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Geomorphic Evolution of a Barrier Island Reflects the History of Natural Sediment Supply and Human Intervention in Taiwan

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ABSTRACT

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We report on the integration of subaerial and subaqueous surveys, on the basis of, respectively, SPOT satellite images and data acquired from a combined side-scan and profiler sonar system, of a barrier island on the west-central coast of Taiwan. Our results establish a case study of a natural barrier island (i) the morphology and position of which have been dramatically affected by human alteration of a sediment-supplying river during the 200-year interval 1790–1990, but (ii) whose partial destruction and migration have been mitigated significantly in recent years by a combination of tectonic and climatic events. These events have been shown elsewhere to have increased riverborne supply of sediment to the Taiwan coast, and we propose that this development, in turn, contributed to the observed stabilization of the barrier island in size and location.

INTRODUCTION

In September 1999, the Chi-Chi region of west-central Taiwan was struck by an earthquake of magnitude $M_w = 7.6$, resulting in tragic loss of life and widespread devastation. The earthquake also had significant geomorphic consequences that scientists are still endeavoring to understand. For example, more than 10^4 landslides and incidents of hillslope failure of various scales were triggered in the western foothills of Taiwan's Central Range (Dadson *et al.,* 2004). During the following monsoon, three typhoons made landfall on Taiwan, and widespread, newly exposed regolith and poorly consolidated bedrock in the Chi-Chi foothills were subjected to additional mass wasting. Hillslope debris mobilized by the typhoons of 2000 and 2001 contributed to significant increases in sediment concentrations in many of the rivers draining the epicentral region and beyond (Dadson *et al.,* 2004). The Choshui and Peikang Rivers of west-central Taiwan were among those most dramatically affected. The Choshui River, for example, discharged a total of 326 Mt of sediment during the period of postseismic 1999 through 2001. Compared with records for the years leading up to the earthquake, this yield corresponds to a fourfold increase in unit-discharge sediment load of the Choshui River (Dadson *et al.,* 2004).

In this report, we document significant changes in the short-term evolution of Waisanding Island, a barrier island that derives its sediment supply primarily from the Choshui and Peikang Rivers, and attribute these changes in part to dramatic, postseismic changes in the sediment load of these rivers. Low-elevation, coastal areas are among the most heavily populated regions on earth, and many such areas are protected by barrier islands from the full onslaught of marine storms. The origin and health of barrier islands is thus of global interest, especially in light of predicted trends in sea-level rise over the next century (Penland *et al.,* 2005; Thurman and Burton, 2001).

In this context, a topic of concern is ongoing deterioration of some barrier islands. Barrier-island deterioration is attributed in different locales and at different times to changes in incident wave power, tidal conditions, the frequency of landscape-altering storms, and sediment supply to coastal waters (Armitage *et al.,* 2006; List *et al.,* 1997; McBride and Byrnes, 1997; Morton, Gibeaut, and Paine, 1995; Simms, Anderson, and Blum, 2006; Stone and McBride, 1998; Stone *et al.,* 1997; Trowbridge, 1995). In many cases, destructive changes in barrier islands arise in part owing to, or are exacerbated by, human activities. We present here a fascinating case study in which tectonic and climatic processes have appeared to work together, in the short term, at least, to overwhelm a century-long pattern of barrier island migration and destruction ascribed in part to human activities.

In the following section we summarize the known history of Waisanding Island. We then report new observations from satellite imagery and seaborne geophysical surveys of the evolution and submarine morphology, respectively, of Waisanding Barrier Island.

BACKGROUND

Taiwan is an active orogenic island resulting from the collision between the north Luzon Arc and Eurasian continental

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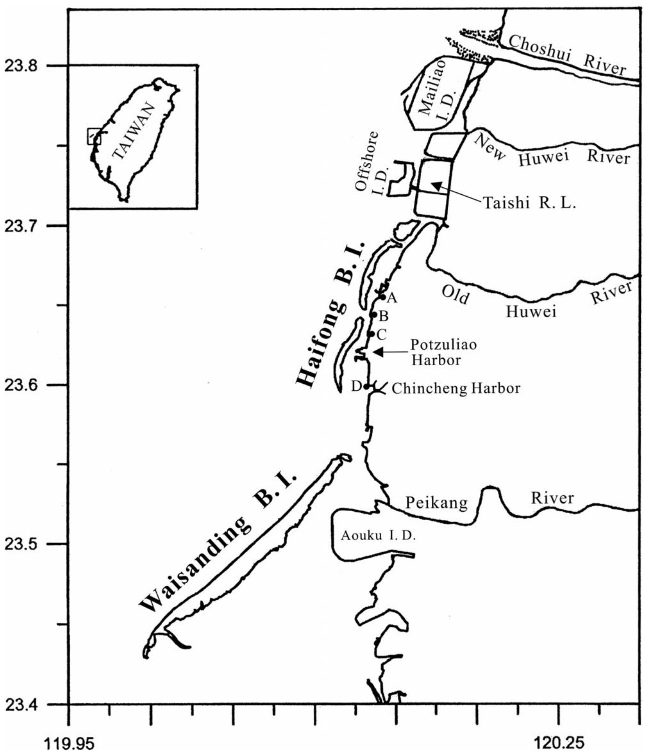

Figure 1. Location map for this study. Shown are Waisanding Barrier Island as well as Choshui River, Old and New Huwei rivers, and the Peikang River. The filled circles, A–D, mark the northernmost position of the barrier at different years, as discussed in the text.

margin (Ho, 1982; Hong, 1997; Teng, 1990). Rapid rates of uplift, large relief, and episodically extreme seasonal precipitation result in significant rates of river incision and hillslope denudation (Milliman and Syvitski, 1992). Large rates of sediment supply have contributed to the formation and maintenance of river-mouth spits, barrier islands, and fan deltas.

The largest river in Taiwan, and among the most geomorphically significant, is the Choshui River of west-central Taiwan (Figure 1). The river drains a total area of 4324 km^2, and during the period 1949–1996 delivered an average 63.9 Mt a^{-1} of suspended sediment to the coastal ocean (Hydrological Year Book of Taiwan, Water Resources Agency). Owing to its significant sediment load, the Choshui River has exhibited rapid and dramatic changes in form during historical times, at least. Of interest here, we note that *ca.* 1790 the Choshui River newly occupied the present Old Huwei River channel until 1911 (*cf.* Figure 1). As a result, Waisanding Island underwent more than a century of significant growth and extension southward from the river mouth, to become the largest barrier island in Taiwan (Chang, 1985; Shih, 1980).

As part of a flood abatement program initiated in 1911, the Choshui River channel was relocated northward 14 km to its present course. Apparently, the resulting dramatic loss of immediate sediment supply to Waisanding Island since 1911 contributed to a significant reduction in the plan area of the barrier in the ensuing decades to at least 1994, as follows. The northern end of Waisanding Island retreated southward at a rate of *ca.* 250 m a^{-1} during the interval 1932 to 1982 (Chang and Chen, 2001; Lin and Juang, 1985), apparently accelerating in its southward retreat to 500 m a^{-1} in the interval 1973–1984. In contrast, the southern end of the island migrated southward at a rate of only *ca.* 110 m a^{-1} during the same interval and, as a result, the island lost an estimated 200 km^2 in subaerial surface area over the 100 years leading up to the mid-1980s (Wu, Peng, and Hsiao, 1991).

Additional historical evidence highlights key milestones in this evolution. A chart dated from 1904 indicates that the submerged, northern end of Waisanding Island was connected to the coast at a location (denoted Figure 1A) *ca.* 8.6 km south of the mouth of the Old Huwei River, and extended southwestward with its southernmost tip at *ca.* 7.3 km to the west of the Peikang River mouth (Shih, 1980). In 1904, there were also few small shoals appearing at the mouth of the Peikang River.

As revealed in subsequent charts published during 1947–1984, Waisanding Island remained more or less attached to the mainland coast but drifted southward. This migration is shown in Figure 1 by the letters B, C, and D, which mark the position of the northernmost extent of the island in 1947, 1973, and 1984, respectively. During this period of time, moreover, Waisanding Island became increasingly fragmented. In 1984, the island consisted of six islets separated by shallow, tidal inlet channels. During the period 1984–1988, however, all but one of these tidal inlets were infilled with sediment probably derived from the Peikang River, as indicated by the concurrent growth of shallow bars at the mouth of the Peikang (Wu, Peng, and Hsiao, 1991).

As noted in our introductory comments, recent seismic and climatic events have resulted in significant increases in the amount and rate of sediment supplied to the coast of west-central Taiwan from the Choshui and other local rivers. To document the changes associated with this shift in sediment supply, we monitored the position and shape of the barrier island as revealed in satellite images and bathymetric surveys using an echo sounder and a combined side-scan-and-profiler SONAR system. We describe our methods in more detail in the next section.

METHODS

Seventeen SPOT satellite images of Waisanding Island and vicinity and spanning the interval 1986–2005 were obtained from the Center for Space and Remote Sensing Research, National Central University, Taiwan. Each of the images was selected for its unobstructed view. No images from 1991 were available that met our selection criteria. The passage over the vicinity of two storms in September 2001 provided us with an opportunity to examine the effect of local storms on the barrier island morphology. Accordingly, we also examined SPOT images acquired in June and October 2001 representing conditions before and after the storm season, respectively. Tide level at the time each image was acquired is noted in Table 1.

Table 1. *Summary of tide level at time of individual images. Tidal data is compiled from the Potzuliao Harbor Tidal Gauge Station. The average tidal range is less than 2 m microtidal range.*

Type of Satellite	Time of Image Taking Year/Month/Day/Time	Tidal Level Annual Mean Tidal Level = 0 m
SPOT	1986/09/28 02:45	No data
	1990/05/29 02:44	No data
	1992/01/22 02:49	No data
	1993/07/13 02:46	No data
	1994/10/16 02:55	No data
	1995/04/21 02:59	No data
	1996/08/04 02:58	+1.32
	1997/11/12 02:59	−1.12
	1998/11/12 02:41	+0.3
	1999/01/31 02:34	−1.04
	2000/05/15 02:37	−0.56
	2001/06/30 03:00	+0.24
	2001/10/24 02:29	+1.18
	2002/01/10 03:04	−1.11
	2003/08/18 02:52	+1.3
	2004/10/06 02:45	+0.92
	2005/07/30 03:01	+0.63

All SPOT images were processed using commercially available software to yield a geometrically correct perspective with enhanced contrast. Our analysis focuses on the infrared (IR) band of each image, as these data most clearly reveal the contrast in temperatures of land and sea, respectively. From each such IR image, we digitized the position of the shoreline of Waisanding Island, for which the spatial resolution is limited by the resolution of the source SPOT image to *ca.* 20 m, with additional interpolation to 12.5 m. These position data were subsequently analyzed using commercial mapmaking software.

The tide level ranged from −1.12 m to +1.32 m during the time of acquisition of any one satellite image (Table 1). As a result, the actual area of the subaerially exposed island observed at any given time by satellite is a weak function of tidal stage. The SPOT satellite imagery can resolve surface features clearly to 15 m below sea level, including changes in shading and color associated with the change in gradient from relatively flat seafloor to emerging island. We used this capability to delineate the surface area of the whole island to *ca.* 5 m below mean sea level.

In addition to the analysis of sequential satellite images described above, shipborne surveys of the bathymetry and distribution of seafloor sediment immediately offshore of Waisanding Island were conducted during annual cruises in years 1995–1997. These surveys used a GeoAcoustic system composed of a three-channel side-scan sonar combined with a sonar profiler, which has been found to be helpful in relating seafloor echo characteristics and reflectivity to the actual microtopography as well as composition and granulometry of the seafloor sediment (Hong and Chen, 2000; Hong, Huang, and Yu, 2004). The profiling component of our system is based on the multifrequency Chirp profiler (LeBlanc, Panda, and Schock, 1992; Morang, Larson, and Gorman, 1997) and therefore represents a significant technological advance from previous studies of subseafloor structure using single-frequency 3.5-kHz systems (Alexander, Nittrouer, and DeMaster, 1986; Harris *et al.,* 1993; Hong and Chen, 2000; Knebel, 1993; McClennen, 1989; Schwab *et al.,* 1996).

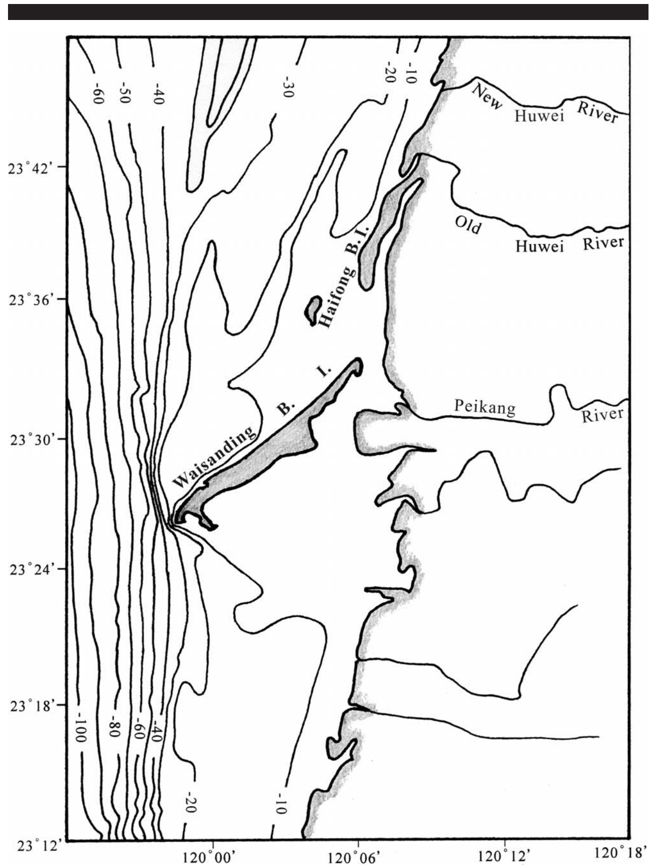

Figure 2. Bathymetry of the study area.

Our seafloor surveys of 1995–1997 were conducted aboard the RV *Ocean Researcher II* and RV *Ocean Researcher III* during the two monsoon seasons of each of the 3 years. Each survey contains continuous, simultaneous seismic profiles, bathymetric profiles (using a 38-kHz Simrad echosounder), and side-scan sonographs obtained along east–west trending tracks spaced *ca.* 800 m, spanning the entire study area, and traversed at approximately 4 knots.

Data appearing in Figure 3 pertaining to records of earthquake activity in west-central Taiwan were acquired from the US Geological Survey NEIC data base (at http://neic.usgs.gov/neis/epic/epic_rect.html). Data appearing in Figure 3 pertaining to records of discharges of water and sediment from west-central Taiwan were acquired from the Water Resources Agency of Taiwan (at http://gweb.wra.gov.tw/wrweb/).

RESULTS

Regional Bathymetry

A new bathymetric map of the region (Figure 2) was generated with the digital sonar data acquired from 1995 through 1997. This chosen interval corresponds to notable, episodic southward migration overall and landward retreat

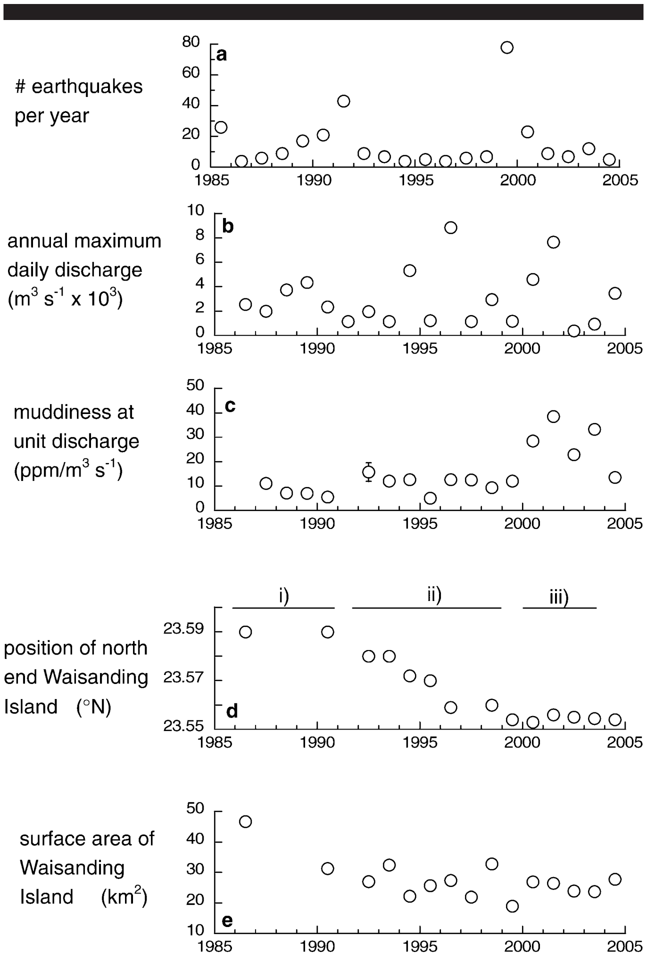

Figure 3. Relevant conditions and position and size of Waisanding Island as functions of time during the period 1987–2005. (a) Seismic activity; (b) maximum daily discharge for each year; (c) sediment concentration of Choshui River at a discharge of 1 $m^3 s^{-1}$; (d) position of north end of Waisanding Island (*cf.* A–D of Figure 1); and (e) surface area of Waisanding Island.

of the head of the island. Further analysis of this data will be reported later in the context of a subaqueous sand ridge observed seaward of the island. As indicated by the map, the seafloor to 20-m depth is a shallow platform with an average slope of about 0.002°. Seaward of the platform margin, west from about 120°E, a slope descends from depths of 30 m to 100 m with an average slope about 0.01°.

Decadal Changes and New, Apparent Stability in the Size and Position of Waisanding Island

In addition to the historical changes noted from charts published during the period 1904–1984 and reported above, we note the following changes in barrier-island form during the period 1986–2006 as indicated by sequential satellite images. From 1986–2000, the northern end of Waisanding Island shifted southward at an average rate approaching 300 m a^{-1}. However, the alongshore migration of the island was episodic (Figure 3d). In 1986, the island was partitioned into three segments, which we refer to here as the northeasternmost 'root' anchored to the coast in the vicinity of Chincheng Port (denoted by letter D in Figure 1), a 'middle' segment, and southwesternmost 'head'.

The subsequent evolution of the island in plan was as follows, where the key historical relationships between tectonics, climate, sediment supply, and the evolution of Waisanding Island are depicted in Figure 3: (i) In 1989–1990, severe storm conditions initiated erosion of the northeastern root of the island. Upon total submergence of this region of the island in 1992, we record a southwestward shift of the island root of 953 m, and a decrease in surface area from 47 km^2 to 27 km^2 from its 1986 position and configuration (*cf.* Figure 3e). These observations represent an apparent continuation of the historical pattern described in an earlier section of this report.

(ii) During the period 1993–1996, and following increased seismic activity in 1991, the Choshui River, at least, exhibited a marked increase in unit discharge of sediment. As a result, the size of Waisanding Island stabilized at a 5-year average of 27 km^2, but progressive erosion of the northeastern tip of the island by wind, waves, and alongshore currents nevertheless resulted in southwestward migration of the island root at an average rate of 804.7 m a^{-1}. After an apparent and brief stasis during 1997–1998, Waisanding Island continued its southwestward migration at a rate of 311.4 m a^{-1} in apparent continuation of historical trends. Overall, during the period 1986–2000 (epochs i and ii), Waisanding Island appeared to rotate counterclockwise at a rate of 67.8 m a^{-1}, evidenced especially by the southeastward retreat of the seaward coast of the island head (Figure 4a).

(iii) After the cataclysmic earthquake activity of 1999, the Choshui and other rivers of west-central Taiwan exhibited as much as a fourfold increase in unit discharge of sediment. Significant floods of 2000 and 2001 resulted in the delivery of significant amounts of sediment to the coastal ocean of west-central Taiwan. We note that these developments are correlated with, for example, the observation that in 2000 the overall southward migration and counterclockwise rotation of the island was arrested and, in 2001, the southwestward migratory trend was reversed by about 350 m. This last observation in 2001 is remarkable given that the west-central coast of Taiwan was traversed by three tropical storms, referred to respectively as Toraji in July, and Nari and Lekima both in September, all of which caused considerable property damage in the region. Subsequent to these storms in the period 2002–2005, Waisanding Island has remained stable in its position (Figure 4b) and has increased in area from 24 km^2 to 31 km^2. Additionally, and anecdotally, we note that the river-mouth bars of the Peikang River have stabilized and grown in areal extent.

DISCUSSION AND CONCLUSION

Waisanding Barrier Island is a natural deposit of sediment delivered by the Choshui and Peikang Rivers to the coastal ocean of west-central Taiwan. The island has exhibited a complex history that, from 1790 through 1984, reflected human influences, including relocation of the Choshui River

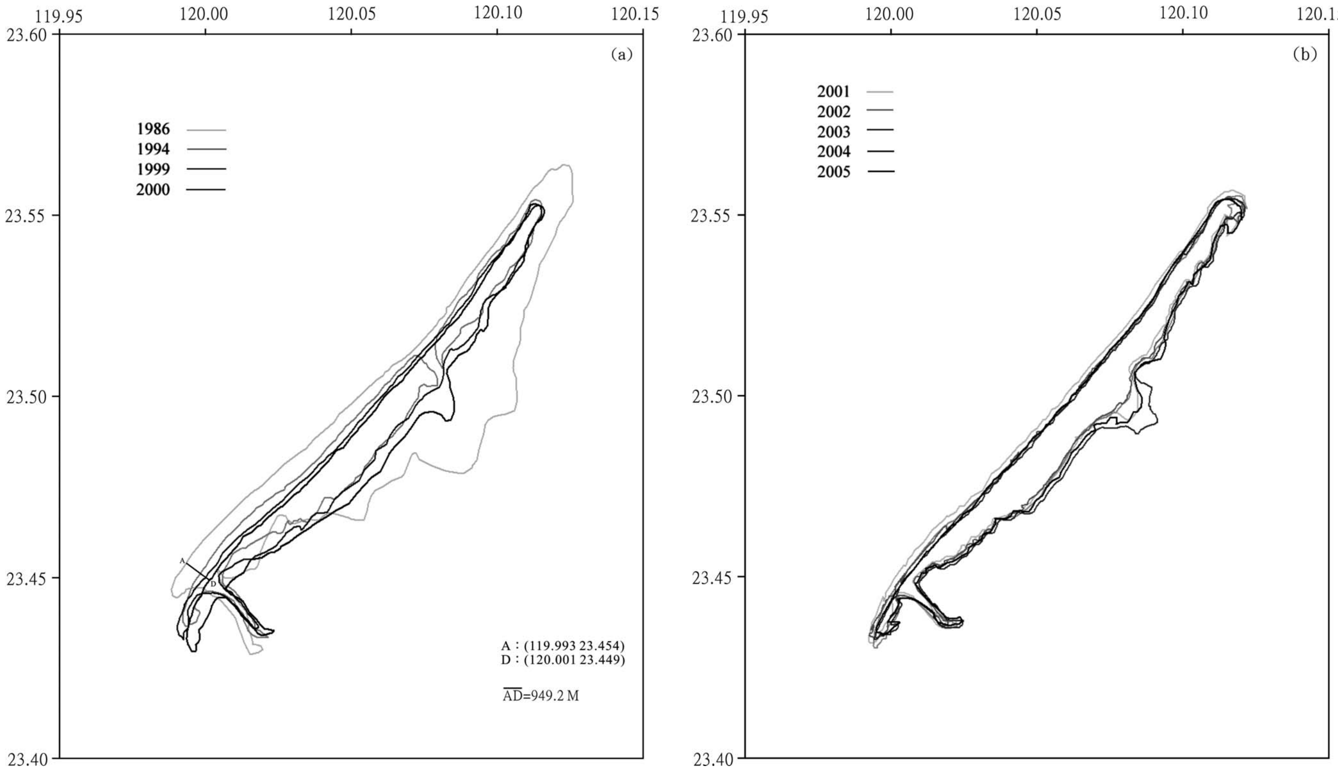

Figure 4. Outlines of Waisanding Island at different times (a) during period 1986–2000, indicating growth in surface area, southwest migration, and counterclockwise rotation of the island. (b) During the period 2001–2005, Waisanding Island remained stable in its position.

channel, dam construction, and sediment impoundment, and development of a coastal industrial complex. Through most of the 20th century, these influences have contributed to, among other things, significant loss of sediment supply to coastal waters and associated contraction, mainland detachment, and southwestward migration of the barrier island. We observe here that minor seismic activity in 1991 and cataclysmic earthquakes and subsequent storms in 1991 and 2000–2001, respectively, resulted in measurable increases in sediment load at unit discharge during recent years. We speculate further, on the basis of compelling correlations in time, that increased rates of sediment delivery to the coastal ocean associated with these tectonic and climatic episodes contributed, respectively, to the stabilization of island size in plan from 1992 onward and the arrest of southwestward migration of the island from 2000 onward.

In ongoing research, we will examine the ideas proposed here regarding whether the recent and intriguing stability of Waisanding Barrier Island, which we attribute here to a combination of recent tectonic and climatic events, is a long-lived development.

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LITERATURE CITED

Alexander, C. R., Jr.; Nittrouer, C. A., and DeMaster D. J., 1986. High-resolution seismic stratigraphy and its sedimentological interpretation on the Amazon continental shelf. *Continental Shelf Research,* 6(1/2), 337–357.

Armitage, S.J.; Botha, G.A.; Duller, G.A.T.; Wintle, A.G.; Rebelo, L.P., and Momade, F.J., 2006. The formation and evolution of the barrier island of Inhaca and Bazaruto, Mozambique. *Geomorphology,* 82, 295–308.

Chang, J.C., 1985. Topographical analysis and landform changes of Choshui plain. *Geographical Research,* 11, 199–228.

Chang, J.C. and Chen, H.L., 2001. Geomorphological changes on coastal plain in southwestern Taiwan. *Western Pacific Earth Sciences,* 1, 107–114.

Dadson, S.J.; Jovius, N.; Chen, H.; Dade, W.B.; Lin, J.C.; Hsu, M.L.; Lin, C.W.; Horng, M.J.; Chen, T.C.; Milliman, J., and Stark, C.P., 2004. Earthquake-triggered increase in sediment delivery from an active mountain belt. *Geology,* 32(8), 733–736.

Harris, P.T.; Baker, E.K.; Cole, A.R., and Short, S.A., 1993. A preliminary study of sedimentation in the tidally dominated Fly River Delta, Gulf of Papua. *Continental Shelf Research,* 13(4), 441–472.

Ho, C.S., 1982. Tectonic Evolution of Taiwan: Explanatory Text for the Tectonic Map of Taiwan. ROC: Ministry of Economic Affairs, 126p.

Hong, E., 1997. Evolution of Pliocene to Pleistocene sedimentary environments in an arc-continent collision zone: evidence from the analysis of lithofacies and ichnofacies in the southwestern foothills of Taiwan. *Journal of Asian Earth Sciences,* 15, 381–392.

Hong, E. and Chen, I.S., 2000. Echo characters and sedimentary processes along a rifting continental margin, northeast of Taiwan. *Continental Shelf Research,* 20, 599–617.

Hong, E.; Huang, T.C., and Yu, H.S., 2004. Morphology and dynamic sedimentology in front of the retreating Tsengwenchi Delta, southwestern Taiwan. *Terrestrial, Atmospheric and Oceanic Sciences,* 15(4), 565–587.

Knebel, H.J., 1993. Sedimentary environments within a glaciated estuarine–inner shelf system: Boston Harbor and Massachusetts Bay. *Marine Geology,* 110, 7–30.

LeBlanc, L.R.; Panda, S., and Schock, S.G., 1992. Sonar attenuation modeling for classification of marine sediments. *Journal of the Acoustical of Society America,* 91(1), 116–126.

Lin, M.C. and Juang, W.J., 1985. A study on shoreline evolution of Waishanding Barrier beach. *Journal of Civil and Hydraulic Engineering,* 12(3), 23–39.

List, J.H.; Jaffe, B.E.; Sallenger, A.H., Jr., and Hansen, M.E., 1997. Bathymetric comparisons adjacent to the Louisiana barrier islands: processes of large-scale change. *Journal of Coastal Research,* 13(3), 670–678.

McBride, R.A. and Byrnes, M.R., 1997. Regional variations in shore response along barrier island systems of the Mississippi River Delta Plain: historical change and future prediction. *Journal of Coastal Research,* 13(3). 628–655.

McClennen, C.E., 1989. Microtopography and surficial sediment patterns in the central Gulf of Marine: a 3.5-kHz survey and interpretation. *Marine Geology,* 89, 69–85.

Milliman, J.D. and Syvitski, J.P.M., 1992. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *Journal of Geology,* 100, 525–544.

Morang, A.; Larson, R., and Gorman, L., 1997. Monitoring the coastal environment: Part III: geophysical and research methods. *Journal of Coastal Research,* 13(4), 1064–1085.

Morton, R.A.; Gibeaut, J.C., and Paine, J.G., 1995. Meso-scale transfer of sand during and after storms: implications for prediction of shoreline movement. *Marine Geology,* 126, 161–179.

Penland, S.; Connor, P.F., Jr.; Beall, A.; Fearnley, S., and Williams, S.J., 2005. Changes in Louisiana's shoreline: 1855–2002. *Journal of Coastal Research,* 44, 7–39.

Schwab, W.C.; Rodriguez, R.W.; Danforth, W.W., and Gowen, M.H., 1996. Sediment distribution on a storm-dominated insular shelf, Luquillo, Pureto Rico, U.S.A. *Journal of Coastal Research.* 12(1), 147–159.

Shih, T.T., 1980. The evolution of coastlines and the development of tidal flats in western Taiwan. *Geographical Research,* 6, 1–36.

Simms, A.R.; Anderson, J.B., and Blum, M., 2006. Barrier-island aggradation via inlet migration: Mustang Island, Texas. *Sedimentary Geology,* 187, 105–125.

Stone, G.W.; Grymes, J.M. III.; Dingler, J.R., and Pepper, D.A., 1997. Overview and significance of hurricanes on the Louisiana Coast, U.S.A. *Journal of Coastal Research,* 13(3), 656–669.

Stone, G.W. and McBride, R.A., 1998. Louisiana Barrier Islands and their importance in wetland protection: forecasting shoreline change and subsequent response of wave climate. *Journal of Coastal Research,* 14(3), 900–915.

Teng, L.S., 1990. Geotectonic evolution of late Cenozoic collision in Taiwan. *Tectonophysics,* 183, 57–76.

Thurman, H.V. and Burton, E.A., 2001. *Introductory Oceanography,* 9th ed. Upper Saddle River, New Jersey: Prentice-Hall, 554p.

Trowbridge, J.H., 1995. A mechanism for the formation and maintenance of shore-oblique sand ridges on storm-dominated shelves. *Journal of Geophysical Research,* 100(C8), 16071–16086.

Wu, C.N.; Peng, M.H., and Hsiao, K.H., 1991. Change analysis of Waisanding Barrier Island. *Remote Sensing,* 15, 1–26.