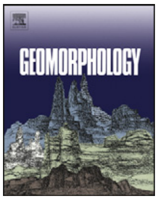
Geomorphology 221 (2014) 187–203

Contents lists available at ScienceDirect

Geomorphology

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



Polar gravel beach-ridge systems: Sedimentary architecture, genesis, and implications for climate reconstructions (South Shetland Islands/Western Antarctic Peninsula)

Sebastian Lindhorst *, Ilona Schutter

University of Hamburg, Institute for Geology, Bundesstr. 55, 20146 Hamburg, Germany

ARTICLE INFO

Article history:
Received 11 September 2013
Received in revised form 4 June 2014
Accepted 8 June 2014
Available online 19 June 2014

Keywords:
Gravel beach ridge
Sedimentary architecture
Storm-wave run-up
Climate archive
Ground-penetrating radar (GPR)
Antarctic Peninsula

ABSTRACT

The sedimentary architecture of polar gravel-beach ridges is presented and it is shown that ridge internal geometries reflect past wave-climate conditions. Ground-penetrating radar (GPR) data obtained along the coasts of Potter Peninsula (King George Island) show that beach ridges unconformably overlie the prograding strand plain. Development of individual ridges is seen to result from multiple storms in periods of increased storm-wave impact on the coast. Strand-plain progradation, by contrast, is the result of swash sedimentation at the beach-face under persistent calm conditions. The sedimentary architecture of beach ridges in sheltered parts of the coast is characterized by seaward-dipping prograding beds, being the result of swash deposition under stormy conditions, or aggrading beds formed by wave overtopping. By contrast, ridges exposed to high-energy waves are composed of seaward- as well as landward-dipping strata, bundled by numerous erosional unconformities. These erosional unconformities are the result of sediment starvation or partial reworking of ridge material during exceptional strong storms. The number of individual ridges which are preserved from a given time interval varies along the coast depending on the morphodynamic setting: sheltered coasts are characterized by numerous small ridges, whereas fewer but larger ridges develop on exposed beaches. The frequency of ridge building ranges from decades in the low-energy settings up to 1600 years under high-energy conditions. Beach ridges in the study area cluster at 9.5, 7.5, 5.5, and below 3.5 m above the present-day storm beach. Based on radiocarbon data, this is interpreted to reflect distinct periods of increased storminess and/or shortened annual sea-ice coverage in the area of the South Shetland Islands for the times around 4.3, c. 3.1, 1.9 ka cal BP, and after 0.65 ka cal BP. Ages further indicate that even ridges at higher elevations can be subject to later reactivation and reworking. A careful investigation of the stratigraphic architecture is therefore essential prior to sampling for dating purposes.

1. Introduction

Beach ridges are relict strand-plain ridges (Otvos, 2000). They mark former coastlines and provide a record of beach progradation through time (Stapor, 1975; Tanner, 1995; Tamura, 2012). In contrast to sandy beach ridges, which undergo erosion if exposed to high-energy waves, gravel beach ridges are seen as sediment accumulations formed by high wave run-up, most likely due to the enhanced percolation rate in coarse sediments which results in reduced backwash energy and landward-directed sediment transport (Orford, 1977; Carter, 1986). Individual gravel ridges are formed as the result of vertical sediment stacking on top of the berm ridge during periods of enhanced storm sedimentation (Neal et al., 2002). Under polar climates, other proposed mechanisms for gravel beach-ridge development are the deposition of ice-rafted material by stranded icebergs and the formation of ice-pushed ridges (Nichols, 1961). Shingle deposits are assumed to have a good preservation potential due to the high mass entrainment threshold of coarse sediments (Carter and Orford, 1984).

Built by storm waves, gravel beach ridges are a potential climate archive. Proxies for past climate variations are morphology, i.e. ridge elevation and frequency of ridges and swales, sedimentary architecture, and sediment composition and texture. Most studies dealing with paleo-climate reconstructions based on data from gravel beach-ridge plains focus on their morphological characteristics. For instance, beach-ridge sequences on Varanger Peninsula, eastern northern Norway, comprise sets of smaller ridges that are terminated by a prominent ridge, which is interpreted to record an exceptional strong storm, culminating an episode of enhanced storminess (Fletcher et al., 1993). Based on this, beach-ridge sets at Varanger Peninsula are seen to record episodic shifts of the polar front on time-scales of decades to centuries. Elevated gravel ridges on the coasts of Kola Peninsula are interpreted to have formed under more stormy conditions, whereas accumulation terraces and ridge-less gentle slopes reflect the predominance of calm conditions (Møller et al., 2002). Synchronous erosional truncations in numerous

---

* Corresponding author. Tel.: +49 40 42838 5024.
E-mail address: sebastian.lindhorst@uni-hamburg.de (S. Lindhorst).

http://dx.doi.org/10.1016/j.geomorph.2014.06.013

beach-ridge systems on the coast of Alaska are attributed to shifts in northern Pacific storminess (Mason and Jordan, 1993). Sediment texture as a climate proxy was used to study beaches on Greenwich Island, 70 km SE of King George Island, where ridges are bundled into sets, delimited by boulder pavements. While ridge-set development is interpreted to take place under periods of warmer climate, pavement formation results from stranded icebergs and is attributed to colder conditions (Santana and Dumont, 2007). A significant increase in the content of ice rafted detritus (IRD) from raised beaches on Livingston Island was interpreted as an indicator of a cooler climate (Hall and Perry, 2004). A combined morphological and sedimentological approach was used to reconstruct past sea-ice and wave conditions based on data from raised gravel beaches on Lowther Island, Canadian Arctic (St-Hilaire-Gravel et al., 2010).

Studies dealing with the internal sedimentary architecture of polar gravel beach-ridge systems are rare, so far. This study therefore aims to contribute to the state of knowledge by revealing the internal sediment geometries of polar beach-ridge systems and by providing a more detailed genetic model for gravel-beach development under polar climates, incorporating both geomorphology as well as internal sedimentary architecture. The characteristics of beach-ridge development on sheltered parts of the coast will be compared to ridge building at more exposed localities. Based on this, the potential of polar gravel beaches as climate archive will be evaluated.

2. Regional setting

King George Island (KGI) is the largest of the South Shetland Islands (SSI), located north of the West Antarctic Peninsula (WAP). KGI is about 64 km long and extends between lat. 61°50′ and 62°15′ S and long. 57°30′ and 59°00′ W (Fig. 1). As about 95% of KGI is glaciated, larger rock outcrops, active beaches, and raised marine features are limited to small ice-free areas along the fjords Maxwell Bay and Admiralty Bay. Situated in the circumantarctic pressure trough (Simmonds, 2003), the so-called "Southern Hemisphere storm belt" (Davies, 1964), the SSI are hit by storms in the Drake Passage and the temperature contrast of the cold Weddell Sea and the warmer Bellingshausen Sea. Instrumental records covering the last 50 years show that the WAP recently experiences an extraordinary air temperature increase, making this area one of the three most rapidly warming areas in the world (Vaughan et al., 2003; Bentley et al., 2009). The annual mean air temperature on KGI is −1.8 °C, and the wind-field is pronounced W-E bidirectional (Klöser et al., 1994; Roese and Drabble, 1998; Lee et al., 2004). In the time period 1947 to 2005, the mean air temperature on KGI rose by 1.1 °C (Ferron et al., 2004). The average winter temperature increased by 1.7 °C over the period 1991 to 2005, whereas the increase was only 0.4 °C for the summer temperature (Schloss et al., 2008). Generally seen as a consequence of increasing air temperatures, glaciers along the WAP showed a rapid retreat during the last century, which was accelerated in the past decades (Cook et al., 2005; Vaughan,

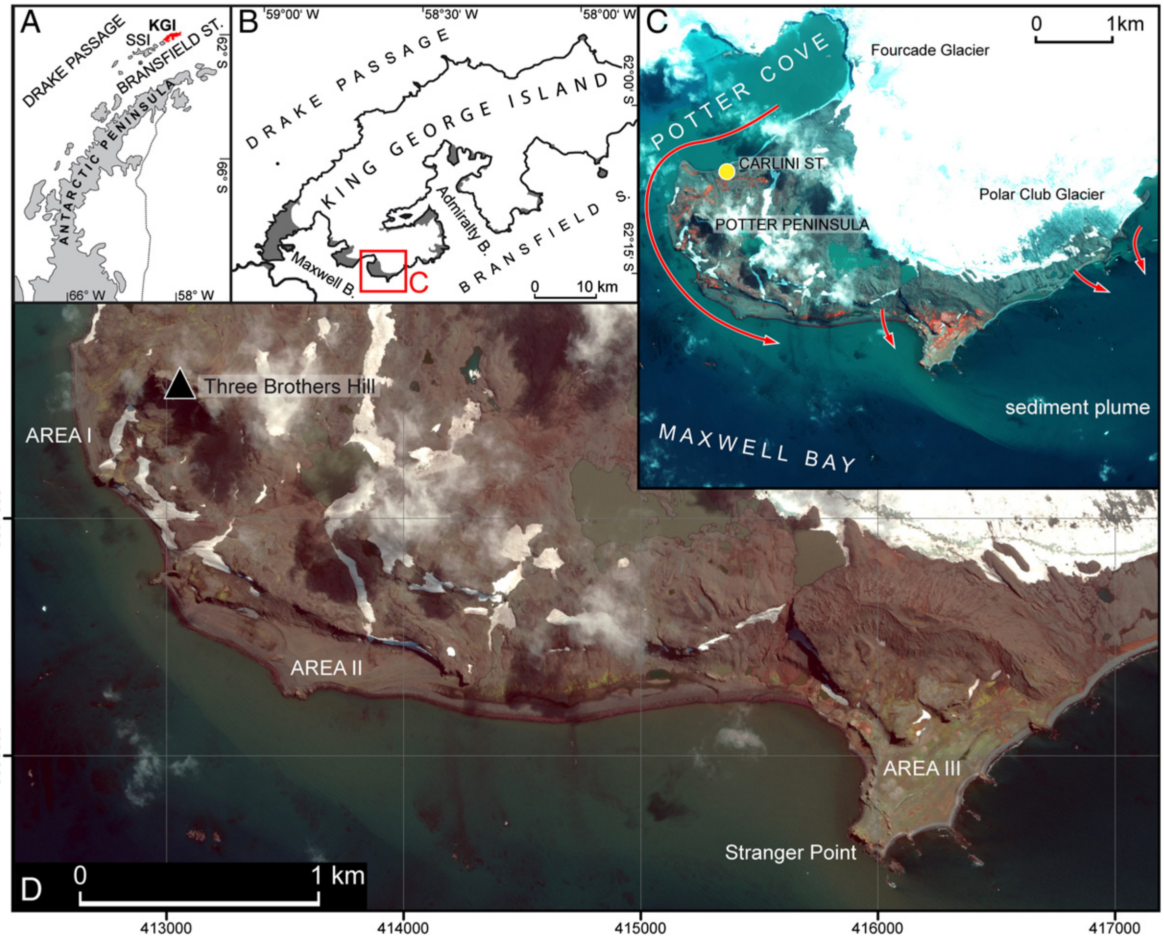


Fig. 1. Geographic situation of the study area. A) King George Island (KGI) belongs to the South Shetland Islands (SSI), located about 120 km north of the Western Antarctic Peninsula; B) KGI is framed by the Drake Passage and the Bransfield Strait. The island is glaciated to a large extent, only some minor coastal areas are ice-free (shaded in gray). Box marks position of Potter Peninsula; C) multispectral satellite image of Potter Peninsula (GeoEye-1 ID 2011020212571241603031607537, composed of near-infrared, green, and blue channel, image data obtained 2012-02-02). Red colors on land reflect vegetation. Note the large suspension load plume (sp) which extends from the Potter Cove along-coast toward the Bransfield Strait. Arrows indicate drainage paths of suspension load originating from the inland glaciers; D) true-color satellite image (RGB, same as C) of the southern coast of Potter Peninsula showing the location of the three working areas.