Highstand transport of coastal sand to the deep ocean: A case study from Fraser Island, southeast Australia

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ABSTRACT

Deep-water sands form a new frontier for marine geology and petroleum exploration, but how does sand reach the deep sea? Existing geological models predict that deep-water sands are mainly supplied from rivers during times of low sea level, or by incision of canyons into the shelf to tap river or longshore-transport sand sources. Here, we demonstrate that at high sea level, southeast Australian deep-water sands are delivered by a wave-driven coastal transport system, interacting with estuarine ebb tidal flows, that transports sand over the shelf edge at a change in margin orientation. Discovery of this new process results from an investigation that combines multibeam acoustic, microfaunal, zircon and luminescence dating, oceanographic, Landsat, remotely operated vehicle, and sediment property methods. Our longshore transport–driven model is capable of forecasting new locations for deep-water sand deposits in a predictive paleoclimatic and paleotectonic setting.

Keywords: longshore transport, sea level, Fraser Island, coastal, deep water, sand transport, highstand, sediment.

INTRODUCTION

The most extensive longshore sediment transport system in the world operates on the SE margin of Australia (Fig. 1) and transports sand 1500 km north from the Sydney Basin of New South Wales to the sandy islands of southeast Queensland (Roy and Thom, 1991). These are the largest sand islands in the world, and they have been progressively built from the northward transport of sand for at least 750,000 yr (Tejan-Kella et al., 1990). The largest and northernmost of these, Fraser Island, has accumulated 203 km^3 of mainly quartz sand on an island 124 km long, 16 km wide, with dunes up to 244 m high. However, Fraser Island is currently not increasing in area, and there is no quartz sand on the equivalent part of the continental margin 60 km further north from Fraser Island (Marshall, 1977). This is despite the present-day continuation of a coastal "river of sand" that moves around 500,000 m^3 of sand each year north along the Gold Coast of southern Queensland (Fig. 1) toward Fraser Island (Pattearson and Patterson, 1983). The northward transport of sand clearly ends in the Fraser Island region, but previous research has failed to identify either the character of the longshore transport system terminus, or the fate of the sand currently in the system.

DATA ACQUISITION AND ANALYSIS

To investigate the sediment transport system in the Fraser Island area, we updated the bathymetric chart by first transforming Landsat-4 pixel color values to water depth, resulting in the confirmation of Breaksea Spit, a subaqueous extension of Fraser Island, which extends 30 km north to the edge of the continental shelf (Fig. 1). Results from two research voyages on RV *Southern Surveyor* show that sand transport beyond Fraser Island is first directed northwest under the influence of wave-generated currents. The tide ebbing out of Hervey Bay (the estuary behind Fraser Island) in turn reworks the sand back toward the east. The combination of waves and tides results in the northward elongation of Breaksea Spit until it intersects the edge of the continental shelf. This situation occurs because the Australian coast further south is oriented NE, but north from Brisbane and past Fraser Island, the coastline and the continental margin trend NW in response to continental-margin breakup patterns (Gaina et al., 1998). This geometry is not unique, and a similar trend is observed at Moreton Island, 250 km to the south, at Cap Lopez Spit in Gabon, and it is interpreted to have occurred in the ancient record in the Ormen Lange field, offshore Norway (Smith and Moller, 2003).

Analysis of sediment composition from bottom grab samples shows that quartz-rich sand

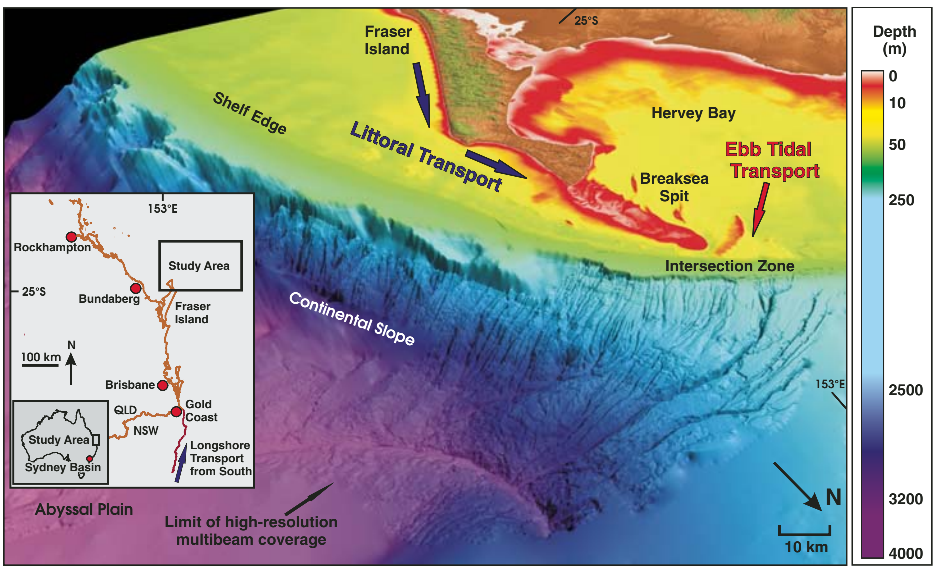

Figure 1. Composite image of seabed north of Fraser Island derived from Landsat data (<30 m depth), regional bathymetry from Royal Australian Navy, and multibeam echo sounding. Colors on legend show depth in meters below sea level. Inset shows location of Fraser Island region and other features in eastern Australia. Image illustrates location of Breaksea Spit extending north from Fraser Island and intersecting shelf edge over a narrow 25-km-wide zone. Blue arrow shows direction of littoral transport on main figure and inset. Red arrow shows tidal sand and bed-form migration out of Hervey Bay toward shelf edge. Note that in index figure, north is oriented upward, but in main figure, north is oriented toward bottom right.

only intersects the edge of the continental shelf in the Breaksea Spit area over a 25-km-wide zone of the shelf edge (intersection zone, Figs. 1, 2, and 3). Farther south, the shelf is dominated by warm- to temperate-water carbonate sediments with exposed seafloor reefs, while further north, tropical carbonates occupy the seabed and subaerial coral reef islands (Marshall, 1977).

Multibeam sonar digital terrain maps (DTMs) from the continental shelf north of Breaksea Spit indicate net sediment transport of quartz sand in large bed forms migrating to the east in response to tidal forcing (Fig. 2). These asymmetrical bed forms are up to 12.5 m high, 650 m long, and have an asymmetry ratio (length of upstream or stoss side to length of downstream or lee side) of 5.2:1. Acoustic Doppler current profiling of the near-bed layer on the shelf shows strong, ebb-dominated (easterly) flows of up to 1.5 m/s. Remotely operated vehicle (ROV) underwater video imagery also indicates active eastward movement of sand on small dunes, 20–50 cm high, superimposed on the larger bed forms. Active dune movement is observed from the continental shelf in 20 m water depth to the upper continental slope in depths of 210 m. DTM imagery of the upper continental slope reveals the presence of 35 submarine gullies up to 300 m wide and 40 m deep, beginning in depths of 150 m (Fig. 2) at the base of a lithified Quaternary carbonate platform. These gullies are only present seaward of the 25-km-wide shelf-edge zone of quartz sand. Bottom photographs show that bed forms migrate into the upslope terminations of the gullies, and bottom grab samples from the gully floors consist of quartz-dominated clastic sand similar to that on Fraser Island and Breaksea Spit.

Together, these data suggest that the quartz sand supplied by the longshore transport system to the Fraser Island area from the south continues north to where Breaksea Spit intersects with the continental margin and is then transported over the carbonate platform shelf edge. To determine the ultimate fate of the sand, and its suitability for constructing continental-margin exploration models, a second *Southern Surveyor* voyage used deep-water multibeam, seismic-reflection, and grab sampling methods to determine the extent of the deep-water supply system and the form of the sand transport seaward from Breaksea Spit. In this study, we surveyed 5360 km^2 of deep ocean floor, from the 20-m-deep shelf edge to the middle of the Tasman Abyssal Plain (Fig. 3) in 4700 m water depth. The combined data (Figs. 3 and 4) show a highly erosional, 20–30-km-wide continental slope with average gradients of 6.5–10°. Incised into the middle-lower slope, there are many submarine canyons that trend from west to east, perpendicular to the continental margin. At the base of the slope, all submarine canyons feed into the Capricorn Sea Valley, which initially runs from north to south, before turning to the SE and continuing across the Tasman Abyssal Plain.

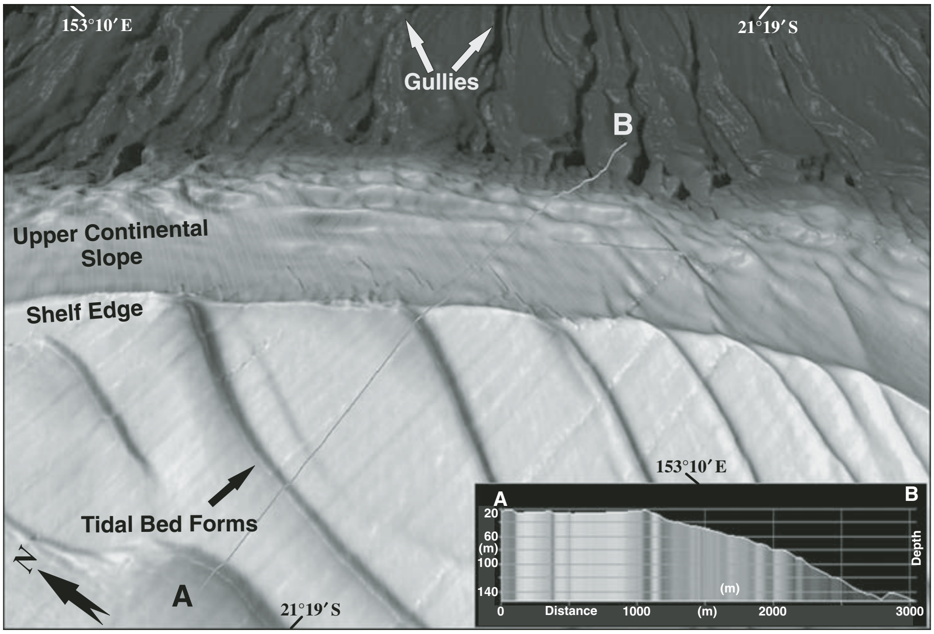

Figure 2. Tidal bed forms migrating eastward out of Hervey Bay, across continental shelf (light shades) and over shelf edge. Note that view is taken directly above shelf break and is oriented looking downslope to east. Sand migrates down upper continental slope and into a network of submarine gullies below 100 m depth (dark gray shades). Inset shows a morphological cross-section A-B across shelf, shelf edge, and upper continental slope. Location of Figure 2 is in Intersection Zone near red tidal transport arrow in Figure 1.

Our deep-water bottom sampling data show the presence of quartz clastic sands only in the bases of submarine canyons seaward of the 25-km-wide shelf-edge intersection zone off northern Breaksea Spit (Figs. 3 and 4). Clastic sand was not present in other canyons, indicating that the sand transport system was utilizing the existing canyons for transport but not creating the canyons. Where clastic sand was present, it was continuous from the upper slope gullies in 150 m depth to the base of the slope at 3500 m depth. Further sampling revealed quartz clastic sand along the floor of the Capricorn Sea Valley to depths of 3920 m, 45 km southeast from Breaksea Spit. Seismic evidence of a continuous thin sediment fill inside levee walls indicates that the quartz sand in the base of the valley continues for a further 120 km into the central Tasman Abyssal Plain in 4700 m depth.

EVIDENCE FOR DEEP-WATER TRANSPORT

To test the hypothesis that the sand in the continental-slope canyons and the Capricorn Sea Valley originated from the East Australian longshore transport system via Fraser Island and Breaksea Spit, we collected evidence from sediment composition and grain size, microfauna, and from dating quartz and zircon tracer grains. Sediment composition in the longshore transport system is distinctive in that it contains more than 90% quartz, with minor heavy minerals. These sands (Table DR1[1]) are dominantly populated by moderately sorted (0.87ϕ standard deviation) fine sands (2.42ϕ mean grain size, >95% sand) with a small silt component (4%) and a low carbonate content (3.5%). Sediments from the 25-km-wide shelf-edge intersection zone, the upper-slope gullies, the continental-slope canyons seaward of the gullies, and the Capricorn Sea Valley all contained more than 90% quartz and were moderately sorted fine to medium sands. Sands from areas outside the canyons, and from canyons not downslope of the 25-km-wide shelf-edge zone, were partly composed of carbonate grains (25%–43%) with a significant to dominant (23%–57%) size component of mud. To determine the age of sand grains in the deep-water transport system, we dated two samples from 190 m and 468 m depth by optically stimulated luminescence (OSL; e.g., Olley et al., 2004) methods; these samples returned zero and 100 ± 70 yr ages, respectively. This indicates that the quartz grains were recently subjected

[1]GSA Data Repository item 2008008, Table DR1 (sediment composition and texture), Table DR2 (foraminiferal biofacies), and Table DR3 (zircon ages of sand samples), is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

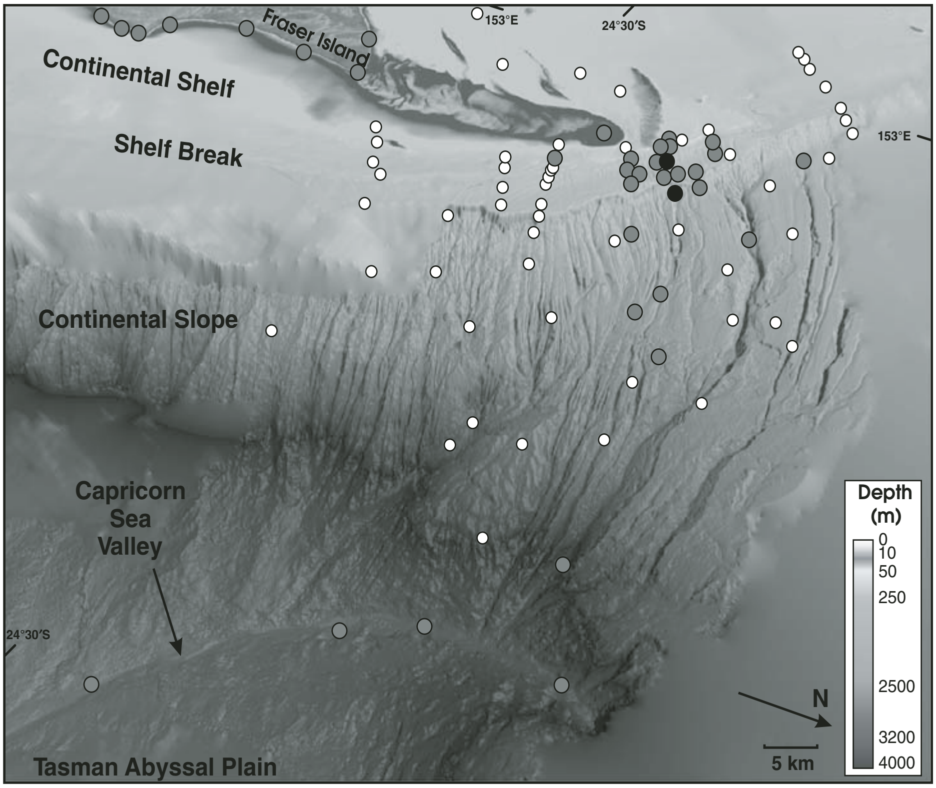

Figure 3. Composite seabed image of continental margin east from Fraser Island and Breaksea Spit and extending down to Tasman Abyssal Plain. Shades in legend show depth in meters below sea level. Location of quartz-rich clastic sands is shown as gray circles while other sediment types are shown as white circles, and quartz-rich optically stimulated luminescence (OSL) samples are shown as black circles. Quartz-rich sands can be traced northward along Fraser Island and Breaksea Spit to shelf-edge intersection zone, down submarine canyons east of this zone, and into Capricorn Sea Valley at base of continental slope.

to shallow-water sunlight exposure and that the sand transport system is active and modern.

Analysis of 62 foraminiferal samples between 24 and 3920 m depth revealed seven distinct depth- and substrate-controlled foraminiferal assemblages (Table DR2, see footnote 1). These consist of predominantly in situ faunas. An additional allochthonous assemblage distinguishes the slope gullies and Capricorn Sea Valley samples. This assemblage is variable in its composition, and additional taxa are added as sediment is transported downward, picking up species along the way. Species diversity in samples along the transport route is relatively high without species dominance. Estuarine and shelf taxa are found abundantly in the deepest samples within the lower-slope gullies and the Capricorn Sea Valley. Degree of test abrasion increases with transport length. Agglutinated, tubular suspension feeders are mainly absent along the route of sediment transport. In one continental-slope canyon location, fresh, intact mangrove roots (*Avicennia marina*) were found mixed with quartz sands and shallow-water foraminifera. These data indicate that shallow-water estuarine and shelf faunal and floral species are being transported over the shelf edge, down submarine canyons, and through the Capricorn Sea Valley. Outside of this transport path, foraminiferal assemblages consist of abundant planktic species and in situ slope and deep-water benthic species (including well-preserved fragile agglutinated foraminifera), indicating lack of transportation and abrasion.

Uranium-lead (U-Pb) dating of zircon grains was conducted on six samples from Fraser Island, Breaksea Spit, and the quartz sand transport pathway on the continental slope and Capricorn Sea Valley (Table DR3, see footnote 1). This method was used to trace a distinctive 500–700 Ma zircon grain population found to originate only in the coastal Sydney Basin of New South Wales, 1000 km to the south of Fraser Island (Sircombe, 1999), which provides a "fingerprint" for the coastal longshore transport system. Sixty grains were counted in each of six samples, and ages ranged from 112 Ma to 3271 Ma. All samples from the beach on Fraser Island, Breaksea Spit, the upper continental slope, canyons on the slope, and the floor of the Capricorn Sea Valley contained the 500–700 Ma zircon grain population. This confirms a source in the Sydney Basin and a continuous transport pathway north to Fraser Island and on to the deep-water Tasman Abyssal Plain. The transport of these sands downslope through this region is supported by evidence of submarine cable breaks in the area seaward of Breaksea Shoal (Hedley, 1911). Cables laid through this area failed in the late nineteenth century, paralleling the famous 1929 cable break event off the Grand Banks, which was a critical event in determining the existence of gravity-driven sediment supply to the deep ocean (Heezen and Ewing, 1952).

DISCUSSION AND IMPLICATIONS

The combined data of sediment composition, texture, foraminiferal assemblages, and ages from coast, continental-shelf, slope, and abyssal plain locations all confirm that a process of modern sand supply from the coastal zone to the deep ocean (Fig. 4) is active on the east Australian coast at the current sea-level highstand (Thom and Roy, 1985). This is a significant change from prevailing sequence stratigraphic models that predict clastic sediment supply to deep water by river systems feeding submarine canyons at low sea level (Posamentier and Vail, 1988) or other mechanisms that require deep-water canyons to traverse the shelf and intercept coastal sand transport (Posamentier and Allen, 1999).

The east Australian combined longshore-tidal transport system is a new way to supply sand to the deep ocean because it is a combination of: (1) texturally and compositionally mature sands that are transported to deep water on an old passive continental margin, across a Quaternary carbonate platform without fluvial processes; (2) sands that are sourced along- (i.e., parallel to) shore and not perpendicular to shore; (3) sands that are supplied by the longshore transport system at a change in orientation of both the coast and the margin at the shelf edge; and (4) tidal currents, which are formed by barrier elongation and estuarine embayment and are a major factor in transporting the sands over the shelf edge. This combination of processes has not been identified elsewhere, although it has some similarities to the submarine canyon sourcing described by Shepard (1973) from southern California. However, the east Australian system provides a contrasting exploration model to southern California, where an active margin supplies immature sands to canyons that extend across the shelf to the modern shoreline.

The implications of this new supply configuration provide a new model for petroleum exploration in deep water settings (e.g., Pettingill and Weimer, 2001) where recent major discoveries have been located (such as the Gulf of Mexico and West Africa; Horn, 2003). The new exploration model predicts petroleum reservoirs to be located in deep-water sands seaward of old passive margins where a persistent climate system

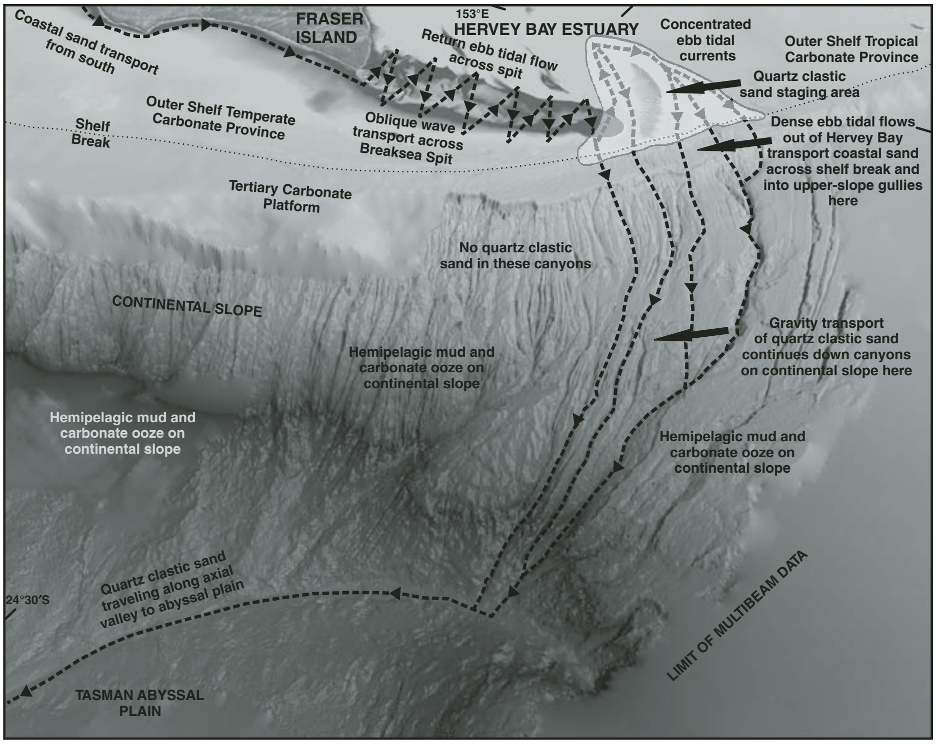

Figure 4. Model for coastal sand transport to deep water in Fraser Island region. Sand is transported by longshore drift from south, past Fraser Island, and it elongates Breaksea Spit by a combination of wave transport to NW followed by tidal transport to east, where it arrives in a triangular "staging area" north of Breaksea Spit. From here, strong ebb-dominated tidal currents transport sand over shelf edge. Gravity processes then continue transport down a series of upper-slope gullies on a Tertiary carbonate platform, along a network of three main submarine canyons on lower slope, and into an axial valley that finally delivers coastal sand onto Tasman Abyssal Plain.

has driven sand alongshore until the coastline intersects a change in structural orientation of the margin. This continental-edge configuration model would be enhanced by the presence of large estuaries that generated strong shelf tidal flows across the sandy coastal system and over the shelf edge.

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