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Permafrost Structure in Siberia by Transient Electromagnetic Method

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Abstract : The transient electromagnetic (TEM) method provides one of the most efficient techniques applicable to delineating deep resistivity structure in continuous permafrost area. The TEM sounding was carried out in order to investigate a subsurface resistivity structure of deep permafrost at alas and pingo in Neleger, Siberia, where permafrost is continuous. The upper resistive layer with resistivity of more than 1,000 ohm-m, which corresponds to an ice-rich permafrost layer with approximately 50-75 m thick, was revealed at the alas and pingo sites. Below the resistive layer thick conductive intermediate layer can be seen with the thickness of more than 150 m, which suggests unfrozen layer, talik. The resistive layer with resistivity of more than 100 ohm-m was observed again, which indicates permafrost. The lower boundary of this layer may represent the permafrost base. The permafrost base was estimated more than 400 m in depth, which agrees with the permafrost depth around this area. Considering the estimated geo-electric structure at the alas and pingo, a model of permafrost formation process was proposed. Deep sounding for vertical resistivity distribution up to the permafrost base may provide a useful tool for reconstructing the history of permafrost aggradations.

1. Introduction

From a geological perspective, permafrost is formed as a result of the interplay between a cold environment and both past and present geologic events. Under a global warming trend, permafrost formed during the last ice age would be thermally unstable, and the area of permafrost would begin to retreat. Therefore, an understanding of the permafrost distribution and its structure is needed to help estimate the overall effects of global warming past.

Geophysical approaches have been widely utilized to provide information on permafrost properties or distribution (Scott *et al.*, 1990). The application of geophysical methods to permafrost areas is based on changes of the physical properties of earth materials associated with the freezing of incorporated water, and formation of varying amounts of ground ice. Specifically, electrical resistivity values drastically increase when soil water freezes. A geo-electrical method continues to be used to study a number of permafrost problems. The transient electromagnetic (TEM) method provides one of the most efficient techniques applicable to delineating deep resistivity structure in continuous permafrost area.

The TEM sounding was carried out to supply basic information to interpret permafrost development in continuous permafrost area of Siberia. This paper introduces the TEM method and its relationship to permafrost, following by an overview of the permafrost conditions and geology of the study site. The measurement configurations and source moments are discussed in order to estimate the permafrost base. Finally, the implications for the history of permafrost are discussed, comparing the permafrost resistivity structure and its formation process.

2. Geological characteristics around study site

The observation was carried out in Neleger located 25 km northwest from Yakutsk shown in Figure 1. The mean annual air temperature and the annual precipitation in Yakutsk are approximately −10°C and 247 mm, respectively (French, 1996). The area has continuous permafrost with the thickness greater than 100 m (Ivanov, 1984). The permafrost on the western side of the Lena River is thicker than that on the eastern side. There are two fluvial terraces on the western side of the Lena River. The permafrost

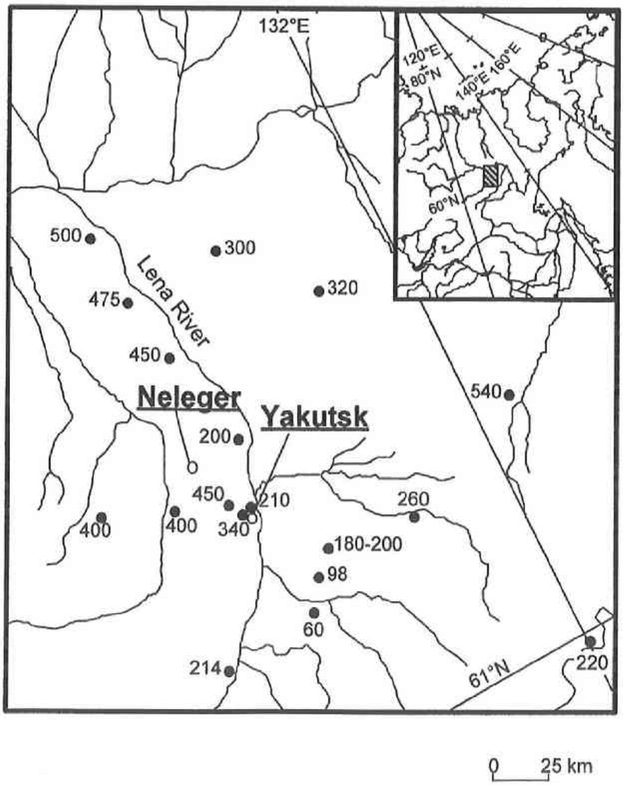

Fig. 1. Location map of study area (modified from Ivanov, 1984). Numbers in closed circles are permafrost thickness in meters (after Wada *et al.*, 2000).

thickness is around 200-300 m at the lower terrace, and 400-500 m at the upper terrace. Neleger is on the upper terrace, where alas are widely distributed.

Surrounding the study site is in the Yakutsk-Kangalassky coalfield and is characterized by named the Viluysky Syncline estimated by deep borings and geophysical soundings (Ignatchenko, 1961). On the eastern side of the Lena River Quaternary deposit has an extensive distribution. On the western side, there can be seen a variety of rock types, from Quaternary to lower Jurassic. Thick Jurassic terrigenous deposit around the study site is widely distributed with the thickness of more than 1,000 m and thicken northward markedly. In the south of this area, around Pokrovks, there exists Pre-/Cambrian carbonate rocks. Generally speaking, there is, however, little information about deep structure of permafrost.

According to resistivity distribution ranges of water-bearing rocks by Keller (1966), geo-electrical properties for Mesozoic terrestrial deposit indicate relatively conductive conditions. It may be inferred that resistivities around the study site are stable low at unfrozen temperature up to nearly 1,000 m in depth. Variation of resistivity will be associated with the amount of clay and salt or thermal condition in permafrost layer.

3. TEM method

The surface TEM method has been used for the detection of permafrost and for defining its spatial distribution and its vertical distribution (Rozenberg *et al.*, 1985; Harada *et al.*, 2000; Wada *et al.*, 2000). Todd and Dallimore (1998) conducted deep soundings to investigate permafrost distribution up to several hundred meters below the ground surface in the Mackenzie River delta of Canada.

The TEM sounding is performed by laying a large loop of wire on the ground and driving current through it. A small receiver coil is used to measure the magnetic transient response. When current flows through the loop, a magnetic field is produced which penetrates the earth. When the current is turned off, this field begins to collapse and secondary currents are induced in the earth near the loop. The secondary currents diffuse outward from the loop and to progressively greater depth. This eddy current flows away from the transmitter loop like a smoke ring. Currents move through resistive earth quickly and linger in conductive zones. Transient magnetic field caused by the eddy current is measured by a coil sensor on the surface ground and is converted to apparent resistivity values.

With the aid of inversion programs we can estimate a picture of the earth resistivity as a function of depth. In this study, equivalence analysis was also performed to estimate uncertainties in the inversion results, varying the unknown parameters in a user-specified fit-error limit. Equivalence analysis indicates the allowable range of each of the model parameter.

Table 1

Site	Sounding mode	Loop size (m)	Max. source moment (Am^2)
Alas	Central induction	100×100	115,000
	In/out loop	200×200	264,000
Pingo	Central induction In loop	160×160	253,440

4. Field operation

In this study, the transient data were recorded by PROTEM (D) system of Geonics Ltd., Canada. In order to collect transient data with a very wide dynamic range, two transmitters (called EM-47 and EM-57) were used. We used two kinds of receiver coils, high and low frequency types, to observe each transient data for EM-47 and EM-57. High frequency receiver coil was used for data collection in the time range from 0.006813 to 6.979 ms after shutting off the transmitted current using EM-47 ; low frequency coil was used in the range from 0.08813 to 76.69 ms using EM-57.

TEM soundings were conducted at two sites in Neleger ; alas and pingo sites. The alas site has an area approximately 300×400 m accompanied with the ground subsidence of about 2 m. The pingo, which is located in the alas, is about 60 m in diameter and 5 m in height.

A central induction measurement configuration (measurement at the center of the loop) was used at two sites. The measurements were performed by using the transmitter loop of 100×100 m and 200×200 m loops at the alas site, and 160×160 m loop at the pingo site (Table 1).

5. Resistivity structure

In this paper, we show the results estimated by one-dimensional inversion using the TEM sounding data by central induction measurement. Figure 2 shows the apparent resistivity data and inverted multi-layered resistivity models of the alas and pingo sites. Figure 2a is the result by using the transmitter loop of 100×100 m at the alas site. Shallow resistive layer had a resistivity of more than 1,000 ohm-m, which corresponds to an ice-rich permafrost. Thick conductive intermediate layer can be seen with the thickness of more than 150 m. The resistivity values of the fifth layer increase at the depth of more than 200 m. Although the bottom layer seems to represent a frozen layer, a definite conclusion must be reserved. High quality data up to 8 ms after shutting off the current were collected in this measurement, however, the source moment, which is a product of loop area and current (Table 1), may be not adequate to obtain deep structure information on the permafrost base estimation by using a 100×100 m loop. In order to delineate deeper resistivity structure, we enlarged the source moment two times by using

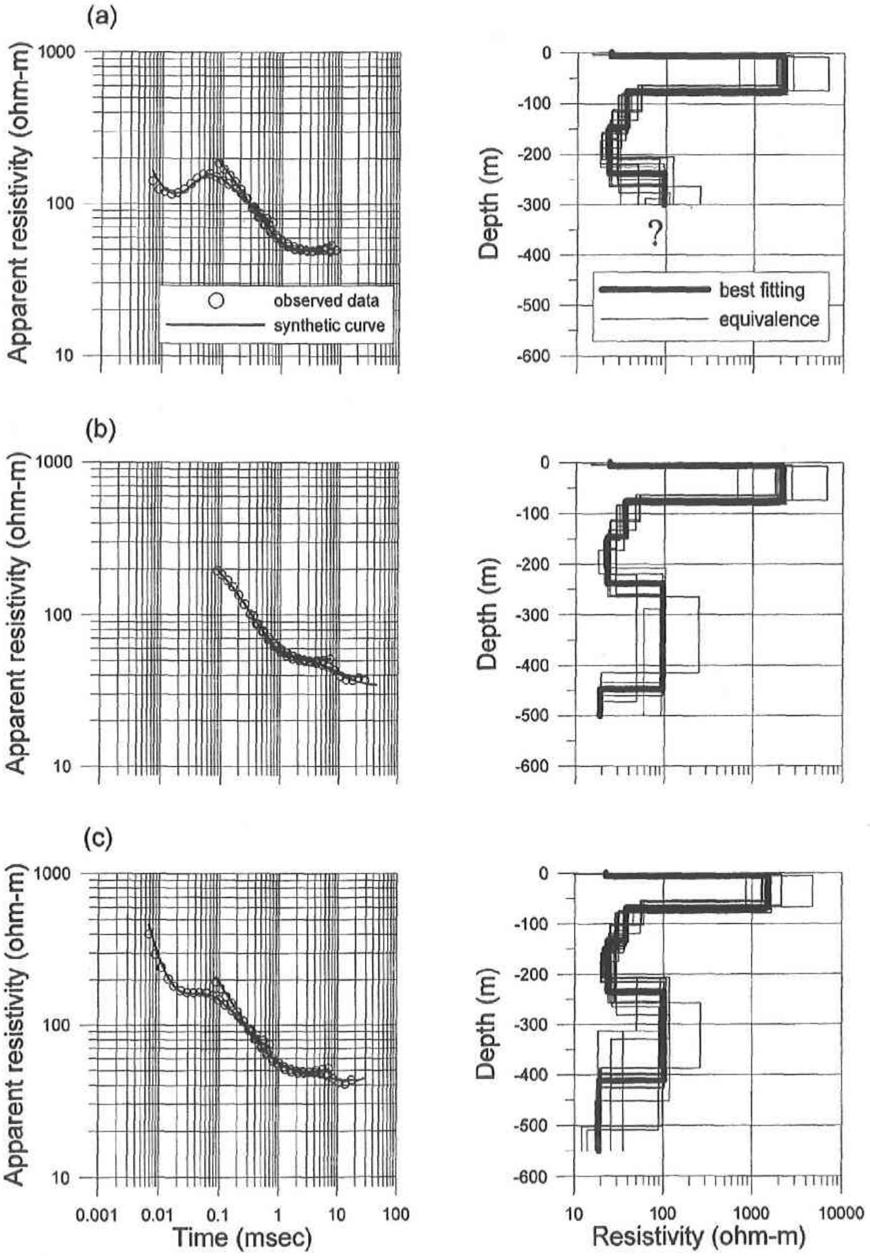

Fig. 2. Apparent resistivity curves and estimated resistivity structures of the alas and pingo sites. Results at alas site using transmitter loop of (a) 100×100 m and (b) 200×200 m. The resistivities of the first and second layers and the thickness of the first layer obtained in (a) were used for the calculation of (b). (c) Results obtained at the top of pingo (after Wada *et al.*, 2000).

a 200×200 m loop. Since the larger source moment was generated by enlarging loop size two times, the late time transient response was obtained up to more than 20 ms shown in Figure 2b. Inversion was done, fixing parameters of the first and second layers obtained from the previous processing, because the late time response contains mainly deeper resistivity information. In the late time response, clear decrease of apparent resistivity can be seen. Inverted resistivity structure detects the upper boundary of conductive base, which may suggest the permafrost base.

Figure 2c is a result of the pingo located in the alas area mentioned above. Using a large loop of 160×160 m, transient data from early time to late time were observed. General features of estimated resistivity structure is very similar to that of the alas site in spite of only slight differences in thickness of the resistive second layer; the thickness obtained at the pingo site is greater than that of the alas site. The lower boundary of the fifth layer, with the resistivity value of about 100 ohm-m, may represent the permafrost base with the depth of around 400 m, which agrees with the permafrost depth reported by Ivanov (1984) (Figure 1).

6. Reliability of data

In order to make clear the reliability of late time data observed at the pingo, we checked confidence limits of measured data measuring data five times. Figure 3 shows the transformed apparent resistivity curves. The confidence limits of 95% of observed data are indicated by vertical bars. The latest measurement time range in which low noise data is obtained reaches nearly 20 ms. Obvious decrease of resistivity curves can

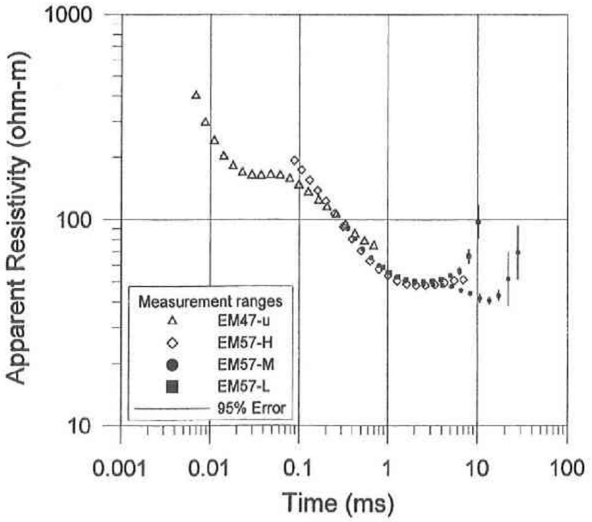

Fig. 3. Apparent resistivity curves observed by central induction measurement configuration at the top of pingo, using transmitter loop of 160×160 m (after Wada *et al.*, 2000).

be seen in the late time ranging from around 6 to 20 ms. Such a decrease of apparent resistivity, which suggest the permafrost base, was revealed only by using large source moment over 250,000 Am².

7. Permafrost formation process

The estimated resistivity structure at the alas and pingo sites is characterized by a conductive layer, approximately 150–200 m thick, in contact with resistive layers at its

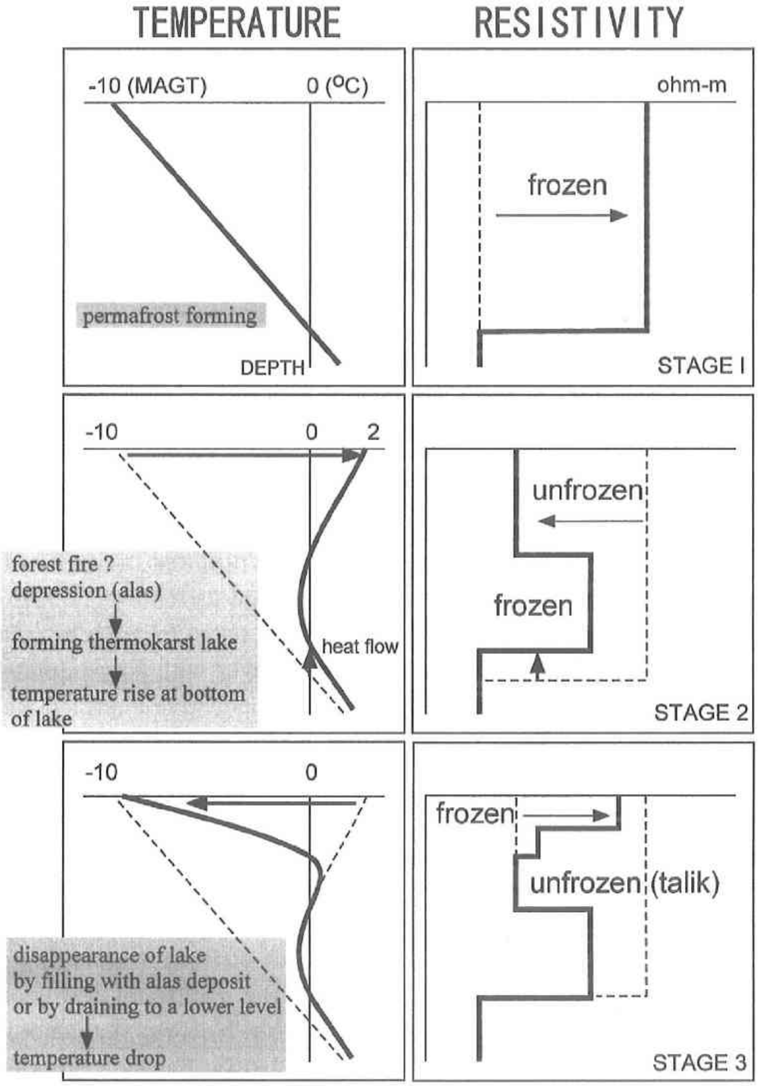

Fig. 4. Model of permafrost forming process for the interpretation of the present resistivity structure (after Wada *et al.*, 2000).

upper and lower boundaries ; the upper ice-rich permafrost layer was usually about 50–75 m thick and the lower permafrost layer was more than 150 m in thickness. According to Fedorov (1971) in the author's discussion of the presence of talik, which is defined as an unfrozen layer among permafrost, at Magan near Yakutsk, it can be concluded that this conductive layer represents talik.

Based on the relationship between permafrost formation process and resistivity structure, the TEM results at the alas and pingo sites provide evidence of the sequential change of permafrost. Figure 4 shows a model of the formation process of the present resistivity structure. This model comprises three stages. The first stage occurred in the ice age. In this stage, the ground surface was exposed to the cold environment and thick permafrost was formed (Figure 4a). The resistivity value was high. At the second stage, changes in surface heating, due to forest fire or climatic change, caused the thawing the sub-surface frozen ground, followed by alas formation (Figure 4b). The age of the formation of alas around Yakutsk is estimated to be 8,000–6,000 years B.P. from radiocarbon dating analysis (Fukuda *et al.*, 1997). After the formation of alas land depression, ground water filled the alas and a thermokarst lake was formed. As the mean temperature of the lake bottom is about 2°C in Arctic Canada (Mackay, 1973), the upper part of the permafrost layer under the lake thawed, and the resistivity value of the upper layer decreased. At the third stage, the lake water disappeared either by infilling with alas deposit or by draining to a lower alas level, whereupon the ground temperature decreased and began to freeze downward again (Figure 4c). The resistivity value of the upper layer increased. This process may form the present resistivity structure.

8. Conclusions

We have completed the TEM survey to investigate deep resistivity structure at two sites of Neleger in Siberia. Our results are summarized as follows.

1) The permafrost base was estimated more than 400 m in depth by using increase the source moment. The upper ice-rich permafrost layer with approximately 50–75 m thick was revealed. Below the resistive layer thick conductive intermediate zone with the thickness of more than 150 m was estimated, which suggest unfrozen layer, talik.

2) Considering the estimated geo-electric structure, a model of permafrost formation process was proposed. The vertical resistivity distribution pattern provides a useful tool for reconstructing the history of permafrost aggradation.

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