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Very large subaqueous sand dunes on the upper continental slope in the South China Sea generated by episodic, shoaling deep-water internal solitary waves

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ABSTRACT

Very large subaqueous sand dunes were discovered on the upper continental slope of the northern South China Sea. The dunes were observed along a single 40 km long transect southeast of 21.93°N, 117.53°E on the upper continental slope in water depths of 160 m to 600 m. The sand dunes are composed of fine to medium sand, with amplitudes exceeding 16 m and crest-to-crest wavelengths exceeding 350 m. The dunes' apparent formation mechanism is the world's largest observed internal solitary waves which generate from tidal forcing on the Luzon Ridge on the east side of the South China Sea, propagate west across the deep basin with amplitudes regularly exceeding 100 m, and dissipate extremely large amounts of energy via turbulent interaction with the continental slope, suspending and redistributing the bottom sediment. While subaqueous dunes are found in many locations throughout the world's oceans and coastal zones, these particular dunes appear to be unique for two principal reasons: their location on the upper continental slope (away from the influence of shallow-water tidal forcing, deep basin bottom currents and topographically-amplified canyon flows), and their distinctive formation mechanism (approximately 60 episodic, extremely energetic, large amplitude events each lunar cycle).

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1. Introduction

Subaqueous dunes, or sediment waves, are found throughout the world's oceans and coastal zones (Ashley, 1990; Heezen and Hollister, 1971). They have been surveyed since the 1800s (Jordan, 1962) and studied since the 1950s using modern echosounders (Wynn and Stow, 2002). Locations of sandy deep-water dunes include west of the Canary Islands (Wynn et al., 2000), northwest of the Strait of Gibralter (Heezen and Hollister, 1971) and the South China Sea basin (Damuth, 1980a). Locations of shallow-water dunes include the Fraser River outflow in the St. of Georgia, British Columbia (Mosher and Thomson, 2002), the mouth of the San Francisco Bay (Barnard et al., 2006), the Monterey Submarine Canyon (Xu et al., 2008), La Chapelle Bank 200 km west–southwest of Brest, France (Cartwright and Stride, 1958), the mouth of the Tiber River (Trincardi and Normark, 1988), the northeastern Mediterranean Sea (Ediger et al., 2002), and the Taiwan Strait (Cai et al., 2003). Descriptive overviews, bedform classifications and naming conventions are presented by Heezen and Hollister (1971), Damuth (1980b), Amos and King (1984) and Ashley (1990).

Deep-water dune formation is attributed to downslope-flowing turbidity currents and alongslope-flowing bottom (contour) currents (Wynn and Stow, 2002). Shallow-water dune formation has been attributed to tidally forced currents (Cai et al., 2003), river outflow (Jordan, 1962; Trincardi and Normark, 1988), mesoscale currents (Ediger et al., 2002), atmospheric forces (wind driven currents) (Butman et al., 1979; Cai et al., 2003), tidal lee waves from flow over a sharp shelf break (Cartwright, 1959), internal waves (Butman et al., 1979; Stride and Tucker, 1960), and topographically-amplified internal wave induced currents in canyons at the shelf break (Shepard et al., 1974). An overview of these and other mechanisms is provided by Jordan (1962), Nittrouer and Wright (1994) and Nittrouer et al. (2007).

This paper presents the discovery in the South China Sea of very large subaqueous dunes which appear to be unique in the world's oceans in terms of their placement on the continental slope and their formation by episodic, shoaling deep-water internal solitary waves.

2. Regional setting

The South China Sea is a large, semi-enclosed, tropical, marginal sea, one of several such marginal seas along the western boundary of the Pacific Ocean (Fig. 1). It is bounded by Taiwan to the north, the Philippines to the east and southeast, Borneo to the south, and

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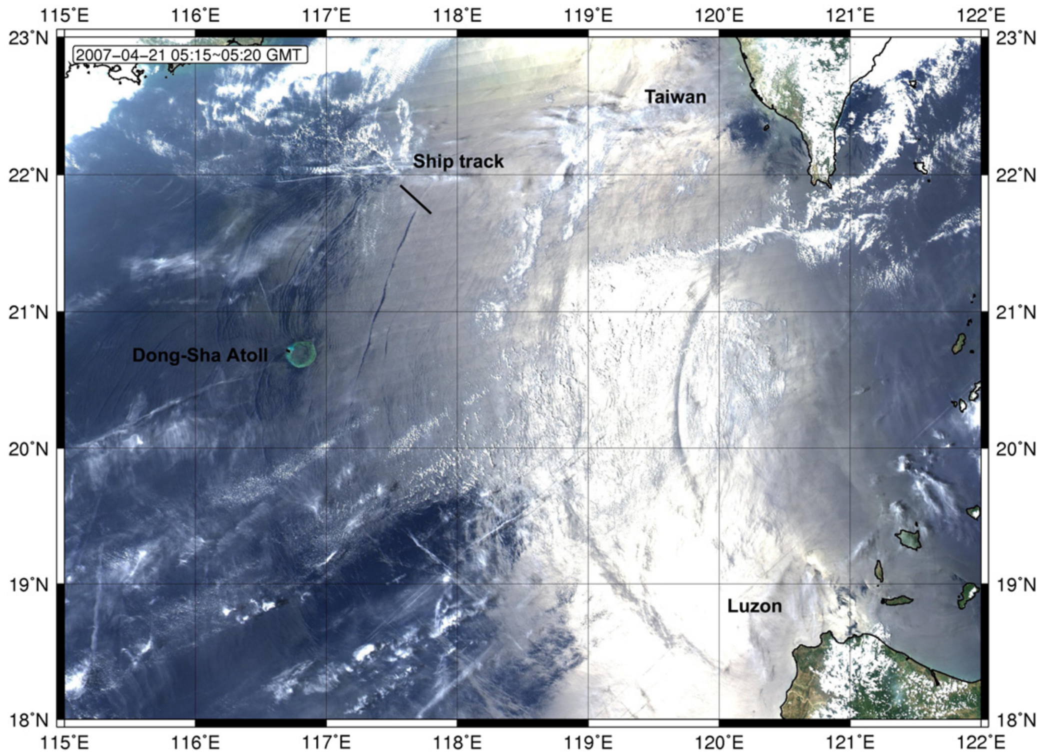

Fig. 1. MODIS image of the northern South China Sea on April 21, 2007 at 0515-0520 GMT. China is to the northwest, Taiwan is to the northeast, Luzon is to the southeast and Dong-Sha Atoll is located at 20.7°N, 117°E. Very large ISWs generated by tidal forcing in the Luzon Strait propagate across the deep basin with an approximate group speed of 3 m/s. The long curved dark bands near 117.5°E, 119°E and 120°E are the surface expressions of the ISWs. The study area is indicated by the solid line.

southeast Asia to the west. Water depths in the deep basin in the northern portion of the South China Sea exceed 4000 m, while portions to the west and south are characterized by expansive shallow-water regions with water depths less than 100 m. An additional distinguishing characteristic of the South China Sea is that it hosts the world's largest observed internal solitary waves (ISW) which generate from tidal forcing on the Luzon Ridge on the east side of the South China Sea, propagate west across the deep basin with amplitudes regularly exceeding 100 m (Ramp et al., 2004), and dissipate extremely large amounts of energy via turbulent interaction with the continental slope (Chang et al., 2006; Lien et al., 2005), suspending and redistributing the bottom sediment. The oceanographic study area is indicated by the solid line in Fig. 1.

3. Materials and methods

Acoustic echosounder systems have long been utilized for the visualization of ISWs (Proni and Apel, 1975; Stride and Tucker, 1960; Warren et al., 2003). During this field experiment, a Simrad EK-500 echosounder system was employed at 38 kHz and 120 kHz. A sub-bottom chirp profiler (Ocean Data Equipment Corporation Bathy 2000), operating at 3.5 kHz, was used to better visualize and estimate the physical dimensions of the dunes. Sediment gravity core and grab equipment was also employed to sample the surficial sediment of the seabed.

4. Results

The bathymetry, along the southeasterly track indicated in Fig. 2, is characterized by a plateau at 115–120 m water depth from 0 to 5 km, a sharp 80 m cliff from 120 m to 200 m at 5–5.5 km, a 2.0° slope from 200 m to 350 m at 5.5–10 km, a 0.3° slope from 350 m to 450 m at 10–30 km, and a 0.65° slope from 450 m to beyond 600 m from 30–45 km.

The water column structure of the ISW (plotted in Fig. 3 using EK-500 echosounder data) whose surface expression appears at 117.5°E in Fig. 1 (at 0515-0520 GMT on April 21) was encountered by

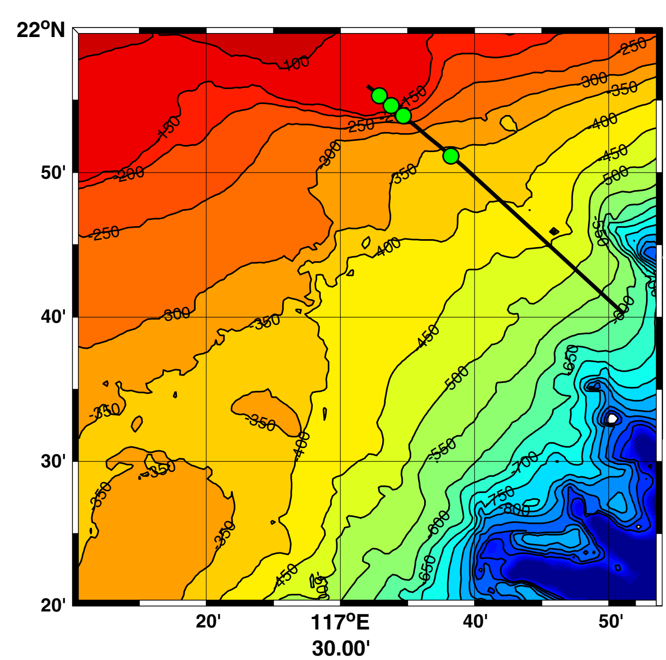

Fig. 2. Bathymetry of the study area, with the acoustic profiling transect (line) and the locations of the sediment grab samples (green circles). (Depth in meters.)