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Geomorphological Evolution Revealed by Aeolian Sedimentary Structure in Badain Jaran Desert on Alxa Plateau, Northwest China

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Abstract: The Badain Jaran Desert, located in the Alxa Plateau, Northwest China, features mega-dunes and a unique dune-lake alternation landscape. This paper presented the aeolian sediment structures of three representative dunes in the Badain Jaran Desert using ground-penetrating radar (GPR). We processed and analyzed the GPR data and investigated the feasibility of using integrated GPR and sedimentological data to reconstruct dunes structure, sedimentary environment and geomorphological evolution. The results show that the internal structures of star dune and transverse dune represent various stages of mega-dune evolution: the main deposition processes of mega-dune are similar to those of transverse dunes but have a more complicated mechanism of sand transport and deposition because of the superimposition of dunes; the upper section of the mega-dune has a structure similar to that of star dune, with vertical aggradations on top. Diffraction hyperbolae in the GPR profile indicates that the presence of ancient dunes characterized by calcareous cementation layers is involved in the maintenance of mega-dunes, and water levels, shown by continuous, sub-horizontal GPR reflections, are supposed to be closely related to mega-dunes and the interdune lakes. Outcrop of wet sand and horizontal stratifications on the GPR image indicate moisture potentials with different levels inside mega-dunes. The multiplex geomorphology in the Badain Jaran Desert is the result of global climatic undulation, the unique geographical location, the geological structural features, *etc*.

Keywords: Badain Jaran Desert; Ground-Penetrating Radar (GPR); mega-dunes; sedimentary structure; geomorphological evolution

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1 Introduction

Desert geomorphological evolution and environmental change are always the problems which desert geographers focus on. The development and migration of aeolian dunes is a complex process which is strongly affected by influencing factors such as wind field, sediment supply, vegetation, *etc*. (McKee,1979; Schenk, 1990; Lancaster, 1992; Baas, 2007). The aeolian sedimentary structure of dunes, which represents dune growth and the influencing factors, is a good record of environmental changes. Therefore, the study to internal structure of aeolian dunes is significant on desert regional and global climates, and geomorphological evolution, especially the study on the dunes with typical morphology.

The Badain Jaran Desert, located in the Alxa Plateau, Northwest China, has received much attention because of its mega-dunes and interdune lakes. Mega-dunes are the most common landforms and are found in the southeastern part of the desert. The height of the mega-dunes typically ranges from approximately 150 m to 350 m,

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the highest dunes are over 400 m, therefore the desert may feature the highest mega-dunes on the Earth (Zhu *et al*., 1980; 1992; Lu and Guo, 1995; Dong *et al*., 2004; 2009). Since the 1930s, researches on the Badain Jaran Desert have primarily concerned with the formation mechanism of the mega-dunes, however, there was still much controvery. In addition to the analysis of the external conditions, such as the sand sources and the wind regime, several ideas have been proposed regarding the internal structure of the mega-dunes. Lou (1962) suggested that drifting sands were obstructed by and then covered on rocky humps in the desert, therefore the patterns of the mega-dunes are controlled by the underlying rocky humps. Sun and Sun (1964) proposed that the mega-dunes were related to the morphology of the underlying structures that were formed by tectonic movements. Tan (1964) reported that lacustrine deposits of the early Pleistocene occurred underneath the mega-dunes. Ancient dunes, which were fixed by calcareous cementation, once existed over the lacustrine deposits, thus the current mega-dunes were formed by drifting sands over these ancient fixed dunes. Wang (1990) noted that it was difficult to imagine how the mega-dunes with orderly space could be controlled by the underlying relief, but Zhang and Wang (2005) hypothesized that some of the mega-dunes on the edges of the desert came from drifting sands over rocky humps. Yan *et al*. (2001) studied the mega-dunes based on the calcareous cementation layers, and concluded that ancient dunes with well-developed calcareous cementation layers occupied 2/3 of the volume of the mega-dunes, and modern dunes covered the ancient dunes. Yang *et al*. (2003) suggested that the calcareous layer represented the old configuration of the dunes and indicated a period of increasing climatic humidity, and they hypothesized that some mega-dunes were related to the underlying relief. Chen *et al*. (2004) suggested that the mega-dune landscapes of the Badain Jaran Desert had been maintained by the presence of ground water. Mischke (2005) assumed that mega-dunes formed upon platform topography composed of cretaceous fanglomerates and sand stones rather than steep inselberg reliefs. Dong *et al*. (2004; 2009) studied the height-spacing relationship for the mega-dunes, and proposed that wind was the most important factor influencing the development of these dunes, but the morphology underneath the dunes did not determine the general pattern of the mega-dunes.

The previous assumptions and interpretations of the internal structure of mega-dunes were based only on surface samples of the dunes, which can not help visualize the subsurface geology or produce an image of the depositional environment. The detection of the internal structure and description of the geomorphological evolution should be included in the further studies of the mega-dune formation mechanism. Ground-penetrating radar (GPR) is a non-invasive technique that can be used to image the internal structure of dunes, leaving no more than a set of footprints on the dune surface. GPR offers a fast and efficient method for the collection of high-resolution and continuous images of the subsurface structure in aeolian sands. Dune sands are suitable targets for GPR surveys because they usually have low conductivity and low magnetic permeability, allowing good depths of penetration (Bristow, 2009). Schenk *et al*. (1993) completed one of the first studies that used GPR to analyze dunes. In their research, a variety of antenna frequencies were used successfully to resolve bounding surfaces, foresets, troughs, and the local water table in the Great Sand Dunes National Monument, Colorado, USA. Bristow *et al*. (1996) compared the results of a GPR survey of dunes in the Liwa area of Abu Dhabi, United Arab Emirates, with a trench section cut by a bulldozer to view the internal structure of the dunes directly. They suggested that the reflections were caused by the changes in the relative permittivity between dry and slightly damp sands that were associated with changes in the grain size in the cross-strata. Bailey *et al*. (2001) investigated the timing of dune activity in a coastal dune field at Aberffraw in Anglesey, United Kingdom. GPR was used to determine the dune stratigraphy, and sand samples were used for optically stimulated luminescence (OSL) dating, which showed that the dune sands had accumulated within the past 700 yr. Many researchers used GPR to produce visualizations of the sedimentary structure within desert sand dunes and coastal dunes, which made it possible to reconstruct the history of dune development and migration (Bristow *et al*., 2000a; 2000b; 2005; 2007a; 2007b; 2010; Neal and Roberts, 2001; Bristow and Jol, 2003; Jol *et al*., 2003; Bristow and Pucillo, 2006; Hugenholtz *et al*., 2007). Yu *et al*. (2004) used GPR to investigate the internal structure of the Sanlong sand dunes in the Kumtag Desert in Xingjiang and Gansu, China. This analysis revealed a proluvial fan under the dunes, but provided only a rough GPR image of 8 m in depth. Li *et al*. (2009) interpreted two 20-m GPR profiles in the windward slopes of mega-dunes in the southeastern part of the Badain Jaran Desert, which was not able to determine the formation mechanism of the mega-dunes based on the internal structure.

All previous researches focused only on the southeastern part of the Badain Jaran Desert, where most of the mega-dunes esixt. However, compound transverse mega-dunes and transverse dunes formed under similar wind regime, while compound star mega-dunes and star dunes formed under similar wind regime. In addition, these mega-dunes were more correctly classified as complex reversing mega-dunes developed from compound barchanoid mega-dunes because they had reversed crest zones and superimposed barchanoid dunes on their stoss slopes (Dong *et al*., 2004; 2009; Li *et al*., 2009). Therefore, it is tentatively proposed that the internal structures of star dunes in the northern part of the desert and the transverse dunes in the central part may be related to the internal structures of the mega-dunes in the southeastern part, and that these different types of dunes represent several periods of mega-dune development.

The aims of this study are to describe and interpret the structures of star dunes, transverse dunes and mega-dunes by GPR profiles in the whole Badain Jaran Desert in China. Through antenna frequency selection, survey design, data processing and stratigraphic analysis, we attempted to determine the internal structures of the dunes using GPR profiles and to explain the evolution of mega-dunes by comparing different sedimentary structures, especially to reconstruct the history of the dune development in the Badain Jaran Desert.

2 Study Area and Methods

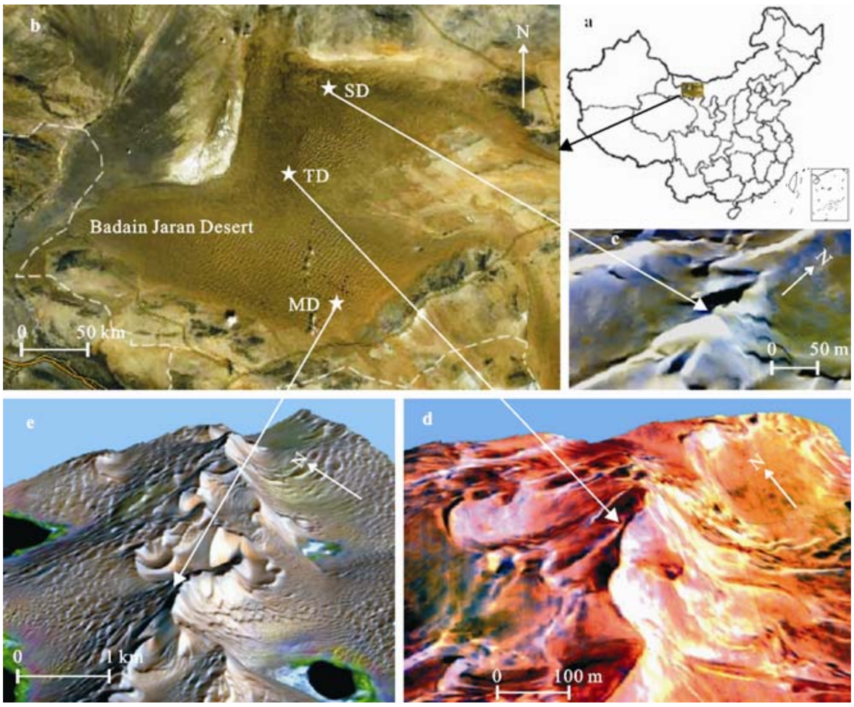
2.1 Study area

The Badain Jaran Desert (39°04'15"–42°12'23"N, 99°23'18"–104°34'02"E) lies in the Alxa Plateau, Inner Mongolia Autonomous Region and Gansu Province, Northwest China (Fig. 1), covering an area of 52 161.96 km^2 (Zhu *et al*., 2010). Migrating dunes occupy over 80% of the total area (Zhu *et al*., 1980; Dong *et al*., 2004), and it is the second largest mobile dune field in China, after the Taklimakan Desert in Xinjiang (Zhu *et al*., 2010). The Badain Jaran Desert area can be zoned approximately into three geomorphological zones from NW to SE: Ruoshui alluvial fan, Yardang zone and dune field. In the dune field, the geomorphic units include star dunes, barchan dunes, barchanoid chains, mega-dunes, interdune lakes, aeolian depressions, denuded hills, *etc*. (Yan *et al*., 2001). The mega-dunes in the central and southeastern Badain Jaran Desert (Liu *et al*., 2010), which cover an area of 29 242 km^2 and occupy 56.1% of the total area (Zhu *et al*., 2010), are the main parts of the desert. The height of the mega-dunes typically ranges from approximately 150 m to 350 m, the highest dunes are over 400 m, and the highest altitude can reach 1700 m. The mega-dunes and interdune lakes alternate with each other in regular geomorphic patterns (Zhu *et al*., 1980; 1992; Lu and Guo, 1995; Dong *et al*., 2004; 2009).

The climate of the Badain Jaran Desert is of extreme continental type, with cold winter. The mean annual precipitation is less than 90 mm, mainly falling from June to September and decreasing from the southeast to the northwest. The annual potential evaporation is over 2500 mm, increasing from the south to the north. The mean annual wind speed ranges from 2.8 m/s to 4.6 m/s, increasing from the south to the north, with the strongest winds in April and May. The mean annual air temperature ranges from 9.5℃ to 10.3℃, increasing from the south to the north as the elevation decreases (Dong *et al*., 2004; 2009), and the highest air temperature can reach 41℃, while the surface temperature is over 70℃ (Zhu *et al*., 1980; 1992; Chen *et al*., 2006; Zhao *et al*., 2010).

2.2 Field survey

Three representative GPR sites were selected (Fig. 1) according to the data of aeolian landforms, lake hydrology, biotic resources and archaeology of the Badain Jaran Desert collected by the College of Earth and Environmental Sciences of Lanzhou University and Gansu Desert Control Research Institute from 2009 to 2010, and the results of Zhu *et al*. (2010). The first site was a star dune (SD) located in northern part of the desert, where three associated GPR profiles were arranged because it had three ridges; the second site was a transverse dune (TD) located in the central part, and the third site was a mega-dune (MD) located in the southeastern part. All of the GPR profiles were designed to be perpendicular to the ridges of the dunes, which were perpendicular to the depositional dip of the sedimentary



(a) location of the Badain Jaran Desert in China; (b) locations of three sites in the Badain Jaran Desert (satellite image); (c) star dune in the northern part of the desert (SD) (DEM image); (d) transverse dune in the central part of the desert (TD) (DEM image); (e) mega-dune in the southeastern part of the desert (MD) (DEM image)

Fig. 1 Locations of Badain Jaran Desert and three ground-penetrating radar sites

structure and showed the width of sets of cross-strata and bounding surfaces (Bristow, 2009).

MALA RAMAC ground-penetrating radar (GRP) (Mala Geosciences Co., Sweden) was employed in this study. A snake-shaped MALA′s Rough Terrain Antenna (RTA, 50 MHz antenna) was selected, which can provide detailed information from both windward and leeward slopes, while other antennas are difficult to move across the leeward slopes of high dunes in China (Yu *et al*., 2004; Li *et al*., 2009). In general, a higher antenna frequency enhances the resolution of the data but reduces the maximum penetration depth, while lower antenna frequency reduces the resolution of the data but enhances the maximum penetration depth. Practical implications of this relationship for sedimentological studies have been examined by Jol (1995), Smith and Jol (1992) and Jol *et al*. (2002). Considering the best compromise between penetration depth in the dunes with great height in the Badain Jaran Desert and the resolution in sedimentary materials, a 50 MHz antenna was used, which is low and intermediate frequency antenna in GPR antennas, and for which the theoretical resolution of damp sand and dry sand is 0.5–0.75 m (Jol, 1995; Doolittle *et al*., 2006; Bristow, 2009). According to the common midpoint (CMP) surveys of the dunes, the radar wave velocities in different depths of the dunes were between 0.12 m/ns and 0.14 m/ns, thus we used a velocity of 0.13 m/ns, which is consistent with published velocities for dry sands (0.12–0.17 m/ns) and saturated wet sand (0.06 m/ns) (Bristow *et al*., 2010). A Leica TPS405 electronic total station was used for the topographic measurements.

2.3 Data and image processing

The data obtained from the radar were processed and topographically corrected using Reflex-W. The processing steps were as follows: 1) Dewow correction: the fields near the transmitter contain low-frequency energy associated with electrostatic and inductive fields, which decay rapidly with distance. This low frequency energy often yields a slowly time-varying component to the measured field data. This energy causes the base level of the received signal to bow up or down. This effect has been known as baseline ′wow′ in the GPR lexicon. The ′wow′ signal process can be suppressed by applying a high-loss temporal filter to the detected signal. This process is referred to as 'dewow'. 2) Time zero correction: ensure that all traces contain the same zero nanosecond start time (for topographic correction). 3) Bandpass (frequency domain filters): use both high-pass and low-pass filters to retain a specific range of frequency components that are defined as a 'pass region'. 4) Background removal: take the mean of all traces in a section and subtracts it from each trace and removes background noise. In relatively lossy materials, strong antenna-ground coupling and shallow nearsurface layers can cause significant reverberation in the signal that can mask later signals. Therefore, background removal filter is a key step in the processing and interpretation of GPR data. 5) Topographic correction: match the radar image with topography of the real profile based on the topographic information obtained by GPS and the electronic total station. 6) Automatic gain control (AGC): display the data with AGC (automatic gain control) function with a time window of 10 ns and a maximum gain function of 500. And 7) Kirchhoff migration: improve section resolution and develop more spatially realistic images of the subsurface.

The interpretation of sand dune morphology and deposit structure was based upon the classification of McKee (1979). Two approaches are commonly used in the interpretation of GPR profiles: 1) radar stratigraphy: identifying the bounding surfaces at reflection terminations; and 2) radar facies analysis: identifying similar reflection patterns (Jol and Bristow, 2003; Neal, 2004). After data and image processing, the GPR survey produced five profiles with strong radar penetration of 20–30 m below the surface.

3 Results

3.1 Star dune

The start dune (SD) in the northern part of the Badain Jaran Desert stands 76.8 m above the interdune surface and is surrounded by barchans and barchanoid chains. The dune has three arms in the directions of WSW (255°), N (0°) and SE (140°). The first two arms are sharp, narrow and long, while the last one is short. The GPR images of the three arms are shown in Fig. 2.

In Fig. 2a, the internal structure of the WSW arm indicates the gradual accretion and migration process of sands. 1) In the left-hand portion of Fig. 2a, a series of inclined reflections dip from left to right. The dotted line across the inflexion point of each reflection suggests the migration and foreslope accretion of sands. These reflections are thought to represent deposition facies of the superimposed dune on the windward slope. 2) In the base of the windward slope, low-angle inclined reflections dipping toward the southeast indicate the deposition of sands from northwest winds. Inclined reflections are interpreted as foresets deposited on the windward side of the dune. 3) In the middle portion of the image, reflections are interpreted as bounding surfaces where the dune has been reshaped by reversing winds and then aggraded vertically. The dotted line indicates the reversal aggradation route. 4) In the right-hand portion of Fig. 2a, the reflections that seem to be connected with the foresets represent gentle slip faces on the dune's leeward slope. The reflections are oblique to the northwest wind, and the dipping reflections are interpreted as sets of cross-stratification.

In Fig. 2b, the GPR profile image of the north arm reveals the presence of sediment packages similar to those within the WSW arm, with similar dipping strata and deposition apparent as packages of cross-strata, which can be interpreted in the same way but indicate the deposition from west winds.

In Fig. 2c, inclined tangential and convex reflections are the dominant reflection pattern on the GPR profile image of the SE arm. The inclined reflections are at a very low-angle with gentle undulations, and the sub-horizontal reflections appear to be discontinuous with the reflections in Fig. 2a and Fig. 2b, which are interpreted as new cross-stratifications formed when the primary ridge (WSW and N arms) became inactive and the vertical accretion of the WSW and N arms began.

3.2 Transverse dune

The transverse dune (TD) in the central part of the Badain Jaran Desert is oriented in NW-SE direction with superimposed barchanoid dunes on its gentle windward slope and no superimposed dunes on the relatively steep leeward side. On the toes of both the windward and leeward slopes, vegetation grows well. The GPR profile across TD showed foreset accretion and slip facies (Fig. 3). 1) In the left-hand portion of Fig. 3, at a depth of approximately 20 m to 30 m below the surface, reflections dipping toward the southeast describe the accretion geometry of the windward structure. This type of structure has been previously described in different works (Bristow *et al*., 2000a; 2000b; Pedersen and Clemmensen, 2005) and is normally interpreted as evidence of migration due to the wind. Sands trapped in the dune by vegetation on the windward side resulted in low-angle sedimentary dips within the dunes. The coincident growth of vegetation and the vertical accretion of dunes resulted in low-angle, windward dipping reflections of cross-strata. 2) In the right-hand portion of Fig. 3, there are steeply inclined reflections dipping toward the southeast that are interpreted as foresets deposited on the leeward side when winds were blowing from the northwest. The 'zigzag' reflection is hypothesized to be the result of cross-bedded aeolian strata formed by migration. The slip faces A and C, which have a dip angle of repose, indicate that the portion overlapping the scarp results from slumping. Slip face B is interpreted as the relatively stationary layer before and after sediment slumping.

3.3 Mega-dune

The internal structure of the mega-dune (MD) in the southeastern part of the Badain Jaran Desert is shown in

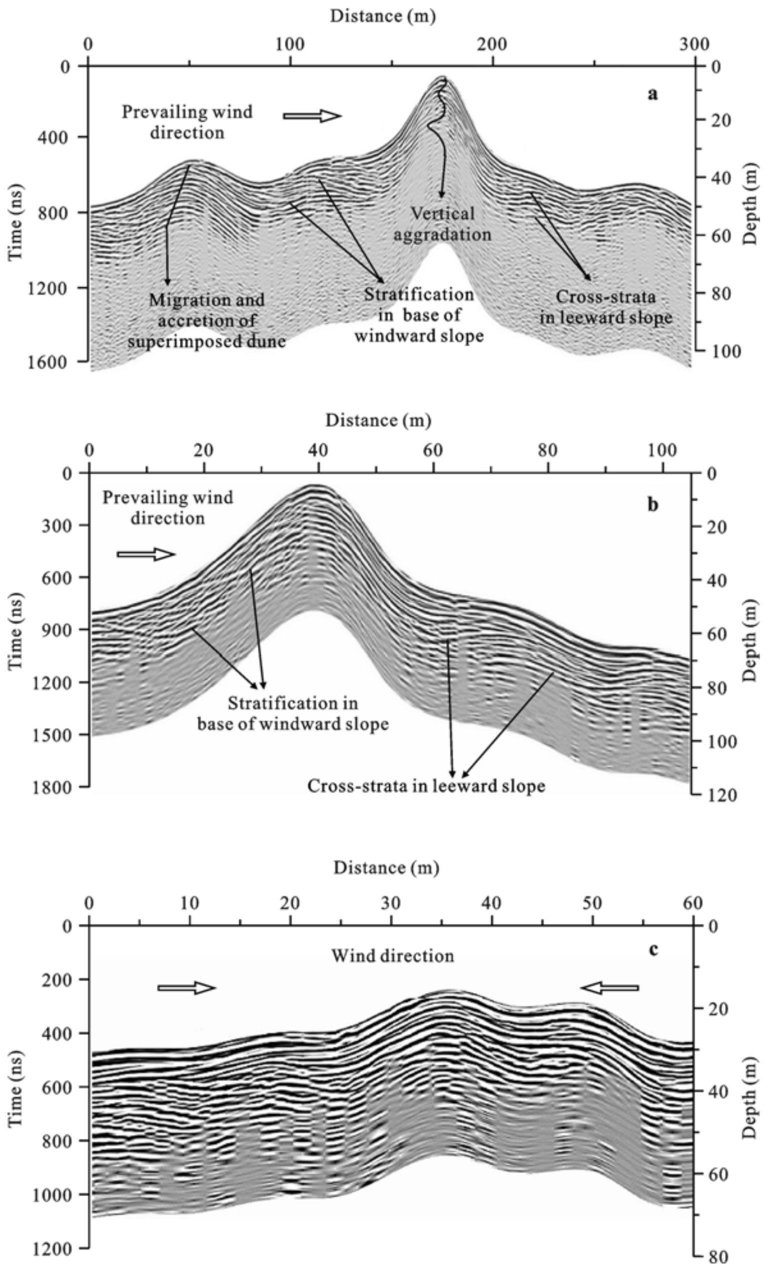


Fig. 2 GPR profiles perpendicular to WSW (a), N (b) and SE (c) arms of a star dune in northern Badian Jaran Desert

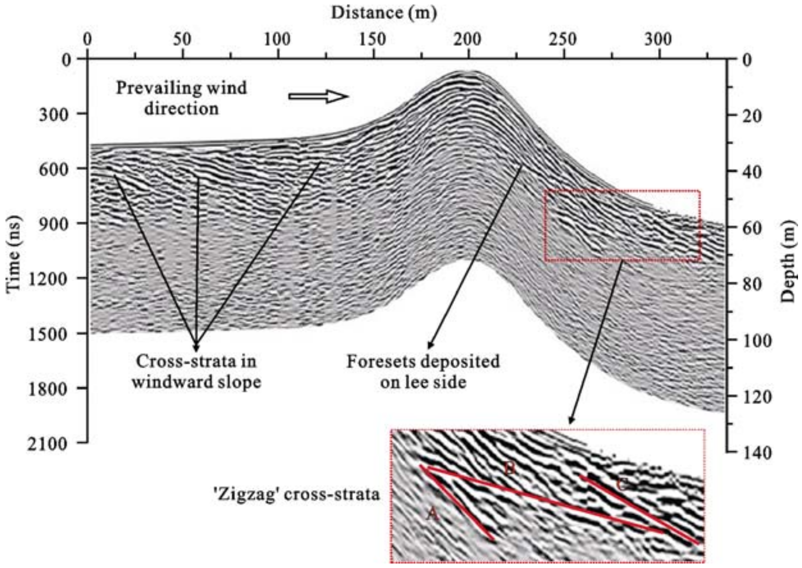


Fig. 3 GPR profile perpendicular to ridge of a transverse dune in central Badain Jaran Desert

Fig. 4. 1) As shown by the whole profile, the lower 3/4 of the mega-dune, with a gentle inclination, has a structure similar to that of TD in Fig. 3, but the sructure is much more complex than that of TD because of the superimposed barchanoid dunes on the windward slope. The complex internal structure of superimposed dunes is defined by the undulating reflections present in the interior of the dune, especially by the reflections located between 400 m and 500 m in the horizontal plane. This dune exhibits reflections with convex and successive layers that have been interpreted as one transverse dune superimposed upon another. Each dune contains inclined tangential reflections that dip toward the southeast, indicating the migration from northwest to southeast. 2) The upper 1/4 of the mega-dune is steeper than the lower 3/4, which is the main arm of the star dune face on the top of the mega-dune and has a structure similar to that of the star dune in Fig. 2. The reflections inside the crest are interpreted as bounding surfaces where the dune was aggraded vertically by reversing winds. The dotted line indicates the aggradation route. 3) Diffraction hyperbolae were found inside both the windward slope and leeward slope, which are characteristic of GPR data from highly heterogeneous sediments and buried objects with a strong contrast in dielectric properties or of voids in sediments (Bristow, 2009). Diffraction was also thought to be caused by large sediment grains throughout the upper part of the sedimentary structure (Neal, 2004). 4) The high-amplitude, continuous, sub-horizontal reflections in Fig. 4 are interpreted as water levels because there is a large contrast in the relative permittivity between the dry sand above the water level and the saturated sand beneath the water level. Furthermore, an outcrop of wet sand was found on the leeward side of the mega-dune, which is linked with a horizontal reflection, suggesting that moisture is stored in dunes.

4 Discussion

Previous studies conducted in deserts have shown that the GPR method has the potential to provide high-resolution images of aeolian strata that are of great value in the geomorphological interpretation of the development of deserts (Harari, 1996; Bristow *et al*., 2005; 2007a; 2007b; 2010; Sandweiss *et al*., 2010). The results of this study demonstrate that GPR provides excellent images of dune strata, including cross-strata, foresets, water table, and large sediment grains.

The internal structure developed in star dune deposits is complex, and it is assumed that cross-strata dip in different directions within trough cross sets. However, the investigations involving trenching only sampled a very small proportion of the total accumulation (McKee, 1966; 1982; Kocurek, 1986; Clemmensen, 1987; Nielson and Kocurek, 1987; Zhang *et al*., 2000). The GPR images of the star dune in the northern part of the Badain Jaran Desert in this study provide the total ac-

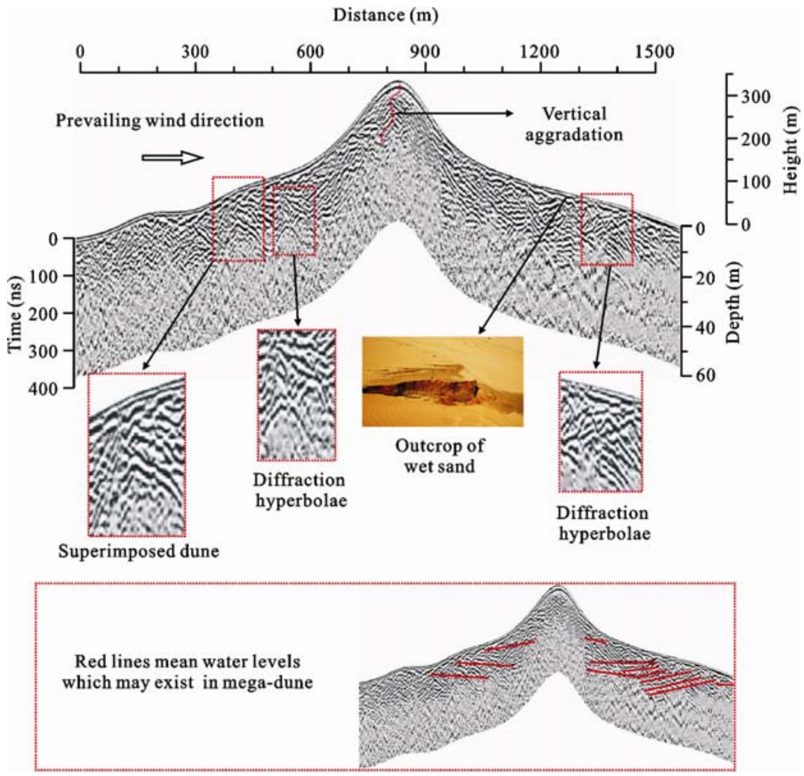


Fig. 4 GPR profile perpendicular to ridge of mega-dune in southeastern Badain Jaran Desert

cumulation of the tree arms. The primary arms (WSW and N arms) have similar reflections that indicate deposition from northwest winds and vertical aggradations in the crests formed by reversing winds. The subsidiary arm (SE arm), which has undulating sediments, may have been formed by the main arms through deformation and separation. Then, vertical accretion became the main movement of the star dune. All of these sedimentary structures were in good agreement with the formation mechanism of the pyramid dunes on the cliff top of the Dunhuang Mogao Grottoes (Zhang *et al*., 2000): the WSW and N arms were formed under the actions of NW and W winds, and these arms often assumed the shape of a transverse dune on one side and formed the second slip face opposite the primary ridge on the other side. Affected by secondary airflow, the subsidiary ridge was generated.

The transverse dune in the central part of the Badain Jaran Desert possessed a structure typical of a transverse dune. The cross-bed sets dipped in almost the same general direction. Parallel laminae formed by the apparent dip of the strata, as seen in the cross-sections, were transverse to the prevailing wind direction. This type of structure has been described in previous trenching works (McKee, 1966; Ahlbrandt, 1973). In this study, the 'zigzag' reflection in the leeward side is hypothesized to be a zigzag cross-stratification that suggests alternate deposition on the opposite flanks of dunes. The secondary flow deflection parallel to the dune crest presumably generated the along-crest-migrating ripples on the downwind flank (Bose *et al*., 1999).

From this study, it can be seen that the mega-dune in the southeastern part of the desert has complex internal structure, which is similar to that of a transverse dune in the lower 3/4 of the mega-dune. However, the structure of the mega-dune is much more complex because of the superimposed barchanoid dunes on the windward slope. Li *et al*. (2009) hypothesized that the foresets inside the transverse mega-dune shown in the GPR profiles climbed up and deposited, but they did not have any detailed evidence based on GPR. In this study, the detailed superimposition of the dunes is indicated by the unit of convex and overlying reflections. The upper 1/4 of the mega-dune has a structure similar to that of a star dune. Li *et al*. (2009) interpreted their GPR image of star dune facies as parallel layers. However, we found that this image shows parabolic layers formed by reversing winds in the form of reversing aggradations. Dong *et al*. (2004) proposed that star dunes were formed by variable wind directions due to the influence of the Yabrai Mountains. The internal structures of star dune and transverse dune represented various stages of mega-dune evolution. Diffraction hyperbolae, which were found in the GPR profile of mega-dune and have not been mentioned in previous GPR works that focused on dunes in China, indicated large sediment grains. Based on the outcrop of calcareous cementation layers (Fig. 5), we hypothesize that the diffraction hyperbolae indicated ancient dunes. From the same field as the mega-dune in this study, Yang *et al*. (2003) took a sample under a calcareous cementation layer in the middle of the windward slope and reported a TL age of 18 500 ± 1500 (TGD-601). They thought that the calcareous cementation represented an increase in the stability of the dunes and reflected a decreased aridity index and a decrease in sediment availability. According to the field work and the discovery of cretaceous fanglomerates and sand stones near the Yabrai Mountains, we suggest that the underlying morphology in the southeastern part of the Badain Jaran Desert is a platform topography that is more or less horizontal rather than composed of rocky humps or a pre-existing surface relief. The primary factor responsible for the formation of the mega-dunes is wind action (Dong *et al*., 2004). However, it can be concluded based on the height-spacing relationship of the mega-dunes that there are a few factors involved in maintaining the evolution of complex mega-dunes in the Badain Jaran Desert, which are unique to this type of dune and do not contribute to the evolution of superimposed simple dunes or dunes in other deserts (Dong *et al*., 2009). The wind regime is the primary but not sole factor affecting dune formation (Kocurek and Ewing, 2005). Diffraction hyperbolae in the GPR profile of mega-dune in the southeastern Badain Jaran Desert indicates that the effect of ancient dunes is another primary factor involved in the maintenance of mega-dunes. The continuous, sub-horizontal reflections in Fig. 4 were interpreted as water levels, although the internal structure of the mega-dune seems to be complex. Chen *et al*. (2004) suggested that the dunes developed progressively when water vapor flux from the groundwater into the dunes was greater than the evaporation flux of the dunes. This water likely acted as a cohesion agent, providing the dunes with resistance against wind erosion and transportation. In contrast, Zhao *et al*. (2010) suggested that inside mega-dunes, the precipitation transformed into groundwater as it moved downward. Yang *et al*. (2010) suggested that the lake water and groundwater in the Badain Jaran Desert could be from the same source, namely local and regional precipitation. Pedersen and Clemmensen (2005) reported that the thickest parts of the aeolian units were accumulated and preserved in the area where the topography facilitated a temporary storage of high-lying ground water. The wet aeolian system is hypothesized to be a factor of formation mechanism of mega-dunes.

Fig. 5 Outcrop of calcareous cementation layers

5 Conclusions

Ground-penetrating radar (GPR) with a Rough Terrain Antenna (RTA, 50 MHz) worked well in the Badain Jaran Desert and successfully imaged the internal structures of three typical dunes. The GPR profiles were used to identify aeolian cross-strata, aeolian bounding surfaces, and water levels, among other features. The internal structures of star dune and transverse dune represent various stages of mega-dune evolution: the main deposition processes of mega-dune are similar to those of transverse dunes but have a more complicated mechanism of sand transport and deposition because of the superimposition of dunes; the upper section of the mega-dune has a structure similar to that of star dune, with vertical aggradations on top. From the north to the south in the Badain Jaran Desert, the internal structure of dunes becomes more complex, which provides evidence of the dune formation processes and geomorphological evolution. The special distribution of mega-dunes is determined by sand movement, from the northwest to the southeast. The bedrock does not play a dominant role in the arrangement of mega-dunes, which instead depends on the principle of aerodynamics. However, the deposition resulting from the wind regime is not the sole factor influencing the formation mechanism of mega-dunes. Diffraction hyperbolae in the GPR profile indicate that the presence of ancient dunes characterized by calcareous cementation layers is another primary factor that is involved in the maintenance of mega-dunes, and water levels, shown by continuous, sub-horizontal GPR reflections, are supposed to be closely related to mega-dunes and the interdune lakes. The outcrop of wet sand and the horizontal stratifications on the GPR image may indicate moisture potentials with different levels inside mega-dunes.

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