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# Beach ridges and prograded beach deposits as palaeoenvironment records

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ABSTRACT

Beach ridges are landforms commonly developed on prograded coasts with beach shorelines. A sequence of beach ridges, coupled with their subsurface deposits, can be regarded as a time series of coastal evolution. Methodological advances in field surveying and chronology applicable to beach ridges have led to detailed palaeoenvironmental reconstructions to be derived from such sequences. This paper reconsiders the basic aspects of beach ridges and deposits, which need to be properly understood for their comprehensive interpretation in a palaeo-environmental context. It also reviews case studies in which beach-ridge sequences have been used to unveil past sea-level history, catastrophic events, and climate changes.

Proposed formative processes of beach ridges include: 1) progradation of sandy beach and berm formations in relation to fairweather waves, coupled with aeolian foredune accumulation; 2) building of gravel ridges by storm waves; 3) welding of longshore bars. Beach-ridge formation through sea-level oscillation is thought to be questionable and caution is suggested for this process when undertaking palaeoenvironmental reconstruction. Beach deposit stratification is known to dip either landwards or seawards, but landward dips are uncommon. Seaward dipping stratification is formed in relation to beachface progradation, and is usually dissected in places by erosion surfaces resulting from episodic beach retreat. The boundary between the foreshore and the underlying shoreface is well defined only in the case that longshore bars lead to complex bedding structure relative to that of the foreshore. Reliable chronology of beach ridges can be determined by radiocarbon and optically-stimulated luminescence (OSL) dating. Radiocarbon dating of articulated shells, which are considered not to be extensively reworked, provides robust results, but OSL dating is more useful as it enables direct dating of sediment grains. It is noted that there are restrictions in chronological resolution and continuity inherent to beach ridge and beach deposits. The plan-view geomorphic expression of beach ridges typically consists of ridge sets with multi-decadal intervals, whereas their internal sedimentary structures define shorter time scales. Records of beach sedimentation and erosion are likely to be reworked by episodic high-magnitude beach retreat, and the resultant record of the net progradation is likely to be sporadic and discontinuous.

The height of sandy beach ridges is often variable due to differing degrees of aeolian sand accumulation, and they are thus not used as sea-level indicators unless purely wave-built. Gravel ridge height is a relatively reliable indicator of sea level, but can vary in response to storminess fluctuations. Subsurface sediment facies boundaries are preferred as sea-level indicators, and those proposed include: boundaries of aeolian/beach, foreshore/shoreface, and upper/lower shorefaces.

Catastrophic events are expressed in both erosional and depositional records. Erosion surfaces, or scarp imprints, revealed in a cross section of beach deposits, indicate storm or tsunami events. However, erosional events are likely to rework previous records of sedimentation and even other erosional events, and thus the apparent history decoded from the resultant deposits tends to be biased. Several attempts for estimating the frequency and intensity of prehistoric cyclones rely on assumed relationships between the level of coarse sand beach ridges and cyclone inundation. The formative process of coarse sand ridges remains uncertain and needs to be clarified, as it constitutes the fundamental basis of these attempts.

The growth rates of beach-ridge systems are expected to reflect fluctuations in river sediment discharge to the coast and in aeolian sand flux due to onshore winds, both of which are affected by climate change. Assessment of the growth rate is potentially improved by ground-penetrating radar survey of subsurface structure and by detailed chronology. Orientation of beach ridges reflects long-term trends in wave direction. Inferred relationships between beach ridges and cyclic fluctuations of sea level and climate rely on weak assumptions and are not substantiated by rigid chronological evidence, and thus remain highly questionable. Correlation between the inherently decadal signal of beach-ridge intervals and possible climate cycles, such as sunspot activity, is probably coincidental as it lacks causal explanations.



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## 1. Introduction

Beach ridges are ubiquitous landforms developed on prograded coasts with beach shorelines. They are formed within or adjacent to the beach by a range of processes, and are subsequently isolated from active nearshore process as further beach progradation occurs, at which point they are preserved as relict elongate mounds parallel to subparallel to the shoreline (Stapor, 1975). Beach ridges and their subsurface deposits thus record past coastal processes, and are indicators of past shoreline position and shape (e.g., Woods and Leahy, 1983, 1986; Mason, 1993) and sea level (e.g., Davies, 1957, 1961; Tanner and Stapor, 1971; Otvos, 2000). A sequence of beach ridges and intervening swales provides a relative chronological palaeoenvironmental record (Tanner, 1988), which is analogous to tree rings and stratigraphic succession. Coastal settings that form beach ridges include barrier islands, spits, and strand plains (Fig. 1), and are collectively referred to as beach-ridge systems in this paper. Coastal ridges with muddy substrates are defined as cheniers, being clearly distinguished from beach ridges (e.g., Otvos, 2000; Woodroffe, 2003).

To utilize beach ridges and their deposits as palaeoenvironmental records requires appropriate understanding of their nature. The formation of beach ridges, first described and examined by Redman (1852, 1864) who considered storm waves a main process, has been a subject of debate since Johnson (1919) proposed low-energy waves as an alternative (Taylor and Stone, 1996). Subsequently, it has been recognised that beach ridges develop in various settings around the world, and that accordingly a diversity of processes are responsible. This variation has caused confusion about the descriptive terminology of beach ridges (Hesp, 1984, 2006; Taylor and Stone, 1996; Otvos, 2000). Conventionally, beach ridges are understood to be linear mound-shaped ridges roughly parallel to the coast (Stapor, 1975), regardless of their formative process. On gravelly coasts, the term typically refers to a relict gravelly storm ridge or berm, while on the well-studied sandy coasts of North America and Australia, a beach ridge is normally associated with relief decorated by aeolian sand accumulation. The term “beach ridge” has thus been ambiguously used in a range of settings. The confusion over terminology, and the history behind this confusion, were addressed in detail by Taylor and Stone (1996) and Hesp et al. (2005). To avoid terminology confusion, Otvos (2000) proposed a broad usage of the term beach ridge regardless of its origin and formative process. However, Hesp et al. (2005) and Hesp (2006) argued that the term should be restricted to referring to ridges formed purely by waves, thus distinguishing them from coastal dunes in particular barrier dunes. This strict definition excludes relict sandy ridges even with a slight aeolian component. This paper thus adopts the broad definition of Otvos (2000). Terminology of other coastal morphology also follows that of Otvos (2000).

Following improved understanding of beach-ridge formation, variation, and terminology, beach ridges have been considered as a reliable record of the past sedimentary environment (Taylor and Stones, 1996). Various advances in methodology, including ground-penetrating radar (GPR) and optical dating, have enabled their detailed palaeoenvironmental reconstruction. GPR is a geophysical method utilizing electromagnetic wave reflection due to heterogeneity in electric properties of subsurface material. While trenching can be limited due to expense and feasibility, GPR is effective for obtaining a continuous image of the internal sedimentary structure of sandy and gravelly coastal deposits without disturbance (e.g., Jol et al., 1996; Meyers et al., 1996; van Heteren and van de Plassche, 1997; Buynevich and FitzGerald, 2005; Buynevich et al., 2009). Optical dating directly determines the length of burial time of mineral grains. This method, especially following its improvement in the last decade (e.g., Murray and Wintle, 2000; Duller, 2004; Jacobs, 2008), has been reliably applied to beach ridges of which analysis had previously been restricted by scarcity of dating material (e.g., Isla and Bujalesky, 2000). Taking advantage of these methodological developments, various case studies have used beach ridges and prograded deposits to reconstruct Holocene palaeoenvironments (e.g., Meyers et al., 1996; Van Heteren et al., 2000; Bristow and Pucillo, 2006; Goodwin et al., 2006; Rodriguez and Meyer, 2006; Buynevich et al., 2007; Brooke et al., 2008b; Tamura et al., 2008a, 2010b; Nott et al., 2009).

Reviewing various applications of beach ridges and their deposits for palaeoenvironmental reconstruction, certain basic aspects of beach ridges are often interpreted inconsistently. This resulted in various degrees of reliability of such palaeoenvironment reconstruction. It is thus important to reconsider current basic understanding of beach-ridge landforms and prograded beach deposits, and to explore their functions and possibilities as palaeoenvironmental records. This paper first summarizes the formative processes, variations, and chronology of beach ridges, and then reviews studies using such features to address three categories of palaeoenvironmental reconstruction: sea level, catastrophic events, and climate. Problems specific to each case study are pointed out, and possibilities and means of improving future research are suggested.