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Sedimentary successions and internal structure of the coastal barrier-lagoon system of Boao, eastern Hainan Island were studied through utilizing data from test holes and trenches and ground-penetrating-radar (GPR) profiles. During late Pleistocene, fluvial and delta plains developed over an unevenly eroded bedrock during low sea level stand, followed by the formation of littoral and lagoon facies and defined coastal barrier-lagoon-estuary system during the post-glacial uppermost Pleistocene-lower Holocene eustatic rise of the sea level, and the upper Holocene high stand. GPR results show that Yudaitan, a sandy coastal bar backed by a low-laying land (shoal) just east of the active lagoon, is a continuous, parallel and slightly-wavy reflectors indicating homogeneous sandy or sandy gravel sediments, and inclined reflectors partly caused by progradation and accumulation of beach sand and gravel. Quasi-continuous, hummocky and chaotic reflectors from the shoal of Nangang village correspond to mixed accumulation of sands and clay. This research indicates the GPR is a non-intrusive, rapid, and economical method for high-resolution profiling of subsurface sediments in sandy gravelly coast.

The application of GPR to barrier-lagoon sedimentation study in Boao of Hainan Island YIN Yong1, ZHU Dakui1, TANG Wenwu1, Martini I. Peter2 (1. The Key Laboratory of Coast and Island Development, Nanjing University, Nanjing 210093, China; 2. Dept. of Land Resource Science, University of Guelph, Ontario, Canada NIE 4E5) Abstract: Sedimentary successions and internal structure of the coastal barrier-lagoon system of Boao, eastern Hainan Island were studied through utilizing data from test holes and trenches and ground-penetrating-radar (GPR) profiles. During late Pleistocene, fluvial and delta plains developed over an unevenly eroded bedrock during low sea level stand, followed by the formation of littoral and lagoon facies and defined coastal barrier-lagoon-estuary system during the post-glacial uppermost Pleistocene-lower Holocene eustatic rise of the sea level, and the upper Holocene high stand. GPR results show that Yudaitan, a sandy coastal bar backed by a low-laying land (shoal) just east of the active lagoon, is a continuous, parallel and slightly-wavy reflectors indicating homogeneous sandy or sandy gravel sediments, and inclined reflectors partly caused by progradation and accumulation of beach sand and gravel. Quasi-continuous, hummocky and chaotic reflectors from the shoal of Nangang village correspond to mixed accumulation of sands and clay. This research indicates the GPR is a non-intrusive, rapid, and economical method for high-resolution profiling of subsurface sediments in sandy gravelly coast. Key words: barrier-lagoon system; shoal; sedimentary succession; GPR; reflector configuration; Boao CLC number: P534.6; P737.1 1 Introduction Boao, belonging to Qionghai City, located at 110.5oE, 19.3oN (Figure 1), has been a well-known locality since it was appointed as a permanent place of Asia Forum in March, 2001. It lies at the junction of three rivers, i.e., Wanquan, Jiuqu and Longgun rivers, on an anastomosing estuary system. Its coast shows a well developed sandy barrier-lagoon system (Wang, 1998). Barrier-lagoon system is a major type of coast, with its length making up 13% of the total coast in the world (Gao, 1992; Wang, 1999). In Hainan it is widely distributed, mainly along the southern coasts (Wang, 1998) and forms on gentle slope receiving much sand, subjected mostly to mesotidal, and variable wave conditions (Chen, 1989; Li et al., 1999). Since late Pleistocene eastern Hainan Island has undergone a complicated interaction between sea and land, including isostatic and eustatic events (Zhang and Liu, 1987; Li, 1990; Zhao et al., 1999; Luo, 1999; Chen and Fan, 1988). This history is recorded in coastal sediments distributed on ancient coast plains from the foot of inland low mountains, hills, marine-deposited terraces, and modern coastal barrier and lagoon systems. Research on modern barrier-lagoons systems can provide valuable information for Quatern ary coastal evolution and for understanding of global changes (Li and Wang, 1993). In this paper the coastal barrier and adjacent environments were studied based on cores, outcrops and GPR reflection patterns and their post-Upper Pleistocene temporal and spatial evolution were reconstructed. 2 Modern environments 2.1 Geology and geomorphology The coastal system of Boao includes a well developed barrier of Yudaitan, named Yudai bar in Chinese, which encloses a vast submerged lagoon (Shameineihai) and sandy exposed terraces and back barriers flats. The Yudai bar is 18 km long, 8 km belong to Qionghai City and the rest to Wanning City (Zhao et al., 1999). It is mainly composed of coarse sands with a narrow and steep slope on the seaside. The bar is unstable and subject to heavy erosion where it narrows toward the north near the mouth of the river estuary, it is more stable to the south where it widens significantly. The emerged back barrier area of the Nanggang village adjacent to the bar is an estuary shoal and constitutes a 1st marine-deposited terrace. Because of frequent flooding of the Wangquan and other rivers, the sediments of the shoal are mostly composed of sand and mud. Shameineihai lagoon is long but narrow and extends from Qionghai City to Wanning City. It receives fresh water from three rivers, the Longgun River from the southwest, Jiuqu River from the south and Wanquan River from the northwest. It is open to the sea through a narrow and shallow channel. The semi-obstructed salt water exchange with the sea and the relatively low evaporation rate, the lagoon maintains a very low (less than 1‰) salinity. 2.2 Hydrology and climate Boao lies in marginal tropical zone and is mainly influenced by East Asia monsoons and typhoons. Summer monsoon from the South China Sea and West Pacific brings most of the annual rainfall to the island, whereas the winter monsoon from Inner Mongolia carries dry winds to the area. Annual average rainfall is estimated at 1653.4 mm and annual average temperature at 23.4oC. Maximum high temperature occurs in July, with monthly average of 28.6oC. Maximum low temperature occurs in January, with monthly average of 19.1oC. The coast is a microtidal and strong wave coast with mean tidal difference of 0.7-0.8 m according to long-term statistical data (Luo, 1999). Tidal excursion in spring and fall is higher than that in summer and winter. Storm wave and swelling are strong with maximum wave amplitude up to 4-7 m. The coast is oriented approximately N-S, and strong longshore current and sediment transport occur prevalently to the north. 3 Methods Drilling cores and Ground Penetrating Radar (GPR) profiles were used to study the sediments of the coastal zone of Boao (Figure 1). 3.1 Drilling cores To determine the stratigraphy and engineering properties of the materials of the area thirty testing holes were drilled by the Environmental Inspection Center, Hainan Bureau of Geology in the Nangang village area and the Yudaitan coastal bar in March 2001. Holes zk001, zk002, zk003, zk14, zk15, zk16, zk17, zk18 and zk23 were logged on the spot, and for five of them, whole cores were sampled (Figure 1). Lithologic data for another five holes (zk3, zk8, zk13, zk14, zk18) were also collected. Only drill hole zk17 penetrated bedrock. 3.2 GPR working principle In this study, an EKKO TM IV system constructed by the Canadian Firm of Sensors & Software (Toronto, Ontario) was used. The system consists of a transmitting and receiving antenna, a console, a computer, cable and storage battery (Figure 2). The survey GPR technique is analogous to seismic reflection profiling except that GPR data are acquired by using transient electromagnetic energy reflection (Smith and Jol, 1997). GPR systems radiate short pulses of radio-frequency electromagnetic energy into the substrate layers from a transmitting antenna (Beres and Haeni, 1991; Van Heteren et al., 1998; Van Dam and Schlager, 2000). For stratigraphic work, the antennae are not shielded, and therefore, part of the energy, however, travels directly to the receiving antenna as airwave and ground waves. Part of the remaining energy, which enters the subsurface, reflects at discontinuities between layers with different electrical properties and turns back to the receiving antenna (Bridge et al., 1995; Beres et al., 1995; Smith and Jol, 1997). The time of arrival of the various reflected waves is recorded by the receiving antenna and stored in a computer as Two Way Time (TWT) in nanoseconds (ns) (Two way time indicates the time that a wave takes to go from the transmitting antenna to the reflecting surface, to the receiving antenna) (Cook, 1975; Tang et al., 2001). A GPR survey consists of two parts: i. The average penetration velocities needed to estimate depth of reflectors is determined with a "Common Mid Point" (CMP) technique at every site that has new materials. The technique consists of relatively short (up to 30-50 m) transects where the antennae of transmitter and receiver are progressively moved away from each other in relation to a central point, in incremental short (for example, 5 cm) steps. In this way the central reflectors are the same and their distance from the instrument and the arrival delay time of the reflected wave increase. ii. Routinely, a "reflection survey" is then performed along pre-established, topographically surveyed transects, keeping the distance between antennae (thus between transmitter and receiver) constant (for example, 1 m depending on what Mhz antennae are used) and shifting their position in equal distance steps (for example, 25 cm). Standard settings are used to record data. Common settings for a 100 Mhz antenna are: Number of points/traces: 640; Total time window: 512 ms; Step size used: 0.2500 m; Nominal frequency: 100.00 mhz; Antenna separation: 1.0 m; Pulser voltage: 1000 v; Number of stacks: 64; Velocity: 0.1 m/ns (for dry sand) 4 Results 4.1 Sedimentary successions of barrier-lagoon system The thickness of Quaternary sediments varies from 20 to 30 m due to altitud e fluctuation of original basement (Figure 3). In the Yudaitan coastal bar and Shameineihai lagoon, the sediments ar e thick. But in the center area of Nangang village the sediments are thinner due to a buried basement. In drill hole zk17 that reached bedrock in Nangang village, the lithology and sedimentary successions are as follows: 1) 0-0.9 m Br own yellow, gray and varicolored silty clay with few disseminated pebbles, showing evidence of pedogenesis; 2) 0.9-3.7 m Light gray-gray yellow coarse sand and medium to fine grained sand containing yellow clay, loose. In the upper layer, medium to fine grained sand contains small shells; 3) 3.7-9.0 m Loose gray-dark gray gravel, mineral contents are mainly composed of quartz, feldspar, containing a little of heavy minerals as ilmenite; 4) 9.0-13.0 m Dark gray c lay and silty clay, micaceous, containing shells in bottom clay layer; 5) 13.0-16.2 m Yellow sandy gravel in lower la yer, yellow-gray clay and yellow fine sand elsewhere. Yellow clay contains a lot of ferric oxide particles; 6) 16.2-20.4 m Yellow sandy gravel, light gray clay and brick-red clay. In the lower layer, light gray clay layer contains a f ew gravels. The color of clay changes much, but oxidized red is main tone. 7) 20.4-24.4 m Variegated colored sandston e, possibly due to paleoweathering. The cores indicate that three main successions occur in the Nangang village shoa l area (Figure 3): 1. The lower succession is composed of varicolored coarse sand and gravel containing varicolored m ud and clay silt. Its thickness is 8-10 m, including three fining up cycles, representing typical fluvial facies. Th e sedimentary successions were formed in deltaic to fluvial environments. Yellow and brown sandy gravels represent di stributary channels; red mud relates to delta plain; red oxidized colouration indicates that this succession is occas ionally exposed. 2. The middle sedimentary succession is composed of dark black, black and gray green mud and silty c lay, containing high content of organic matter and shells. In zk14 and zk18 there exist humic matters. In zk15 there exist carbonaceous fragments and vegetable detritus. In southeast Nangang village close to Shameiniehai, the thicknes s of this succession is the biggest, such as the core of zk14 is 19 m long and nearly completely composed of mud. Th e thickness of this succession declines toward center of Nangang village. This middle sedimentary succession is inter preted as lagoon deposit. 3. The upper sedimentary succession is mostly composed of poorly sorted gray gravel and mu d. The coarser particles are sub-angular. Interlayered brick-red clay and pedogenesis material with root traces is pr esent. The sedimentary evidence suggests an estuarine paleoenvironment, where both sandy fluvial and muddy lagoonal s ediments are deposited. Only upper and middle sedimentary successions are observed in Yudaitan coastal bar because dr illing did not reach bedrock. The sediments of the middle succession are similar to that of Nangang village, namely, they are mostly composed of gray, dark gray and gray green mud with high content of organic matter, carbon and vegeta tion fragments, trumpet and other shell fossils. In zk23 Crustacea fossils were also found. This succession is interp reted again as a paleolagoon deposits. The upper sedimentary succession (about 12 m thick) is mainly composed of yell owish gravel and pebbly medium to coarse sand. The color of sediments is similar to that of modern beach sand, and th e sediments show good sorting and the particles are subrounded. The sedimentary characteristics indicate these deposi ts to represent coastal bar settings. The topmost part of the cores and outcrops are characterized by yellowish, medi um to fine grained sand ascribed to aeolian dunes. Figure 4 shows a profile of the wave-cut bar berm. The bottom par t of the profile shows light gray fine-grained sand with muddy silt and a millimeter band of organic matter. The midd le part is composed of light gray coarse-grained sand with minor gravel and middle-scale cross-beds and inclined bed s. The upper part shows yellowish fine-grained, well sorted and well cemented sand. The various layers, from the bott om to up, have been interpreted to represent a shoreface to backshore to shoreface to coastal dune. Carbon dating of the various sediments indicate an age of about 10,230?20 a BP of organic bands intercalated in basal gravel immediate ly on the top of the basal weathering crust, 8,460?70 a BP for the middle succession, and 8,460?70 a BP for the uppe r succession (Zhao et al., 1999). According to analysis of 210Pb of a 1.4-m-long muddy core collected from the Shamei neihai lagoon, the average accumulation rate of mud was less than 1.4 mm/yr. Based on this result it can be conclude d that the oldest age of Quaternary sediments in this area did not exceed 15 ka BP. This compares favorably with the carbon date obtained from the deepest layers of land cores. 4.2 GPR profiles Theoretically, useful information can b e obtained from the EKKO42 GPR system down to 25 m in depth. In reality, the instrument can provide good insight of t he sediment structures and water content down to half to one fourth of that depth, because of variable lithological a nd interstitial fluid characteristics. In the research area, effective resolution was possible down to about 6 m to 1 2 m. Below this depth clay deposits and salty water impeded any penetration of the electromagnetic waves. A show in t he main four GPR profiles (NANGANG1, NANGANG2, NANGANG3 & YUDATAN) is presented here, and the coastal bar in Yudaita n and shoal in Nanggang village had completely different reflection configurations (Figure 5). 4.2.1 Reflection patte rns of Yudaitan coastal bar Total profile length, including YUDAITAN and part of NANGANG3, is 712 m and the terminati on spot of the profile is located in modern beach at the high tidal level. Near high tidal level the GPR penetration is less than 3 m (Figure 5c); below this depth, the reflection signals disappeared completely because sediments are s aturated by salt water. Inland from the beach the depth of water table increases gradually and reaches 6 m deep below the surface in profile YUDAITAN and NANGANG3 (Figures 5a and 5b). According to hole zk23 and zk003, the boundary between sand and mud is 12-14 m below the surface. Above are coastal bar facies sediments and below is clay of lagoon facies. Because electromagnetic wave can not penetrate clay, the sediment structure of lagoon deposits is not revealed. Figure 5 shows that the Yudaitan coastal bar is mostly characterized by continuous, parallel and slightly-wavy reflectors, which probably represents uniform, bedded medium to fine-grained sand with good sorting and roundness (Beres and Haeni, 1991). Locally there are also oblique reflectors including tangential and sigmoidal types, indicating progradation and accumulation of beach sand and gravel. Some hummocky, chaotic and hyperbolic reflectors appear below about 6 m deep. We suggest, in accordance with information from cores, that this results from the concentration of coarse sands and gravels, although the diffraction effect by coarser particles can not be ruled out.

4.2.2 Reflection patterns of the shoal in Nangang Village

The profiles NANGANG1, NANGANG2 and NANGANG3 show the reflector patterns of the shoal in Nangang village (Figure 6). GPR reflectors are mainly quasi-continuous, hummocky and chaotic (Figure 6), suggesting that the deposits of being a mixed accumulation of sand and mud with local gravels. This conforms with the point-based information form cores. More than cores, though, the GPR profiles show the existence of channel-shaped reflections suggesting paleochannels. Furthermore in lower lands closer to the modern lagoon, the GPR profiles indicate lots of penetration at shallow depth everywhere indicating extensive muddy deposits (Figure 6a). All this confirm the fluvial origin of the coarse-grained deposits on the Nangang village shoal, which is actually located near the mouth of the modern Wanquan River, and the lagoonal or coastal plain muddy deposits in the surrounding lower lowland.

5 Discussion and conclusions

(1) The modern barrier-lagoon system of the Boao area in eastern Hainan Island formed during the post-glacial sea level rise. The sediment successions from bottom to top indicate an eroded, weathered bedrock surface, overlain by fluvial and delta plain sandy, gravelly and muddy deposits, overlain by littoral and lagoon muddy facies, and overlain by coast barrier sands, semi-closed lagoon and estuarine mud facies. This succession developed during the last stages of the Upper Pleistocene-middle Holocene transgression that peaked at about 6000 a BP (Huang, 1996) and the subsequent high stand stages that experienced only slight fluctuations in sea level (Wang, 1998).

(2) GPR results show that the Yudaitan coastal bar has continuous, parallel and slightly-wavy reflectors indicating homogeneous sandy or sandy gravel sediments (Yin et al., 2002). Hummocky, chaotic and hyperbola-shaped reflectors 6 m deep below surface suggest more concentration of coarser sands and gravels. Oblique reflectors are common in the profiles, indicating accumulation of sand and gravel in a seaward prograding coastal ridge. (3) GPR profiles from the shoal of Nangang village show quasi-continuous, hummocky and chaotic reflectors, indicating mixed accumulation of sands and clay. Some channel-shaped reflectors also appeared in the profiles. (4) Cores and GPR results demonstrate that the deposits of the Nangang shoal possibly formed in late Holocene. At the early stage a coastal/deltaic plain and shallow paralic settings, not a well-defined lagoon, may have existed in the area. An extensive lagoon became well defined as it was enclosed by the landward migrating coastal bar/barrier, leading to a transgressive succession whereby the lagoonal deposits were in part buried by the bar sands (Wang, 1999). Eventually the southern part of the lagoon was filled and the Nangang shoal and Yudaitan coastal bar joined via an exposed land tract. (5) GPR technique is a non-intrusive, rapid and economical exploration method for, among others, sandy, gravelly and peat deposits with interstitial freshwater. It is a good method to determine depth and lateral behavior of the water table. Geological logs from test drill holes, outcrops and trenches are nevertheless needed to calibrate the GPR reflectors and to lead credibility to the interpretation, particularly in areas where complex distribution of various sediment types occurs.

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关键词： barrier-lagoon system; shoal; sedimentary succession; GPR; reflector configuration; Boao

