Catena 149 (2017) 529–537

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Evaluation of frozen ground conditions along a coastal topographic gradient at Byers Peninsula (Livingston Island, Antarctica) by geophysical and geoecological methods

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ARTICLE INFO

Article history:
Received 29 February 2016
Received in revised form 3 August 2016
Accepted 4 August 2016
Available online 10 August 2016

Keywords:
Byers Peninsula
Maritime Antarctica
Geophysical surveying
Electrical resistivity tomography
Geomorphology
Permafrost

ABSTRACT

Geophysical surveying and geoelectrical methods are effective to study permafrost distribution and conditions in polar environments. Geoelectrical methods are particularly suited to study the spatial distribution of permafrost because of its high electrical resistivity in comparison with that of soil or rock above 0 °C. In the South Shetland Islands permafrost is considered to be discontinuous up to elevations of 20–40 m a.s.l., changing to continuous at higher altitudes. There are no specific data about the distribution of permafrost in Byers Peninsula, in Livingston Island, which is the largest ice-free area in the South Shetland Islands. With the purpose of better understanding the occurrence of permanent frozen conditions in this area, a geophysical survey using an electrical resistivity tomography (ERT) methodology was conducted during the January 2015 field season, combined with geomorphological and ecological studies. Three overlapping electrical resistivity tomographies of 78 m each were done along the same profile which ran from the coast to the highest raised beaches. The three electrical resistivity tomographies are combined in an electrical resistivity model which represents the distribution of the electrical resistivity of the ground to depths of about 13 m along 158 m. Several patches of high electrical resistivity were found, and interpreted as patches of sporadic permafrost. The lower limits of sporadic to discontinuous permafrost in the area are confirmed by the presence of permafrost-related landforms nearby. There is a close correspondence between moss patches and permafrost patches along the geoelectrical transect.

1. Introduction

Frozen ground conditions exert a key control on geomorphological dynamics in ice-free areas of periglacial environments, which have been broadly defined as those regions with mean annual temperatures ranging from −2 to 3 °C (French, 2007). However, frozen ground conditions can be permanent (permafrost) or seasonal (seasonal frost). The soil frost regime has large implications on soil, hydrological, biological and geomorphological processes prevailing in cold-climate environments (Oliva et al., 2014).

In some cases, though, it may be difficult to identify the spatial boundary between seasonal frost and permafrost conditions. With the purpose of detecting this limit, increasing number of boreholes and shallow drillings are recently been established for monitoring permafrost and active layer dynamics in mid-latitude mountain regions as well as in polar environments (e.g. Harris et al., 2003; Haeberli et al., 2010; Romanovsky et al., 2010). Also, two international programmes (Global Terrestrial Network for Permafrost and Circumpolar Active Layer Monitoring System), led by the International Permafrost Association, have been implemented in order to establish protocols to monitor permafrost and active layer parameters worldwide. In the case of Antarctica, by 2010 there were 73 boreholes and 28 CALM sites (Vieira et al., 2010) although this is clearly insufficient for a vast continent, exceeding 14 million km^2.

Permafrost in Antarctica is both present in ice-free areas of Maritime (Vieira et al., 2010; Bockheim et al., 2013) and Continental Antarctica (Bockheim and Hall, 2002), as well as beneath the ice-sheet where subglacial permafrost exists (Bockheim and Hall, 2002). However, it is in ice-free environments of Maritime Antarctic where permafrost conditions are found in boundary climatic conditions. In the case of the South Shetland Islands (SSI), permafrost has not been generally detected in elevations below 20 m a.s.l. but has been found widespread above 40 m a.s.l. (Serrano, 2003; Serrano et al., 2008; Ramos et al., 2009; Vieira et al., 2010). Therefore, a transition belt with sporadic or discontinuous was established in the SSI between 20 and 40 m a.s.l. Nevertheless, local

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http://dx.doi.org/10.1016/j.catena.2016.08.006
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factors can induce changes in this general distribution. In the SSI geomorphological landforms features related to permafrost conditions, such as rock glaciers, protalus lobes or moraines with ice-rich permafrost, have been observed close to sea level (López-Martínez et al., 2012; Oliva and Ruiz-Fernández, 2015).

Vegetation cover also can generate a strong control on permafrost distribution and active layer dynamics. In discontinuous permafrost regions there is a close relationship between vegetation assemblages and the existence or absence of permafrost conditions in the area (Dingman et al., 1974). A tundra-type vegetation has also a strong impact on active layer thaw since it intercepts incoming radiation (Kelley et al., 2004). Besides, the distribution of snow across the landscape can alter active layer dynamics and induce changes on the vegetation communities (Johansson et al., 2013). However, it is necessary to note that in the Maritime Antarctic the vegetation forms an open tundra (Serrano, 2003), sparser than other types of tundra.

Most of these studies have used geomorphological indicators or boreholes data to determine the permafrost conditions. However, there are other methods that can provide accurate data on the distribution of permanent frozen ground conditions. In this regard geoelectrical methods can be useful in detecting and delineating permafrost and/or frozen ground and space and time evolution (Hauck and Kneisel, 2008). Field and laboratory data indicates that electrical resistivity of rocks and soil increase several times after freezing temperature is reached (Hoekstra et al., 1975; Olhoeft, 1978; Scott et al., 1990; Vanhala et al., 2009). Depending on the salts content freezing can take place at temperatures lower than 0 °C and the electrical resistivity increases slowly until all water is frozen; after complete freezing rocks and soil generally present very high electrical resistivities. The use of geoelectrical methods for detecting permafrost must also consider that electrical resistivities depend on ground ice content.

The main objective of this research is to evaluate the present-day distribution of permafrost conditions in Byers Peninsula (Livingston Island), the largest ice-free environment in the SSI archipelago, along a topographic gradient from sea level to Sealer Hill, a summit plateau at 91 m a.s.l. in the SE area of Byers Peninsula. We analysed the geoecological settings along this transect in order to understand the relationship between the geomorphic features and the biological activity. The geophysical surveying was carried out along the raised beaches transect of this profile to infer the distribution of frozen ground conditions at the coastal zone. Also, we discussed how the distribution of permafrost conditions in Byers fits the geographical pattern of frozen ground conditions in the SSI.

2. Study area

The study area is located in Byers Peninsula (between 62°34′35″S–62°40′35″S latitude and 60°54′14″W–61°13′07″W longitude) in Livingston Island. With ~60 km^2, this ice-free environment is the largest of the SSI. This archipelago is composed of 11 main islands located 120–130 km NW of the tip of the Antarctic Peninsula (AP) (Fig. 1). About 90% of these islands is covered by glaciers (Serrano, 2003). The ice-free environments correspond mostly to nunataks and small peninsulas distributed along the coastal fringes of those islands. It is in these deglaciated terrestrial ecosystems of Maritime Antarctica where biodiversity is greatest (Convey and Smith, 2006).

Climatic conditions in Byers Peninsula are characterized by a maritime polar regime, with relatively abundant annual precipitations between 500 and 800 mm mainly as snow. The mean annual temperature is about −2 °C at sea level (Bañón et al., 2013). In Byers Peninsula the relief is organized on a series of stepper platforms reaching elevations of 70–100 m a.s.l. in the central plateau. They are composed of volcanic, volcanoclastic, and detritic materials (mainly sandstones, mudstones, and conglomerates) of Jurassic and Cretaceous age, as well as intrusive rocks such as sills and dikes of Cretaceous age (Smellie et al., 1980, 1984; Hathway and Lomas, 1998; Parica et al., 2007). These platforms are surrounded by seven levels of Holocene raised beaches (Arche et al., 1996; López-Martínez et al., 1996; Hall and Perry, 2004; Moura et al., 2012). Some volcanic plugs stand out from the central plateau, such as Cerro Negro (143 m a.s.l.), Cerro Penca (217 m a.s.l.) or Cerro Start (265 m a.s.l.), which constitutes the highest elevation in the peninsula. The present-day geomorphological dynamics is strongly influenced by the presence of permafrost and the annual evolution of the active layer. Consequently, periglacial activity, such as solifluction, frost shattering, cryoturbation, and nivation processes are widespread.

Byers Peninsula has been defined as one of the terrestrial ecosystems of Antarctica with greatest biodiversity (Toro et al., 2007). The vegetation consists of an open tundra composed of several species of mosses and lichens (Lindsay, 1971; Serrano, 2003). Moreover, the two only autochthonous vascular plants in Antarctica (*Deschampsia antarctica* and *Colobanthus quitensis)* are also present in Byers Peninsula (Vera, 2011; Vera et al., 2013), especially abundant in the lowest raised beaches.

Human impact in Byers has been limited and restricted to the shelters built by the sealers and whalers that visited the coastal areas of the SSI at the end of the 18th and first decades of the 19th centuries (Zarankin and Senatore, 2005). Since the early 2000s, scientific activities in Byers Peninsula have been numerous, always limited to a small number of researchers and to the summer season. Taking into account its geological and biological heritage, Byers Peninsula was declared Antarctic Specially Protected Area number 126 in 1966 within the framework of the Antarctic Treaty.

This work focuses on the SW corner of Byers Peninsula, particularly in the Sealer Hill area and the raised beaches distributed in its eastern side. The Sealer Hill (91 m a.s.l.) is composed of a basalt plug showing columnar jointing (Parica et al., 2007).

3. Materials and methods

Field work was conducted in late January 2015 after a snowy year in the SSI, which conditioned research activities in the field as well as the results obtained and presented in this paper. A geomorphological sketch of the landforms along a transect from sea level to Sealer Hill was carried out in the field together with the support of a high resolution WorldView2 satellite image of Byers Peninsula from 2-1-2011. These data were compared also with geoecological observations conducted in the field along the same area following the approach proposed by Troll (1968, 1972), implemented in Antarctica by several authors (e.g. Serrano, 2003; Oliva et al., 2016a, b). These observations consisted in the identification of the vegetation communities in the area examining their distribution with regards to topography and geomorphology.

To try to detect and delineate possible permafrost or frozen ground a geoelectrical survey using an electrical resistivity tomography (ERT) approach was used. Initially, the idea was to obtain an electrical resistivity transect from the sea shoreline to the top of the Sealer Hill (Fig. 2) along a NW-SE direction approximately. To accomplish that four ERT profiles were done in such a way that the first half of the second ERT profile would overlap the second half of the first ERT profile, the second half of the second ERT profile would overlap the first half of the third ERT profile, and so on until the end of the fourth profile. The overlapping profiles were composed in a 158 m long profile which was then processed to obtain the geoelectrical model shown in Fig. 3. Each ERT profile was done using 40 stainless electrodes spaced by 2 m, each one with an active electrode. An earth resistivity meter “4point light 10 W”, manufactured by LGM LIPPMANN was used to control the measuring process with a chain of 40 active electrodes and record the field data which were downloaded latter for processing. During the acquisition state a few problems related with high electrical contact resistances between the ground and the stainless electrodes had to be solved. By eye inspection those problems were the result of frozen ground or dried mosses. Those problems were solved by watering with sea water the zone of the electrodes affected by high electrical contact resistance.