sci. (2015) 12(5): 1135-1144 e-mail: jms@imde.ac.cn http://jms.imde.ac.cn
DOI: 10.1007/s11629-014-3207-x

Characteristics of Permafrost along Highway G214 in the Eastern Qinghai-Tibet Plateau

SHENG Yu http://orcid.org/0000-0002-8210-4334; e-mail: sheng@lzb.ac.cn

CAO Yuan-bing http://orcid.org/0000-0002-0391-0603; e-mail:caoyb@126.com

LI Jing[1] http://orcid.org/0000-0001-9802-7006; e-mail: li_jing9797@lzb.ac.cn

WU Ji-chun http://orcid.org/0000-0002-8999-611X; e-mail: wujichun@lzb.ac.cn

CHEN Ji http://orcid.org/0000-0002-6103-3098 ; e-mail: chenji@lzb.ac.cn

FENG Zi-liang http://orcid.org/0000-0002-9609-4659; e-mail: chdfeng_2007@163.com

State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China

Citation: Sheng Y, Cao YB, Li JC, et al. (2015) Characteristics of permafrost along Highway G214 in the eastern Qinghai-Tibet Plateau. Journal of Mountain Science 12(5). DOI: 10.1007/s11629-014-3207-x

Abstract: The characteristics of the permafrost along National Highway No. 214 (G214) in Qinghai province (between kilometer markers K310 and K670), including the distribution patterns of permafrost and seasonally frozen ground (SFG), ground ice content and mean annual ground temperature (MAGT), were analyzed using a large quantity of drilling and measured ground temperature data. Three topographic units can be distinguished along the highway: the northern mountains, including Ela Mountain and Longstone Mountain; the medial alluvial plain and the southern Bayan Har Mountains. The horizontal distribution patterns of permafrost can be divided into four sections, from north to south: the northern continuous permafrost zone (K310-K460), the island permafrost zone (K460-K560), the southern continuous permafrost zone (K560-K630), and the discontinuous permafrost zone (K630-K670). Vertically, the permafrost lower limits (PLLs) of the discontinuous zone were 4200/4325 m, 4230/4350 m, and 4350/4450 m on the north-facing/south-facing slopes of Ela Mountain, Longstone Mountain and Bayan Har Mountains, respectively. The permafrost was generally warm, with MAGTs between -1.0°C and 0°C in the northern continuous permafrost zone, approximately -0.5°C in the island permafrost zone, between -1.5°C and 0°C in the southern continuous permafrost zone, and higher than -0.5°C in the discontinuous permafrost zone. In contrast, the spatial variations in ground ice content were mainly controlled by the local soil water content and lithology. The relationships between the mean annual air temperature (MAAT) and the PLLs indicated that the PLLs varied between -3.3°C and -4.1°C for the northern Ela and Longstone Mountains and between -4.1°C and -4.6°C in the southern Bayan Har Mountains.

Keywords: Permafrost characteristics; National Highway No. 214 (G214); Eastern Qinghai-Tibet Plateau; Qinghai-Tibet Plateau; Temperature

Introduction

The stability of linear engineering in permafrost regions is largely governed by permafrost characteristics (Wu et al. 2002).

Received: 1 July 2014
Accepted: 7 November 2014

Studies have been conducted on the permafrost environments and changes along the Qinghai-Tibet engineering corridors, including the Qinghai-Tibet Highway and Qinghai-Tibet Railway (Wu et al. 2010; Jin et al. 2008c; Wu et al. 2001). However, there have been relatively few studies on National Highway No. 214 (G214). Highway G214, from north to south, begins in Xining city, Qinghai province, passes through the southern part of Qinghai province, the eastern edge of the Tibet Autonomous Region, the western part of Yunnan province, and ends in Jinghong city, Yunnan province. The total length of the road is 3,256 km, more than 1,000 km of which is in Qinghai province. The start and end points of the highway in Qinghai province are Xining and Yushu, respectively. The highway is located on the eastern edge of the Qinghai-Tibet Plateau, approximately parallel to the Qinghai-Tibet engineering corridors (G109) in the interior Qinghai-Tibet Plateau (Figure 1).

Geocryologically, the highway G214 traverses the eastern edge of the continuous permafrost areas of the southern Qinghai Plateau (Zhou et al. 2000). Previous studies have indicated that permafrost is mainly distributed in the section between Ela Mountain, Xinghai county, and Qingshuihe town, Yushu county, and that the general distribution patterns of permafrost were controlled by latitude, longitude, and elevation, as well as other local factors (Wang et al. 1999; Wang et al. 1991). Additionally, local permafrost degradation caused by climate warming and intensive human activities has been given some attention (Jin et al. 2010; Zhu et al. 1996). The objectives of this paper are to use existing drilling and ground temperature data to describe the permafrost characteristics along the highway, including its present distribution patterns, ground ice content and underground thermal regimes. The study area is approximately 360 km in length and begins at the north-facing slope of Ela Mountain and ends south of Qingshuihe. This area corresponds approximately to kilometer markers K310 to K670.

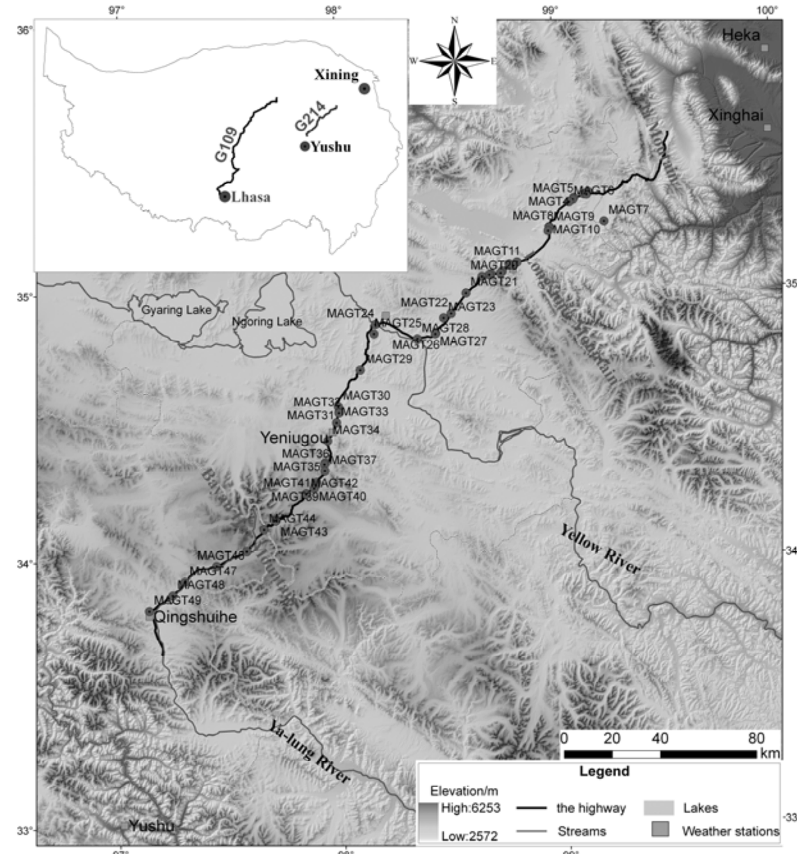

Figure 1 Study area and topographic conditions along Highway G214 in China.

1 Study Area

The stretch of Highway G214 from Ela Mountain to Qingshuihe town is located in the southeastern Qinghai Plateau (97°-99.5°E, 33.4°-35.6°N). The highway crosses a series of high mountains and intermountain graben basins. From north to south, the mountains are Ela Mountain, Longstone Mountain, and the Bayan Har Mountains. The Zuimatan basin and the alluvial plain that forms the source area of the Yellow River (SAYR) are located between the mountain ranges. Ela Mountain and the Bayan Har Mountains are components of the middle and southern branches of the East Kunlun mountain ranges. The strata are mainly composed of a sedimentary cover of Mesoproterozoic erathem, lower Paleozoic erathem, middle Paleozoic erathem and upper Paleozoic erathem. All of the mountain ranges are oriented northwest-southeast and are perpendicular to the direction of the highway (Figure 1). Quaternary alluvial-proluvial sediments generally cover the basins, intermountain valleys and the piedmont plain. The sediments are composed of fine- and coarse-grained soils that are composed primarily of sand, sand loam and clay in the upper layer and gravels in the bottom layer (Fang et al. 2009). The elevation varies between 4000 and 5000 m. The highest elevation, which exceeds 4800 m, is the peak of Bayan Har Mountain, and the lowest elevation, appropriately 3900 m, is located in the Wenquan valley.

Climatically, the highway is in the subfrigid zone of the Plateau, which is characterized by mean air temperatures in the warmest month of 6°C-12°C (Zhang 2009). The high-elevation Bayan Har Mountains can block the warm-and-wet airflow from the Indian Ocean flowing into the southern Yellow River basin, resulting in large differences in climate type and natural landscapes between the north-facing and south-facing slopes. To the north of the mountains, the climate is semi-arid, with a mean annual precipitation (MAP) ranging between 200 and 499 mm, and precipitation mainly occurs in May through September. To the south of the mountains, the climate is semi-humid, with a MAP generally exceeding 500 mm (Lin and Wu 1981). In addition, evaporation is far greater than precipitation in the area to the north of the mountains. The wind is strong throughout the year, which further intensifies the evaporation and contributes to the aridity.

Alpine meadow, dominated by *Kobresia*, *Carex* and forb species, is the main vegetation type along the highway. The *Kobresia pygmaea*, *K. scheoenoides*, *K. pygmaea*, *Stipa purpurea*, and *K. humilis* meadows are widely distributed in the gentle terrain of mountainous piedmont plains, river valleys and other places with moderate soil water content. High cold steppes dominated by *Stipa*, *Achnatheherum*, *Festuca*, and *Carex* species are the second most dominant vegetation association and is usually found in dry, well-drained areas. In addition, the alpine scrub vegetation type, dominated by *Salix* and *Dasiphora fruticos* species, is mainly distributed in the mountainous areas of Ela and Longstone Mountains (Figure 2) (Hou 2007).

2 Data and Method

2.1 Data collection

Four complementary drilling investigations were carried out along the highway in the summers of 2004, 2009, 2010 and 2011. The drilling in 2004 occurred in the northern part of Ela Mountain and to the south of the Bayan Har Mountain pass. The drilling in 2009 was on Ela Mountain and in the Zuimatan basin and surrounding areas. In 2010 and 2011, drilling extended from Longstone Mountain to the Bayan Har Mountains. The drilling locations were generally at the foot of a subgrade. The density of the drilling sites varied according to frozen ground conditions, usually one

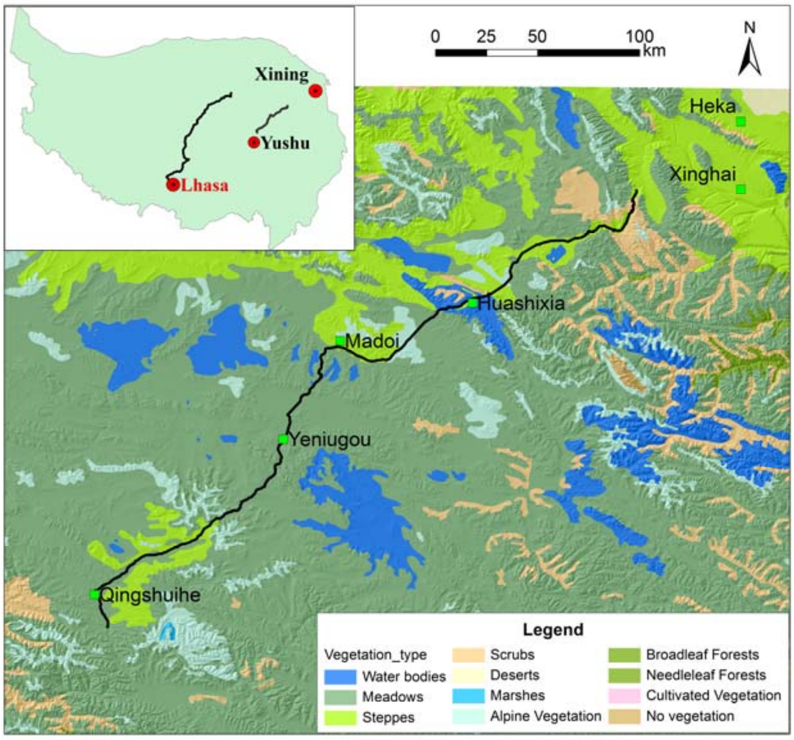

Figure 2 Vegetation map along Highway G214 based on the Vegetation Map of China (Hou 2007).

per kilometer in permafrost areas and one per two kilometers in seasonally frozen ground (SFG). The depths of the boreholes used to measure the ground temperature generally ranged between 10 m and 20 m. The resulting drill cores revealed the composition of the soil/rock at various depths. The ground ice content was empirically estimated and coarsely divided into two types: ice-rich permafrost with volumetric ground ice content greater than or equal to 20% and ice-poor permafrost with volumetric ground ice content less than 20%. The geographical locations of all drilling sites were recorded with a handheld GPS. After drilling, approximately 5-cm-diameter steel pipes with lengths equal to the depth of the hole were inserted into the boreholes with depths exceeding 10 m. The pipe was then capped and tightened to prevent it from adjusting to ambient temperatures. Ground temperatures were manually measured using a cable equipped with a string of thermistors made by the State Key Laboratory of Frozen Soil Engineering (SKLFSE China). The thermistors were calibrated in the laboratory and had a sensitivity of ± 0.05°C (Liu et al. 2011; Wu et al. 2010). The first measurements usually began two months later. For the measurements, the cable was put into the pipe for at least two hours to stabilize it. The thermistors had a depth increment of either 0.5 or 1 m. The frequency of the measurements was generally twice a month. The ground temperatures at 15 m were generally regarded as a substitute for the mean annual ground temperature (MAGT) on the Qinghai-Tibet Plateau because this depth generally avoids most variations in the ambient environment (Zhou et al. 2000). The depth of the zero annual amplitude in the area generally varied from 7 to 8 m (Wang et al. 1999). In this study, the ground temperature at 10-15 m, i.e., temperatures with an annual variation of less than 0.1°C, was used as the MAGT. Permafrost with a MAGT higher than -1°C was warm and sensitive to the variations in ambient temperatures and the disturbance caused by human activities.

Meteorological data from the weather stations were collected and used to analyze the climatic setting of permafrost development along the highway and the relationship between the MAAT and permafrost lower limit (PLL). The topographic variation along the highway was determined based on the elevation measured using the GPS receiver combined with the SRTM DEM data with a 90 m resolution.

2.2 Method

Permafrost on the Qinghai–Tibet Plateau is classified as predominantly continuous (occupying 70%-90% of the area), widespread island permafrost (30%-70%), or sparse island permafrost (<30%) (Zhao et al. 2010; Zhou et al. 2000). In the zone of continuous permafrost, permafrost exists everywhere except for fault zones filled with groundwater, large river beds, the area beneath large glaciers and lakes, and sandy sediments on south-facing slopes. In the zone of discontinuous permafrost, the permafrost distribution is influenced by aspect, and permafrost is generally absent on south-facing slopes. In the zone of island permafrost, permafrost occurs in certain soils (peat and coarse-grained soil with no fines) on north-facing slopes (Cheng and Francesco 1992; Gorbunov 1988).

3 Results

Due to the rugged topography and the large climatic boundary of the Bayan Har Mountain, the highway was divided into three parts to analyze permafrost characteristics in detail: the northern mountainous areas between Ela Mountain and Longstone Mountain (approximately 98.5-99.5 °E, 35.0-35.7 °N, corresponding to kilometers K310-K420), the middle piedmont alluvial plain of the SAYR (98.0-98.5 °E, 34.5-35.0 °N, corresponding to kilometers K420-K540), and the southern Bayan Har Mountains (97.0-98.0 °E, 33.7-34.7 °N, corresponding to kilometers K540-K670) (Figure 3).

3.1 Northern mountainous areas

This area begins from the north-facing slope of the Ela Mountain, passes through the Zuimatan basin, and ends at the south-facing slope of Longstone Mountain. The elevation varies between 3900 and 4500 m. Three field investigations of frozen ground conditions were carried out in 2004, 2009 and 2010. A total of 83 boreholes and 21 MAGT measurements (MAGT1-MAGT21, Figure 1) were collected.

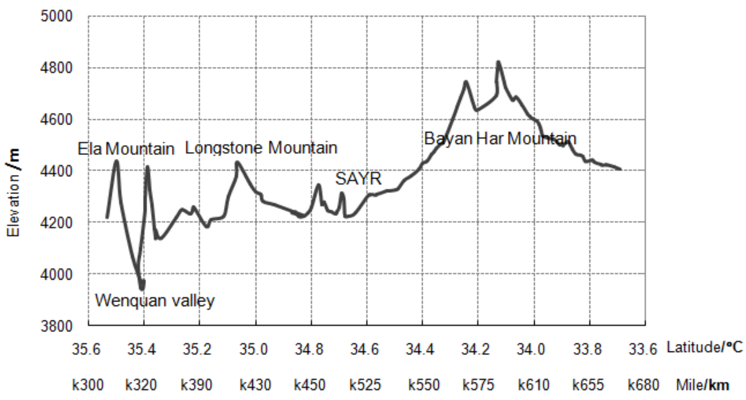

Figure 3 Elevation variations along Highway G214 in China.

The drill cores indicated that gravel soil with various grain sizes was the main lithological component (Figure 4a), and the vegetation map indicated that alpine steppe and alpine meadow were the two major vegetation types in this section (Figure 2). The topography, including elevation, slope angle and aspect, played an important role in the distribution of permafrost. Permafrost occurred above 4200 m on the north-facing slope of Ela Mountain and was present at 4325 m on the south-facing slope. The middle Zuimatan basin can be divided into two parts according to the geomorphological units. The first is the valley with elevations between 4150 and 4200 m, and the second is the area of low hills with elevations between 4200 and 4280 m. Controlled by the relief, the local soil moisture content in the valley was higher than on the low hills, which led to the wide distribution of permafrost in the valley. In contrast, permafrost in the low hills was locally distributed in shady wet meadows with MAGTs ranging between -1.0°C and 0°C. On Longstone Mountain, permafrost and wet alpine meadows coexisted at approximately 4230 m, and permafrost was widely distributed above 4350 m. A large amount of turf hummocks were distributed in the gently sloping terrain below the summit, along with an extremely developed area of permafrost. The ground ice content in the turf hummocks was high, and the measured MAGTs were between -1.0 and -0.8°C. Beyond the summit, the highway continues gradually down the south-facing slope of the mountain and enters the SAYR plain. Permafrost was distributed discontinuously above 4300 m (Figure 4b). The PLLs in the discontinuous zone were estimated to be 4230 m and 4300 m on the north-facing and south-facing slopes, respectively, of Longstone Mountain.

3.2 Medium piedmont alluvial plain

This area begins at the foot of Longstone Mountain and ends at the foot of the north-facing slope of the Bayan Har Mountains. The highway traverses the piedmont plain, broad gullies and low hills. The soil moisture content was generally high. The field investigation of frozen ground was carried out in June 2010. A total of 65 boreholes and 13 measured MAGTs (MAGT22-MAGT34, Figure 1) were obtained in this area.

Influenced by the long-term alluviation of rivers, fine and coarse sand of various grain sizes were the main components of the soil (Figure 5a).

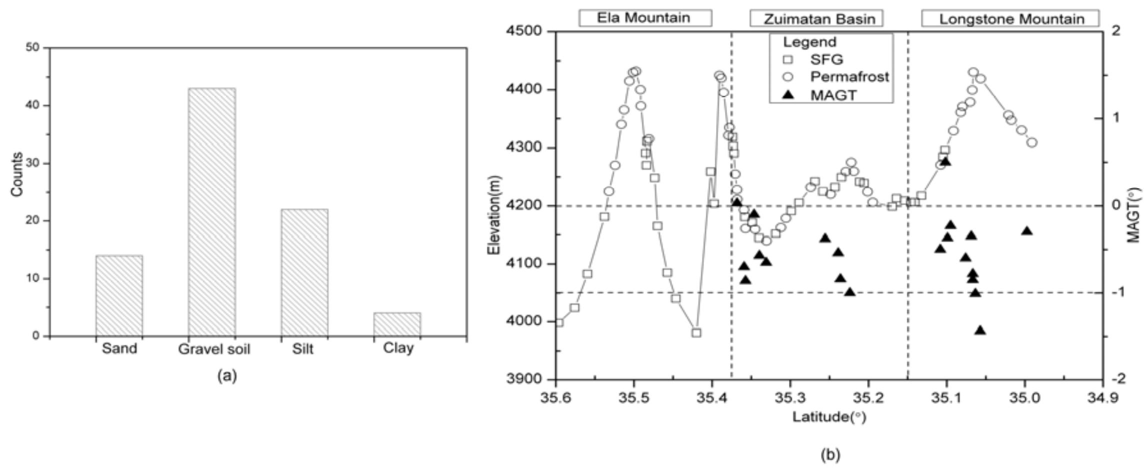

Figure 4 Lithological compositions (a) and variations in the boreholes and the measured MAGTs (b) of the northern mountainous areas along Highway G214 in China.

The topographic variations are small; the elevation ranged from 4210 m to 4430 m. Permafrost was distributed continuously between the mountain pass of Longstone Mountain and the piedmont plain of the SAYR above 4250 m. Below this elevation, permafrost was completely absent. The measured MAGTs ranged between -0.5 and 0°C (Figure 5b), and the ground ice content of the permafrost was generally high. Continuing to the south, the highway enters the foothills of Bayan Har Mountain, where permafrost and SFG were alternately distributed. Permafrost was mainly distributed in the pockets of wetland meadows (Figure 5b).

3.3 Southern Bayan Har Mountains

This area includes the foot of the north-facing slope of the Bayan Har Mountains, the Chalaping highland, and the south-facing slope foot of the mountains. The elevation of the mountains varies between 4300 and 4850 m. A total of 76 boreholes and 15 MAGT measurements (MAGT35-MAGT49, Figure 1) were obtained during the field investigation in 2010.

The drill cores indicated that gravel soil with various grain sizes was the main lithological component (Figure 6a), and the vegetation map indicated that alpine steppe and alpine meadow were the two major vegetation types along the highway (Figure 2). Permafrost was widely distributed above 4350 m on the north-facing slope. Paludal turf hummocks were highly developed in the highland. Additionally, in this area, there was an extremely developed area of permafrost with measured MAGTs ranging between -1.5 and -1°C, and the ground ice content of the permafrost layer exceeded 20%. At the summit of the mountains, the depth to bedrock is shallow. The measured MAGT was approximately -1°C, yet the ground ice content of permafrost was low. Permafrost was distributed continuously above 4500 m on the

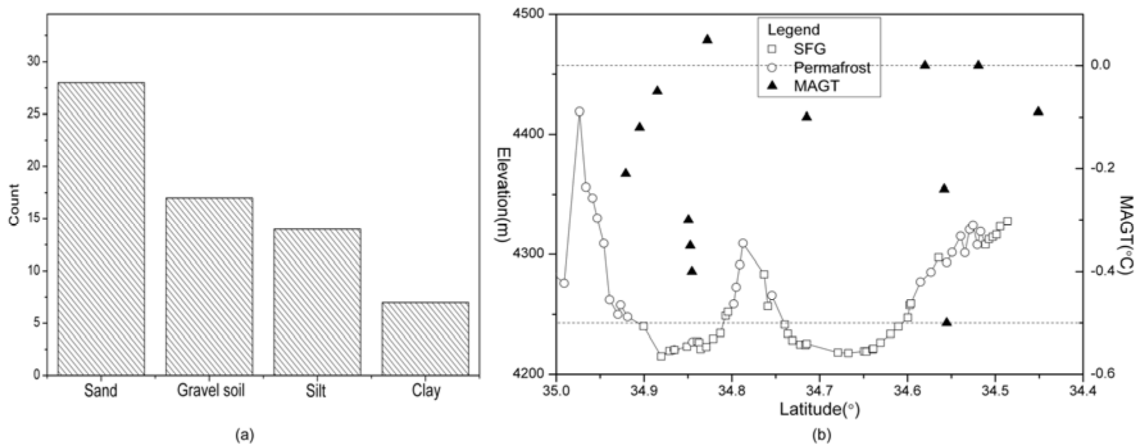

Figure 5 Lithological compositions (a) and variations in the boreholes and the measured MAGTs (b) of the medium piedmont alluvial plain along Highway G214 in China.

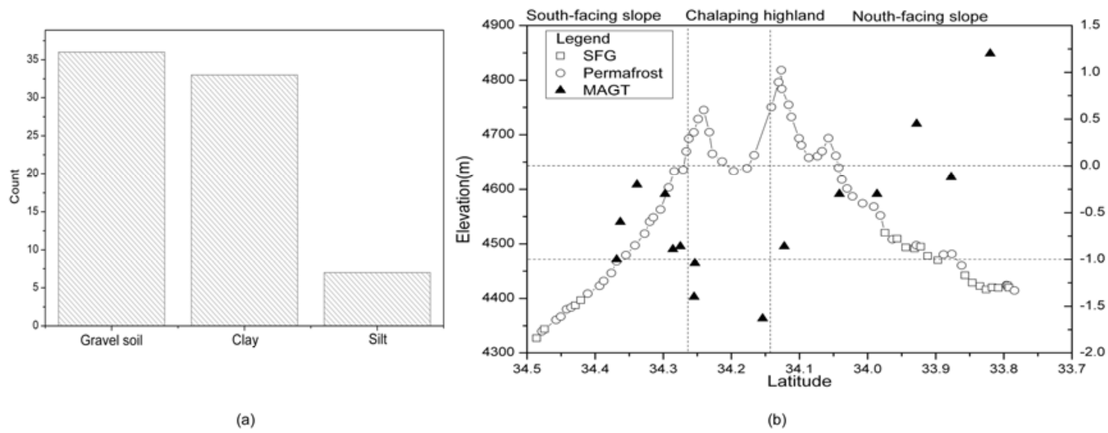

Figure 6 Lithological compositions (a) and variations in the boreholes and the measured MAGTs (b) of the southern Bayan Har Mountains along Highway G214 in China.

south-facing slope of the mountains. To the south of the mountain pass, the highway crosses into the piedmont plain and foothills. Permafrost was isolated and discontinuous in the moist lowland. The ground ice content of the permafrost was high, and the measured MAGTs were generally higher than -0.5°C. A permafrost island was found at 4450 m at the southernmost point of the section of highway. Therefore, the elevation 4450 m was estimated to be the PLL of the discontinuous zone on the southern slope of the Bayan Har Mountains (Figure 6).

4 Discussion

4.1 General patterns and regional differences of permafrost along the highway

Generally, the primary influence on permafrost distribution along the G214 was topography. From north to south, the PLLs of the discontinuous zone were 4200/4325 m, 4230/4350 m, and 4350/4450 m on the north-facing/south-facing slopes of Ela Mountain, Longstone Mountain and the Bayan Har Mountains, respectively. In addition, the local soil moisture content and vegetation type are both important factors in the permafrost distribution. In the Zuimatan valley, the SAYR, and the Chalaping highland, the high soil moisture content and well-developed wet meadows contributed to the local development of permafrost with high ground ice content.

The horizontal distribution patterns of permafrost along the highway can be divided into four sections (Figure 7). The first section, from approximately K310 to K460, is a continuous permafrost zone and corresponds to the northern mountainous areas and the northern part of the SAYR plain. The second section, from approximately K460 to K560, is an island permafrost zone, corresponding to the southern part of the SAYR plain. The third section, from approximately K560 to K630, is a continuous permafrost zone in the Bayan Har Mountains. The fourth section, from approximately K630 to K670, is a discontinuous permafrost zone in the Bayan Har Mountains. In the northern and southern mountains, permafrost was continuous and discontinuous, whereas permafrost was patchy and isolated in the medium river valley and plain areas. Vertical variations in the PLL were evident in discontinuous and island zones between the tops of mountains and the foot of the mountains.

The PLL is usually expressed as a MAAT in order to reflect the climatic conditions of permafrost development in high-altitude permafrost regions (Zhou et al. 2000; Zhang et al. 1985). Previous studies have indicated that the MAAT of the PLL varied between -2°C and approximately -3°C on the Qinghai-Tibet Plateau (Cheng and Wang, 1982). Seven weather stations with observation records from the 1960s to the present are located along the highway. Five are located north of the Bayan Har Mountains, and two are located south of the Bayan Har Mountains (Figure 1). The MAAT and MAP values of each station are listed in Table 1. The minimum MAAT, -4.5°C, occurred at Qingshuihe at 4415 m elevation, followed by the MAAT of -4.2°C for Huashixia and Yeniugou, both of which lie at approximately 4300 m. The mountain mass effect of the Bayan Har Mountains is remarkable. Qingshuihe and Yeniugou are two weather stations located on the

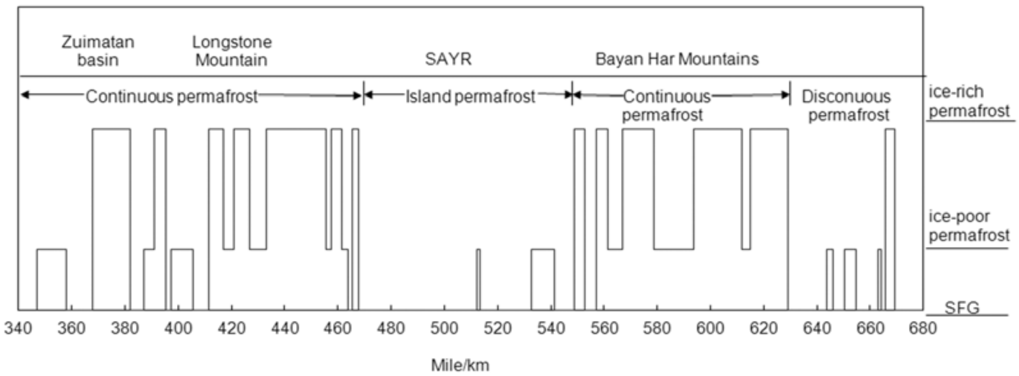

Figure 7 Characteristics of the frozen ground and ground ice content along Highway G214 in China.

Table 1 The geological and climatological attributes of the meteorological stations

	Heka	Xinghai	Huashixia	Madoi	Yeniugou	Qingshuihe	Yushu
Longitude	99°59'	99°59'	99°48'	98°13'	97°58'	97°08'	97°01'
Latitude	35°53'	35°35'	35°05'	34°55'	34°29'	33°48'	33°01'
Altitude(m)	3245	3323	4300	4272	4370	4415	3681
MAAT(°C)	1.2	1.4	-4.2	-3.6	-4.2	-4.5	3.4
MAP(mm)	378	353	412	322	335	523	496

Notes: MAAT = Mean annual air temperature; MAP = Mean annual precipitation.

south-facing and north-facing slopes of the Bayan Har Mountains at elevations of 4415 m and 4370 m, respectively. The observed MAPs were 523 mm and 335 mm at Qingshuihe station and Yeniugou station, respectively. The southernmost station, Yushu, had a MAP of 496 mm. Taking the Bayan Har Mountains as a climatic boundary, the lapse rate of the MAAT was 5.1°C×km^{-1} to the north of the mountains. It was estimated that the MAATs at the boundaries of the discontinuous permafrost were -3.3°C to -3.9°C on Ela Mountain, -3.4°C to -4.1°C on Longstone Mountain and -4.1°C to -4.6°C in the Bayan Har Mountains. These results update the previous results that defined the MAAT at the boundary between island and discontinuous permafrost zones as -4.5°C to -5.0°C along the highway (Wang et al. 1999).

4.2 Characteristics of permafrost along the highway

The measured MAGTs were -1.0°C to 0°C in the northern continuous permafrost zone, -0.5°C in the middle island permafrost zone, -1.5°C to 0°C in the southern continuous permafrost zone and generally greater than -0.5°C in the southern discontinuous permafrost zone. Compared to the Qinghai-Tibet transportation corridors with permafrost MAGTs of approximately -4°C or higher, the permafrost was generally “warmer” along the highway (Wu et al. 2010). The lapse rate of the MAGT was 3.6 °C×km^{-1} along the highway, whereas the lapse rate was 5.7 °C×km^{-1} along the Qinghai-Tibet transportation corridors. The difference in lapse rates was most likely the result of different regional climates within the eastern and interior Qinghai-Tibet Plateau. The MAAT varied from -4.0°C to -6.9°C, and the MAP was approximately 300 mm along the Qinghai-Tibet Highway (Wang et al. 1979). The MAAT varied from -4.5°C to 3.4°C, and the MAP varied between 320 and 520 mm along the highway. In addition, local factors contributed to the difference in MAGT lapse rates along the two corridors (Jin et al. 2008b; Lv et al. 2008).

In contrast to the above results, the spatial variations in ground ice content are mainly controlled by the local soil water content and lithological conditions (Cheng 1988). Ice-rich permafrost develops in places with lacustrine and alluvial sediments, whereas ice-poor permafrost is generally found in places with well-drained debris and gravelly sands (Gravis et al. 2003). In the permafrost areas in China, wetlands usually have rich permafrost development (Jin et al. 2008a). The Zuimatan basin was dominated by alluvial sediments in the paludal meadow and featured an area of ice-rich permafrost. In the SAYR, with its lacustrine sediments, permafrost was distributed in isolated patches within wet meadows. In the mountains, ice-rich permafrost was located in gently sloping terrain below the summit and at the foot of the mountain within areas of turf tussock and paludal meadows. In general, ice-poor permafrost was predominantly found along the highway.

4.3 Comparison of the permafrost characteristics along G214 and G109

The highways G109 and G204 are two approximately parallel transportation corridors in central and eastern Qinghai-Tibet Plateau. The permafrost along the Qinghai-Tibet Highway (usually referred to as G109) has received the most attention. Highway G109 crosses three major generally east-west-trending mountain ranges: the Kunlun Mountains, Fenghuo Mountains, and Tanggula Mountains. Approximately 80% of the highway is above 4000 m in elevation, and approximately 50 km is above 5000 m. Permafrost has been shown to occur along approximately 531 km in the section between Golmud and Lhasa (Jin et al. 2008c). In the northern part of the Kunlun

Mountains, the PLL of island permafrost corresponded to an MAAT of approximately -2°C to -3°C and an elevation range of 4150-4200 m. The PLL of continuous permafrost corresponded to an MAAT of approximately -4°C and an elevation range of 4350-4560 m. To south of Andoi, the PLL of continuous permafrost corresponded to an MAAT of approximately -4.0°C to -3.5°C and an elevation of approximately 4780 m (Wang et al. 1979). The MAGTs of the permafrost range from -3.5°C in the Kunlun Mountains and Fenghuo Mountains to approximately -2.0°C in the Tanggula Mountains (Wu et al. 2010). In comparison, the elevations along the G214 ranged between 4000 m and 4800 m. The PLLs of the discontinuous permafrost were 4200/4325 m, 4230/4350 m, and 4350/4450 m on the north-facing/south-facing slopes of Ela Mountain, Longstone Mountain and the Bayan Har Mountains, respectively. The corresponding MAATs at the boundaries of discontinuous permafrost were -3.3°C to -3.9°C on Ela Mountain, -3.4°C to -4.1°C on Longstone Mountain and -4.1°C to -4.6°C in the Bayan Har Mountains. The permafrost MAGT was -1.0°C to -0.8°C in the northern Ela Mountains, -0.5°C to 0°C in the medium SAYR plain, and -1.5°C to -1.0°C in the southern Bayan Har Mountains.

Previous studies have indicated that the permafrost on the Qinghai-Tibet Plateau has been undergoing significant changes due to climate warming and increasing human activities (Zhao et al. 2010). Records from the national weather stations indicate a rising trend in the MAAT along Highway G214 (Figure 8). The lack of long-term ground temperature data, however, has made it impossible to evaluate the permafrost changes caused by the climatic warming. This will form the basis of future work.

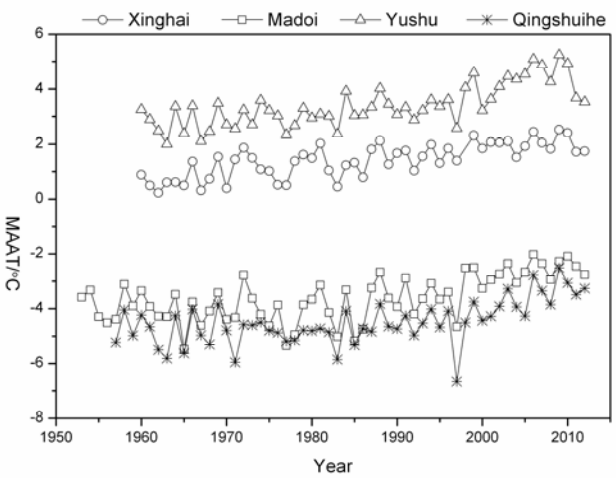

Figure 8 Changes in the mean annual air temperature (MAAT) at the weather stations since the 1950s.

5 Conclusions

Generally, topographic features determine the permafrost distribution patterns, which can be divided into four types: the northern continuous permafrost (K310-K460), the medial island permafrost (K460-K560), the southern continuous permafrost (K560-K630) and the southern discontinuous permafrost (K630-K670). From north to south, the PLLs of the discontinuous zone were 4200/4325 m, 4230/4350 m, and 4350/4450 m on the north-facing/south-facing slopes of Ela Mountain, Longstone Mountain and the Bayan Har Mountains, respectively. These values corresponded to MAATs of -3.3°C to -3.9°C on Ela Mountain, -3.4°C to -4.1°C on Longstone Mountain and -4.1°C to -4.6°C in the Bayan Har Mountains.

The permafrost is fairly warm along this corridor, with MAGTs of -2°C or higher, in contrast to the Qinghai-Tibet transportation corridors, which have MAGTs of -4°C or higher. This finding was most likely the result of regional differences in the eastern and interior Qinghai-Tibet Plateau caused by latitude, longitude and elevation. Ice-poor permafrost was the major type along the highway based on the ground ice content threshold assumed here. Ice-rich permafrost was scattered in paludal meadows with lacustrine and alluvial sediments, such as those in the Zuimatan basin, the SAYR valley and other places below summits with ample precipitation.

These conclusions could be helpful in road construction design, the maintenance of road embankments and permafrost protection. However, the differences in the MAGTs and the lapse rates of the MAGT along Highway G214 and the Qinghai-Tibet Highway in the eastern and interior Qinghai-Tibet Plateau, respectively, were remarkable. The reasons for these differences should be analyzed in future work.

Acknowledgements

This research was supported financially by the Chinese Academy of Sciences (CAS) Key Research Program (Grant No. KZZD-EW-13), the Major State Basic Research Development Program of China (Grant No. 2013CBA01803), the National Natural Science Foundation of China (Grant No. 41271084), the Research Program of State Key Laboratory of Frozen Soil Engineering of Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences (Grant No. SKLFSE-ZT-10), and the Natural Science Foundation of Gansu Province (Grant No. 145RJY304). The meteorological data were provided by the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/home.do). The Vegetation Map of China data set was provided by the Environmental and Ecological Science Data Center for West China, National Natural Science Foundation of China (http://westdc.westgis.ac.cn). Many thanks should be given to the two anonymous reviewers, who gave pertinent advice for the improvement of the paper.

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