The Ground Penetrating Radar facies and architecture of a Paleo-spit from Huangqihai Lake, North China: Implications for genesis and evolution

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1. Introduction

Barrier islands characterize >10% of the world’s coastline and are well-developed on microtidal coasts (Galloway, 1986; Cooper, 2001; Anthony et al., 2002; Hesp et al., 2007; Dillenburg et al., 2009; Garrison et al., 2010). They are elongate accumulations of sand and/or gravel formed by wave processes and longshore drift, separating the open sea from a lagoon or a terrestrial drainage. Barrier islands often terminate with a landward bending spit morphology (Lindhorst et al., 2010). The spit, a type of barrier, is typically attached to the proximal mainland area (Van Heteren and Van de Plasche, 1997; Davidson-Arnott, 2010). The architecture of these marine barrier spits has been documented well since the advent of integrative studies involving Ground-Penetrating Radar (GPR), trenching and radiocarbon dating (Møller and Anthony, 2003; Rink and López, 2010; Otros, 2012). The spit stratigraphy records the evolution of growth and the sedimentation processes involved, reflecting sediment supply and sea level change. Ollerhead and Davidson-Arnott (1995) documented both the short- and long-term evolution of Buctouche Spit on the northeast shore of New Brunswick, Canada, using a sediment budget approach based on optical-luminescence dating. Van Heteren and Van de Plasche (1997) found evidence for relative sea-level rise and tidal inlet migration within a barrier spit stratigraphy along the southeastern New England coast, and that this enabled investigation of the spit evolution. Lindhorst (2008) proposed that swash bars were important architectural elements of a barrier spit in the southern German North Sea by means of GPR and coring. Lindhorst (2010) further indicated that the growth of the hooked spit was controlled by the interplay of alongshore migrating beach drifts under fair-weather conditions and rare severe storms. Despite this progress in understanding marine barrier spits, lacustrine spits are relatively rarely studied. Barrier spits may also form in lakes, because the absence of tidal processes is good for spit development and preservation. Some of the earliest research on lacustrine barrier spits was conducted by Gilbert (1890) along the shoreline of Lake Bonneville. Smith (2003) surveyed this classic cross-valley barrier and associated the Stockton Spit in this lake using GPR and recognized two packages of stacked prograding foresets at the distal end of the Stockton Spit. He proposed that a reorientation of the longshore transport pathway, induced by continued basin subsidence and/or a lake level rise, produced a new spit (Smith et al., 2003). However, detailed radar surface and radar facies descriptions of lacustrine spits are relatively rare. Spit architecture and genesis in other lakes are also understudied. Furthermore, lacustrine barrier spits are one of the most dynamic depositional coastal landforms and respond quickly to changes in littoral sediment supply and lake level, as well as severe storms and overwash processes (Drake and Bristow, 2006). As a result, conducting detailed surveys of radar surfaces, radar facies and sedimentary architecture on

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a lake barrier spit is important for addressing some of the deficiencies in our understanding of lacustrine spits.

In this paper, we identify a barrier spit and present results from the north shore of Huangqihai Lake, northern China (Fig. 1). Recently, quartz optically stimulated luminescence (OSL) dating, combined with sedimentlogic analysis, has been undertaken along a profile running from the east to west shores of Huangqihai Lake to reconstruct Holocene paleoclimate and lake level change (Li et al., 1992; Li and Wang, 1993; Zhang et al., 2011, 2012). Those studies indicated that the evolution of the lake is linked with the varying strengths of the Asian monsoon. These recent observations, together with a new understanding of the barrier spit, allow us to explore the relationship between lake level fluctuations and barrier spit evolution in Huangqihai Lake, which we propose as a classic active example that can be used to understand ancient deposits of this type. Ground Penetrating Radar (GPR) facies and trenching data are reported from this spit. These data reveal detailed radar surfaces, radar facies and architecture of this spit, and thus the sedimentary processes that allow these features to form.

2. Geological background

Huangqihai Lake is located in Inner Mongolia, northern China (Fig. 1). It is a hydrologically closed basin with a maximum length of 20 km and a maximum width of 9 km encompassing an area of 110 km². The lake lies 1262 m above sea level and drains an area of more than 4500 km². The lacustrine basin is fed by 19 rivers including the Quanyulin, Dahewan and Bawanghe Rivers (Fig. 1a). The maximum water depth is 10 m (Fig. 1b). In past decades, the river discharge has been small due to human impact on the environment via agriculture and an arid climate. The supply of sediments is often seasonally controlled. In summer, the sediments are transported mainly by rivers, while in contrast during the winter the lake receives little input when it is frozen. In winter, the lake area is dominated by northerly winds. The mean annual temperature is about 4.5 °C and the mean annual precipitation and evaporation are 362 mm and 1927 mm, respectively (Zhang et al., 2011, 2012). Vegetation in the drainage area is dominated by semi-arid shrub (Fig. 1c). Huangqihai Lake is characterized by a high-
energy wave regime caused by the long fetch and dominant South winds in the summer. Strong winds are responsible for storm surges in combination with powerful surf energy. The average wind speed is about ~9 m/s and the maximum wind speed is ~20 m/s in study area (Gao et al., 2003; Hoffmann et al., 2008). The barrier spit system formed in the foreshore area, which is in the swash zone along the northern shore of the lake. The gradient of the depositional coastlines in this area is less than 2°. The barrier spit is about 1 km long and 150–175 m wide (Fig. 1d). It is gently curved at the east side (Fig. 1) and generally trends northwest–southwest. The maximum thickness of the whole spit bar unit is more than 1.6 m (Fig. 1d). The lake level has fallen dramatically in past decades as a result of the combined effects of agricultural processes and bioturbation by shrub and grasses. The barrier spit deposits are mainly composed of medium-coarse grained sands and subrounded to subangular granules. The likely source of the sediment feeding the northern barrier spit is the range of mountains, comprising igneous rocks that lie to the north, and brought in mainly by the Bawanghe rocks that lie to the north, and brought in mainly by the Bawanghe rocks that lie to the north, and brought in mainly by the Bawanghe.

In the study area, the radar imaged the barrier spit to a depth of ~50–55 ns two-way travel time (TWT), which corresponds to a depth of about 2.5 m. The TWT in ns is also indicated for each profile for completeness. The depths of all the profiles exceed that of the spit bar deposits. All depth readings in the profiles refer to the level of water in Huangqihai Lake in May 2013 when we conducted the GPR survey. The altitude of the lake level at that time was measured at 126.1 m using global-positioning system (Trimble GEO XT 2008).

3. Methods and materials

The internal radar facies and architecture of the barrier spit were determined by using GPR combined with trenching in key locations. GPR is a geophysical method, which is based on the transmission of high-frequency electromagnetic signals and the reception of energy that is reflected back from the subsurface (Bristow and Jol, 2003; Baker and Jol, 2007). GPR signals record changes in dielectric properties of sediments, which are determined by the degree of water saturation, water salinity, mineralogical changes and porosity (Møller and Anthony, 2003; Jol, 2008). To link GPR results with sedimentologic data, trenches were dug at selected positions along the GPR profiles to confirm sedimentary interpretations made from the acoustic data. The aim of trenching was to characterize the sedimentology and internal architecture of this barrier spit, especially at scales too small to resolve by the GPR imaging.

3.1. Ground penetrating radar

The GPR system employed in this work was the TerraSIRch SIR 3000 system, with a 400 MHz antenna that provided high-resolution imagery to depths of about 2.5 m. The profiles were arranged parallel and perpendicular to the long axis (west to east) of the barrier spit. Over 3 km of GPR profiles was collected (Fig. 1). A total of seven GPR profiles (over 1 km) were selected in this paper to illustrate the internal architecture of this spit.

GPR data were collected in a discrete mode with a GPR survey wheel acting as the distance trigger. GPR surveys were mainly applied to mostly flat areas to avoid non-vertical radar beam orientation (Lehmann and Green, 2000). Signal ringing, i.e., horizontal coherent noise (Kim et al., 2007), occurred in the GPR profiles because of thriving shrubs and grasses, caused by high ion-bearing liquid concentrations in the roots (Lindhorst et al., 2008).

Software Reflexx version 5.6 was used for editing and processing the GPR data. All GPR data were post-processed (frequency filtering, down-the-trace, trace-to-trace stacking, constant-velocity migration and gain adjustment). The GPR wave velocity in spit sediments was determined by correlation of sediments in trenches to GPR data and via hyperbolic velocity analysis. The velocities for saturated sands and dry sands are ~0.06 m/ns and ~0.12 m/ns, respectively. These velocities are in the range of velocities for saturated and dry sands suggested by Jol (2008). A mean velocity of 0.09 m/ns was used for time-depth conversion. Topographic correction of GPR data along survey lines was undertaken using a global-positioning system (Trimble GEO XT 2008) with a horizontal and vertical accuracy less than 1 m.

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3.2. Trenching

The locations of trenches were selected on GPR survey lines or on the crosspoints of two lines on the spit. A total of 17 trenches (1.5 m long, 1 m wide) was excavated using shovels and hoes to a depth of 1–2 m (Fig. 1d). Trenches were selected to show the internal structure of the system and the relationship between radar and lithologic surfaces. In this study, seven trenches were selected to show the sedimentary characteristics of the barrier spit. The radar surfaces were correlated with clearly defined lithologic surfaces marking distinct changes in grain size and sedimentary structures between different trenches. Subsequently, the radar facies were compared to lithofacies based on reflection characteristics (amplitude, termination patterns and internal configuration) and sedimentary characteristics (colour, grain size, sorting, rounding and sedimentary structures) observed in radar profiles and trenches, respectively.

4. Results

4.1. Ground-penetrating radar data

4.1.1. Radar profiles

Seven radar profiles with a total length of ~1050 m were selected for documenting the internal structure of the spit (Figs. 2–8). Four GPR survey lines are in shore-normal direction (A-1, A-2, A-3 and A-4) and the other three are shore-parallel (B-1, B-2 and B-3). The location of each profile is shown in Fig. 1d. All the GPR lines have a maximum depth of 55 ns two-way-travel time corresponding to a depth of ~2.5 m. All depth readings in the profiles refer to 1261.1 m (the lake level of Huangqihai Lake in May 2013).

The SW–NE striking GPR Profile A-1 has a length of 65 m (Fig. 2). One sigmoidal-shaped sedimentary body was imaged as having high-amplitude reflections. Two different reflection patterns can be identified. The upper part contains landward dipping reflections. On the landward side of the line, the thickness of the upper part is ~1.6 m, much thicker than on the lakeward side. The lower unit mainly shows a reflection-free pattern.

GPR Profile A-2, has a length of 80 m, and was acquired along a SSW–NNE survey line (Fig. 3). Signal ringing (horizontal system noise) shows...
in the lower part. Above the lower part, two architectural elements, displaying middle-high angle landward dipping reflectors, which are a characteristic of washover lobes, can be distinguished. Gently dipping reflections dominate in the distal end of the upper lobe. In the upper lakeward part, lakeward dipping reflections dominate and are interpreted as swash laminated sands.

The length of the N–S oriented radar Profile A-3 is ~80 m (Fig. 4). The reflection-free lower part shows the characteristics of a salt marsh peat. Middle to high amplitude reflections above this part are bundled into a bar shaped body, which forms the upper part of the stratigraphy. The units in this part are composed of vertically stacked washover sheets and lobes.

110-m-long GPR Profile A-4 is oriented in a SE–NW direction (Fig. 5). In addition to lakeward-dipping reflection between 30 and 65 m along the profile, two packages of middle-high angle landward-dipping units can be distinguished with thicknesses of 0.8 m and 0.5 m, respectively. Reflections are of middle to high amplitude. At the distal (lakeward) end, above steeply dipping reflectors, reflections gently dip to the NW.

The NW–ES striking GPR Profile B-1 is 240 m long (Fig. 6). Two distinct reflection patterns can be identified. The upper part has a thickness of ~1.1 m. Cut-and-fill structures between 65 and 220 m along this profile can be easily distinguished. Reflection amplitudes are highest on the basal boundary of this structure. The lower part is reflection free.

Four channel-shaped cut-and-fill structures can be identified in 240-m-long shore-parallel GPR Profile B-2 (Fig. 7). The lowest channel between 120 and 190 m in this line was cut by another washover channel on its western side. This phenomenon comprises two packages of landward-dipping reflectors interpreted as two washover lobes, identified in shore-normal radar Profile A-3 (Fig. 4). With an average thickness of ~1.4 m, a maximum thickness of the upper part is ~1.6 m between 140 and 160 m on this GPR line.

The SW–NE striking GPR Profile B-3 has a length of 240 m (Fig. 8). Two parts can be distinguished, based on reflection amplitude and patterns. Middle to high amplitude, concave-upward, or channel shaped reflections dominate in the upper part. Five distinct cut-and-fill structures are identified in this part. The thickness of the upper part is ~1.5 m. The lower part is largely reflection-free which is a characteristic of sediments formed in a salt marsh.

4.1.2. Radar surfaces
Depositional barrier spit landforms in lacustrine settings contain various accretionary and erosional elements that are created through wind, wave and other geological processes. As a result, there exist two major groups of radar surfaces (rs), associated with depositional and erosional surfaces (Fig. 9). A total of six types of surface are identified (Fig. 9). Radar surfaces and radar stratigraphy are determined using the terminology and principles introduced in Section 3.1.

Depositional surfaces form by migration of subaqueous dunes over salt marsh or previous washover deposits. These surfaces tend to be flattened. This group can be further classified into two types (rs 1–1 and rs 1–2). Rs 1–1 is common at the distal part of the washover lobes in shore-normal GPR profiles (Fig. 3). Radar reflections downlap directly on this flattened surface, which indicates a stable progradation pattern. Sediments above this surface tend to be tabular cross-bedded sands reflecting the greater stability of the waning current velocity on the landward side of the dune (Fig. 9). Rs 1–2 often occurs in the middle or distal parts of a lobe indicating a lobe stacked...
on previous washover deposits. Unlike reflections above rs 1–1, these reflectors downlap at a lower angle, indicating the characteristics of the middle lobe.

Erosional surfaces are formed when the existing stoss face of a dune is eroded as a result of changes in morphology in response to fluctuations in current direction or velocity. These surfaces are very common in the spit because water flow is unsteady. This group can further divided into four types (rs 2–1, rs 2–2, rs 2–3 and rs 2–4). Rs 2–1 is common in the proximal part of a washover lobe in shore-parallel GPR profiles (Fig. 7). Rs 2–2 lies below the high amplitude reflections and overlies the reflection-free base that is interpreted as a salt marsh peat that has been eroded during deposition of a washover lobe. It is common in the proximal part in the shore-normal GPR profiles (Fig. 4). Rs 2–1 and 2–2 both indicate the surface below the lobe in the proximal part, which tends to be erosional because of high current velocities that exist during the washover event. Rs 2–3 is interpreted as the product of older sediments that have been eroded and altered by eolian processes. The surface below the swash laminated sediment (rs 2–4) that overlies the lobe is also a type of erosional surface reflecting a change in current flow mechanisms. Above this type of surface, the reflections are lakeward dipping, which is a characteristic of swash laminated deposits. Although the surfaces are flattened, deposits above the surface are parallel laminated sands, which are formed in an upper flow regime. As a result, these surfaces are also erosional. Deposits below these surfaces are usually salt marsh peat or washover deposits.

4.1.3. Radar facies

A radar facies is defined as a three dimensional body that we image along two dimensional profiles and is bounded by radar surfaces. Eight different radar facies (rf) were identified in the radar profiles (Fig. 10). They fall into three groups. The first group consists of radar facies that display inclined reflections. Radar facies that exhibit predominantly horizontal reflections are included in the second group. In the third group, the reflection characteristics are irregular.

Radar facies displaying inclined reflections are from shore-normal radar profiles. The inclined group can be further classified into four types (rf 1–1, rf 1–2, rf 1–3 and rf 1–4). Radar facies with landward-dipping reflections in a shore-normal direction are interpreted as deposits of washover processes (rf 1–1, rf 1–2 and rf 1–3). The landward dip of moderate to high angle reflections in the GPR profiles is interpreted as washover lobe clinoforms (rf 1–1 and 1–2; Fig. 10). Rs 1–1 is characterized by high amplitudes and dips at a moderate angle. The corresponding lithofacies comprises parallel or high-angle laminated coarse-grained sands, indicating an upper flow regime within the proximal part of a lobe. Rs 1–2 has characteristics of low amplitude and downlap termination pattern. It is interpreted as representing undifferentiated sands dumped directly on a salt marsh peat at the distal part of a lobe. Landward dips at a low angle are interpreted as reflectors of the washover sheets (rf 1–3; Fig. 10). The proximal part of each washover lobe displays higher amplitude reflections, contrasting with the distal part. Radar facies with lakeward-dipping reflections are interpreted as laminated sediments formed by swash processes (rf 1–4; Fig. 10). The swash laminated sands often have parallel lamination formed by turbulent flows at high flow velocities.

Radar facies with horizontal reflections in a shore-parallel direction are interpreted as stacked washover sheets or lobes based on their
Fig. 4. A 400 MHz GPR collected by a TerraSIRch SIR 3000 (shore-normal profile A-3; 80 m length) with the processed GPR profile, and the sedimentological interpretation based on internal reflection characteristics. T6 shows the location of Trench 6.

Fig. 5. A 400 MHz GPR collected by a TerraSIRch SIR 3000 (shore-normal profile A-4; 110 m length) with the processed GPR profile, and the sedimentological interpretation based on internal reflection characteristics. T2 and T9 show the locations of Trenches 2 and 9.
internal reflection. The horizontal reflector group comprises rf 2–1 and rf 2–2. RF 2–1 is characterized by high-amplitude horizontal reflections, which are interpreted as vertically stacked washover sheets. Radar facies with concave-upward reflections are channel-form in shape (rf2–2; Fig. 10). In this radar facies, horizontal or gently inclined reflectors that terminate against radar surfaces represent the internal

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**Fig. 6.** A 400 MHz GPR collected by a TerraSIRch SIR 3000 (shore-parallel profile B-1; 240 m length) with the processed GPR profile, and the sedimentological interpretation based on internal reflection characteristics. T14 shows the location of Trench 14.

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**Fig. 7.** A 400 MHz GPR collected by a TerraSIRch SIR 3000 (shore-parallel profile B-2; 300 m length) with the processed GPR profile, and the sedimentological interpretation based on internal reflection characteristics. T6 shows the location of Trench 6.
stratification within washover channels, abutting against the erosional base of that channel form. These reflections are interpreted as deposits of scour and fill structures.

Radar Facies 3–1 which is almost free of internal reflections is commonly found beneath the washover deposits and is interpreted as a salt marsh peat deposit. System noise is always at the top of the spit bar

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<th>rs type</th>
<th>GPR example</th>
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<th>sf reflection</th>
<th>Trench exam.</th>
<th>Interpretation</th>
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<tr>
<td>rs 1–1</td>
<td></td>
<td>Low amplitude.</td>
<td>Identified by downlap</td>
<td></td>
<td>Depositional surface. Washover lobe (coarse-grained sediments) was deposited on salt marsh.</td>
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<td>rs 1–2</td>
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<td>High amplitude.</td>
<td>Low-angle downlap</td>
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<td>Depositional surface. Washover lobe sediments deposited directly on washover sheet.</td>
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<td>rs 2–1</td>
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<td>High amplitude.</td>
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<td>Erosional surface. Shore-parallel profile. The sediments were eroded by washover lobe channel.</td>
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<td>rs 2–2</td>
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<td>High amplitude.</td>
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<td>Erosional surface. Shore-normal profile. The sediments were eroded by washover lobe.</td>
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<td>rs 2–3</td>
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<td>High amplitude.</td>
<td>System noise.</td>
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<td>Erosional surface. System noise. The sediments were eroded and altered by eolian processes.</td>
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<td>rs 2–4</td>
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<td>High amplitude.</td>
<td>Downlap or parallel</td>
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<td>Erosional surface. The former sediments were eroded by swash processes.</td>
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Fig. 8. A 400 MHz GPR collected by a TerraSIRch SIR 3000 (shore-parallel profile B-3; 240 m length) with the processed GPR profile, and the sedimentological interpretation based on internal reflection characteristics. T2 show the location of Trench 2.

Fig. 9. Characteristics of the defined radar surfaces. The radar surfaces fall into two groups (depositional and erosional).
deposits (rf 3–2; Fig. 10). So rf 3–1 is best interpreted as deposits influenced by bioturbation and/or eolian processes.

### 4.2. Trenches and sediments

Seven of seventeen trenches (Trenches 2, 6, 7, 9, 10, 14, 17) were selected to show sedimentary characteristics and the relationships between the radar surfaces and lithologic surfaces (Figs. 11–13). The location of the trenches is shown in Fig. 1d.

The sediments from the entire barrier spit system on the north shore of Huangqihai Lake cover a broad grain size range, from mud to granules. The sediments in the spit bar unit are characterized by sands of medium-grain to granule size, and vary from sub-angular to sub-rounded, after the definition of Udden (1914) and Wentworth (1922). In general, most of the sands and granules are moderately sorted based on the definitions of Pettijohn (1987). Maximum grain size is about 2.2 cm, as found in Trench 10, where we identified sub-angular granules and coarse-grained sands (Fig. 12). The trenches show good correspondence between the radar stratigraphy and internal structure of the barrier spit (Fig. 2). Lithologic surfaces can be correlated well with the corresponding radar surfaces in the trench profiles (Figs. 11–13). Trench 6 cuts the shore-normal profile A-3 and the shore-parallel profile B-2 (Figs. 1d, 4, 7, 12a). The depositional record indicates two stacked washover lobes with cross-lamination dipping both to W and E (Fig. 12a), indicating two directions of landward sediment transport in the two lobes. Trenches 2 and 9 are on GPR Profile A–4 line, with a distance between them of ~53 m (Figs. 5, 13). Trench 5 is in the proximal part while Trench 2 is in the distal part (Fig. 5). In Trench 2

### 5. Discussion

#### 5.1. Sedimentary architecture

Seven GPR profiles and seven trenches were used together to determine the sedimentary architecture of the barrier spit in Huangqihai Lake. Six types of radar surfaces and eight types of radar facies were defined and compared to lithofacies to deduce the sediment geometries
Fig. 11. (a) Image of Trench 14. Middle part of the washover lobe identified in Fig. 2. Note the flattened surface and tabular cross-bedding deposited on a salt marsh which indicates the surface tends to be depositional. (b) Image of Trench 17. Note the flattened surface and differentiated sands deposited on a salt marsh which indicates the surface tends to be depositional. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 12. (a) Image of Trench 6 taken in a shore-parallel direction. Cross-lamination within two washover lobes dips to the right (W), as shown by the black arrow, while the lower grey arrow shows lamination dipping left (E). (b) Image of Trench 7. Note the greenish grey and yellowish grey mud, which indicates a salt marsh deposit formed in saline water. (c) Image of Trench 10. Note the granule grain-size deposits.
and sedimentary process responsible for spit formation on the northern shore of the lake. Two distinct parts, spit bar and salt marsh, are distinguished. The contact between spit bar and salt marsh peat often tends to be erosional (radar surfaces 2–1.2–2; Fig. 2) in the proximal part of each lobe and depositional (rs 1–1) in the distal part.

The uppermost part represents the sediments of the spit bar (e.g., Fig. 3, the washover lobes and sheets, swash laminated sands, as well as the eolian cover). This part contains radar facies rf 1–1, 1–2, 1–3, 1–4, 2–1, 2–2, and 3–2 (Figs. 2–8, 10). Rf 1–4 corresponds to deposits formed by swash processes. The top of the spit bar is formed from sediments reworked by bioturbation processes. The surface between washover deposits and eolian and/or bioturbated deposits is erosional.

The thickness of the spit bar unit ranges up to 1.6 m (Fig. 1d). The bar exhibits predominantly landward-dipping reflections of low to high amplitude in a shore-normal direction, which are bundled into packages bounded by radar surfaces (Figs. 2–5). The GPR data indicate that the system was mainly formed by washover processes. The spit bar unit is interpreted as being formed dominantly from vertically and laterally stacked washover sheets and lobes (Figs. 4, 6, 7). Development of washover sheets alternating with washover lobes indicates a sequence to their development. On the stoss side, the deposits between washover deposits and the top cap of eolian and bioturbated sands are interpreted as having swash lamination because their GPR reflections are characterized as lakeward-dipping (Figs. 3, 5). In the shore-parallel direction, in the proximal and middle part of the washover deposits, the salt marsh peat is scoured or eroded by the overlying washover channels (Figs. 6–8). The interpreted shore-parallel GPR profile has both horizontal and concave-upward radar reflections. The concave-upward or channel-shaped reflectors above the salt marsh deposits are the shore-parallel representations of the landward-dipping reflectors, identified in shore-normal profiles.

Salt marsh peat lies beneath the spit bar (Figs. 2–8). The radar facies corresponding to this unit is rf 3–1 (Fig. 10). It is characterized by either reflection-free or reflection-poor units with very low amplitude reflections where they are present. The radar characteristics reflect serious attenuation caused by conductive materials like salt water in the pore volume, clay minerals or fine grained organic material, or due to metals formed under reducing conditions within the sediments.

5.2. Sedimentary processes

The grain size of washover deposits ranges from medium-grained sand to granule. In the proximal part of the lobe, the amplitude is higher, indicating higher contrasts in sedimentary texture and bedding thickness. The sedimentary structures are typified by trough and tabular cross-bedding, which were identified in Trenches 6 and 10 (Fig. 12a and c). A fining-upward trend through each lobe represents waning, high-energy hydrodynamic conditions. In contrast, in the distal part of the lobe, the sedimentary structures are differentiated or tabular cross-bedding indicates relatively weak hydrodynamic conditions. In Radar Profiles A-2 and A-4, the lakeward-dipping reflections are interpreted as images of swash-laminated sands (Figs. 3 and 5). They are characterized by moderately well sorted, parallel bedded or low-angle, tabular cross-bedded, medium-grained sands, indicating sediments that formed in a stable high-energy environment (Fig. 13b).

This study distinguishes three major subaqueous regimes for formation of the spit bar (Fig. 14): (1) washover lobes: in which run up is above the level of the crest and washover currents reach the steep-dipping landward side of the spit (Fig. 14a); (2) washover sheets: in which wave run up is above the level of the crest, and which result in some swash overtopping. Sedimentation takes place entirely on relatively flattened topography (Fig. 14b); (3) swash laminated sands: in which run up fails to climb over the crest, resulting in swash processes (Fig. 14c). We conclude that the sedimentary processes responsible for the formation of the spit bar unit are swash, washover, eolian and bioturbation processes.
5.3. Evolution and conceptual model

Combined with analysis of radar surfaces, radar facies and sedimentary architecture, the evolution of the barrier spit can be reconstructed (Fig. 15). In the early stages, occasional wave overtopping results in small-scale washover sheet sedimentation, although swash erosional processes may also operate. During bigger storm events, the more frequent overtopping results in transportation and erosion of sediments in the proximal part of the barrier spit, and deposition of more and coarser sediments in the distal part. The erosionally deepened and widened channels increase the length and width of the lobes identified in shore-parallel profiles (Figs. 6–8). As a result, sediments deposited in the washover lobes are derived from erosion of the foredune. Particularly large storms may exceed the threshold for carrying more and coarser sediments. Washover occurs when storm-induced waves run-up and climb over the crest of pre-existing dunes, carrying large quantities of sediment. A requirement for waves overrunning the crest is elevated water levels due to storm surge eroding and flattening the stoss slope of the previous dune (Matias et al., 2008). Depending on the dip of reflectors identified in GPR profiles, washover deposits can be further classified into two types (washover lobe and sheet), following the terminology of Neal et al. (2003). Washover lobes are often reactivated by subsequent storms (Sedgwick and Davis, 2003; Switzer and Jones, 2008) and thus lobes may contain units from more than one event. In the later stage of the cycle, the sediments are deposited as units of gently landward-dipping washover sheets, because the previous steep-dipping topography was filled by earlier washover lobes. As the lake-level falls, run up currents fail to climb over the crest and swash processes erode the stoss slope of older dunes, as identified in Figs. 3 and 5. When the lake-level falls dramatically, the previously deposited sediments provide a source area for eolian reworking and bioturbation. The internal architecture of the spit bar indicates that it was formed during a single cycle of lake-level rise and fall (Fig. 15).

If the same is true of marine barrier spit systems then this would imply that sediment storage and release within these features of the coastal zone is of relatively short duration (<100 k.y. in the Late Quaternary) and while this may affect our ability to interpret the marine record over millennial timescales it would not affect sediment transport on longer timescales.

Barrier spits themselves represent depositional records of past environments. This barrier spit is mainly built up by washover deposits. The landward-dipping reflections in GPR profiles (shore-normal direction) are evidence of washover sedimentation (Figs. 3, 4). If the barrier spit is totally above the lake level, it will be reworked by eolian processes and become eolian deposits. When the lake level rises sufficient enough to completely submerge a barrier spit, the flows over the barrier are no longer overwash (Sallenger, 2000). As a result, washover deposits contained in this barrier reflect the paleo-shoreline position. We hypothesize that the location of this barrier spit is the exact location of the paleo-shoreline (1265 m above sea level). Despite the lack of direct chronological data, based on known lake level change we try to assign a relative chronological framework.

In the early Holocene (9–8 kyr BP) the lake was at a highstand (>87 m above modern lake level) (Zhang et al., 2012). In the middle Holocene (8–5 kyr), the lake level was ~50 m above the modern lake level (Zhang et al., 2011, 2012). At 5–3 kyr the lake had shrunk to a level of ≥35 m above the modern lake level (Li et al., 1992). Between 3 and 1 kyr, the lake level was about 25 m above the modern. During the Liao, Song and Yuan dynasties (1.0–0.7 kyr), the lake level was about 15 m above the modern level (Li and Wang, 1993). During the Ming and middle Qing Dynasties (0.7–0.2 kyr), the lake-level was about 1275 m asl (~10 m above modern) followed by a lake level drop at 0.2 kyr to about 1265–1270 m asl (Li et al., 1992; Li and Wang, 1993), corresponding to the elevation of the barrier spit. In the 1880s and 1960s, the lake-level rose to 1275 m asl and 1270 m asl, respectively, because of large storms which are recorded in local government “county” records (Li et al., 1992; Li and Wang, 1993). These storms contributed significantly to building the spit bar, and correspond to two washover lobes identified in Radar Profiles A-2, A-3 and A-4 (Figs. 3–5). We conclude that the spit bar initiated its formation at about 0.2 kyr when lake level was about 1265 m asl, the same elevation as the top of the spit bar. This hypothesis could be tested by 14C dating if appropriate material could be found. Construction rates are believed to be very rapid despite the relatively modest sediment supply to the lake.

Barboza et al. (2011) showed that a barrier was formed during the last glacio-eustatic transgressive cycle that started at ~18 kyr BP in Pelotas Basin, Southern Brazil. The shoreline of this basin has experienced transgressive, regressive and aggradational behaviour during
the Middle to Late Holocene. Hein et al. (2013) proposed transgressive barrier formation driven by small high-frequency sea-level oscillation from 3.3 to 2.8 kyr BP. This was discussed by Dillenburg et al. (2014) based on detailed GPR interpretation that it is unlikely to have happened, because Pinheira barrier is very complex showing very variable morphological features. Compared to these complex barriers, our barrier spit was relatively young spanning only ~200 years and shows dominant washover characteristics.

6. Conclusions

GPR data and trenches were used together to define radar surfaces, facies and the sedimentary architecture of different parts of a barrier spit system on the north shore of Huangqihai Lake. Based on the principles of seismic stratigraphy, two groups of six radar surface types were identified (both depositional and erosional). Radar facies bordered by radar surfaces were interpreted based on the reflection characteristics and termination patterns. Eight different facies were identified in the radar profiles, which fall into three groups (inclined, horizontal and irregular). Two distinct units — spit bar and salt marsh units were distinguished using GPR profiles.

This study distinguishes three major subaqueous regimes for the formation of the spit bar. Linking radar and sedimentologic data allows us to develop a model of spit bar evolution. The model demonstrates that the spit bar was formed rather rapidly during a cycle of lake-level change spanning just ~200 years. Furthermore, we conclude that washover deposits (lobes and sheets), swash sediments, and eolian and bioturbated sediments are important building blocks of the spit bar unit. Finally, a relative chronological framework was assessed using lake-level record. Two storms in the 1880s and 1960s contributed significantly to building the spit bar. This suggests that if sediment is being stored in the coastal zone within spit bar systems they should not introduce significant lag times to the total transport between source and sink. Moreover, the volumes involved are unlikely to form a major sediment buffer in most fluvial-deltaic systems.

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