

Southeast Australia: A Cenozoic Continental Margin Dominated by Mass Transport

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Abstract The Southeast Australian continental margin extends for 1,500 km northward from Bass Strait to the Great Barrier Reef. Mass transport dominates the continental slope, which stretches from the shelf break around 150 m depth to the abyssal plain around 4,500 m depth. The continental slope has average slopes of 2.8–8.5° and extends seaward from the shelf break an average distance of 50 km. Margin structure results from Late Cretaceous rifting, producing exposed fault blocks and igneous complexes on the lower slope, and an overlying sediment wedge around 0.5 km thick, centered at the shelf break. Recent collection of multibeam echosounding and high-resolution seismic data provide a detailed view of mass-transport features over a 900 km length of the margin. The features are mostly slab slides, box canyons, and linear canyons. They are ubiquitous along the steep rifted margin, but absent in regions of gentler slopes such as submarine plateaus and failed rift arms. Submarine landslides range in scale from hundreds of small slides of <0.5 km³ volume, up to the largest documented slide of 20 km³. However, potential future slide masses of basement blocks up to 105 km³ have been identified. Cores that penetrated the basal-slide surface show variable sediment accumulation, since the mass-movement event, but four penetrations show

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accumulations of <2 m, and one of <0.6 m. At current accumulation rates, these data indicate that many landslides occurred less than 25 ka, with some as recent as 6 ka. Mass movements appear to follow a pattern of box canyon development exploiting structural trends in pre-rift and syn-rift strata, until the canyon head intersects the toe of the Tertiary sediment wedge. Once this occurs, sediment creep, faulting and failure of the wedge toe migrates up slope, finally reaching the upper slope and Quaternary deltaic depocenters.

Keywords Continental margin • multibeam • mass transport • Southeast Australia • continental slope • submarine landslide

1 Background

The Southeast (SE) Australian continental margin (Boyd et al. 2004) stretches 1,500 km north from Bass Strait ($37^{\circ}30'$ S) to the Great Barrier Reef ($24^{\circ}15'$ S). This passive rifted margin fronts the Tasman Sea, and by world standards is narrow, deep and sediment deficient. The SE Australian shelf is narrow and flat with a thin sediment cover, apart from a Tertiary-Quaternary depocenter up to 500 m thick beneath the shelf break. The shelf break ranges between 55 and 180 m depth, the margin varies from 48–135 km wide, and the base of the margin occurs where the continental rise joins the Tasman Abyssal Plain around the 4,500 m isobath. Cretaceous rifting began around 90 Ma, and Tasman Sea and adjacent margin formation was completed by around 65 Ma. Since then, margin subsidence has been slow and sediment accumulation minor. The margin structure consists first of bed-rock outcrop along most of the coast and inner shelf, and again on the middle to lower continental slope. The middle slope is where Paleozoic fold belt rocks outcrop, adjacent to abundant igneous intrusives associated with Mesozoic-Cenozoic rifting.

Late Quaternary sea-level changes of around 120 m have resulted in the shoreline regressing to a position on the mid to outer shelf off central and southern NSW, (seaward margin of yellow color in Fig. 1), whereas in northern New South Wales (NSW) and SE Queensland, the sea-level lowstand position occurred on the upper slope. A strong south to north wave-driven longshore transport occurs at the shoreline at all sea-level positions, whereas the shelf and slope is impacted by the south-flowing East Australian Current. The coastal hinterland consists of the Paleozoic Lachlan and New England Fold Belts drained to the east by a series of small coastal rivers such as the Hunter and Clarence, with courses less than 250 km long, catchment areas of less than 22,500 km² and suspended sediment yields of less than 750 kilotons/year (OZcoasts 2008). Submarine slope failures on the Southeast Australian margin were first identified by Jenkins and Keene (1992) using widely spaced seismic profiles, supported by bottom photographs of one slide.

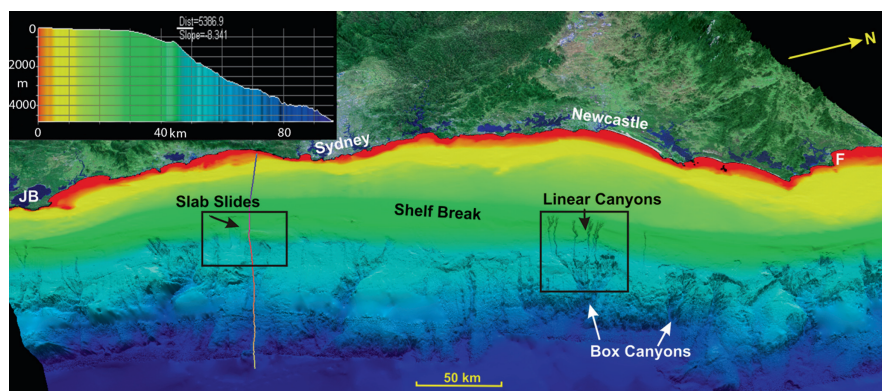


Fig. 1 The Central New South Wales (NSW) margin extends from 35°S at Jervis Bay (JB) to 32°S at Forster (F) and includes clear examples of slab slides, linear canyons and box canyons. Location of Fig. 3 is shown on left box, and Fig. 4 as right box. Profile line extends from shoreline to abyssal plain across the Bulli Slide of Fig. 3, and colors indicate depth scale

2 Methods

Investigation of mass-movement features on the SE Australian margin was conducted mainly by morphological analysis derived from bathymetric surveys, augmented by acoustic backscatter data and geological sampling of grabs, dredges and cores. Deeper subsurface data was derived from high-resolution sub-bottom profiles and lower resolution multichannel seismic data (e.g., Glenn et al. 2008). Bathymetric data used in this study were initially derived from single-beam echosounder data throughout the entire SE Australian margin provided by the Royal Australian Navy, combined with regional data sets including ETOPO2 (Smith and Sandwell 1997). More detailed data from the central NSW and SE Queensland margin were derived from four surveys on the Marine National Facility *Southern Surveyor* (SS12/2008, 10/2006, 1/2005 and 4/2003). These surveys used a *Simrad EM300* multibeam echosounder to acquire bathymetry and acoustic-backscatter data as well as both high and medium resolution seismic-reflection data. Additional deep-water data were incorporated from ship-of-opportunity tracks along the base of the margin, including R/V *Ewing* and *l'Atlante*.

Following data acquisition, raw bathymetric data from all sources was processed and merged to generate integrated data sets extending for the entire 1,500 km of the study area. These marine data sets were then displayed as depth-dependant color maps and given artificial sun illumination in *Fledermaus* software. The final bathymetric product was combined with coastal land digital elevation models that had

been draped with *Landsat* imagery (e.g. Figs. 1 and 2) to generate an integrated morphological model for the coastal and continental margin region of SE Australia. Geological sampling was used to identify sediments and rocks mapped from the geophysical surveys including more than 100 *Smith-Macintyre* grab samples, 20 cores and 25 dredges over the entire region from the 80 to the 4,000 m isobaths.

3 Mass-Movement Features

The SE Australian margin ranges in width from 48 to 135 km from the shoreline to the abyssal plain, which begins around 4,500 m depth. This variation in morphology results from tectonic rifting processes that alternated small continental crustal plateaus with steep rifted segments along the length of the margin (e.g. Fig. 2). The shelf is relatively flat, ranging between 14 and 78 km wide. The continental slope ranges from 28–90 km wide and average slopes range from a minimum of 2.8° on plateaus to a maximum of 8.5° off steeper rifted segments. This steeper continental slope is mantled with finer sediments and has a wide range of mass movement features developed along the entire 1,500 km section from Bass Strait to the Great Barrier Reef. The main mass movement and associated features include: (1) slab slides; (2) debris flows; (3) box canyons; (4) linear canyons; (5) carbonate platform slides; (6) plunge pools; and (7) pockmarks.

3.1 Slab Slides

Slab slides (Figs. 1 and 3) occur in the planar-bedded, seaward dipping, pelagic-hemipelagic carbonate and clastic-mud deposits on the upper slope. The scars are up to 250 m deep, relatively flat based, with steep (up to 15°) linear walls and a steep crown scarp. Large examples such as the Bulli and Shovel slides (Fig. 3) on slopes of around 4.5° are up to 13 km long and 5 km wide, with volumes of up to 20 km^3 . They initiated right from the base of the Tertiary sediment wedge around 1,100 m depth to the upper slope in 400 m depth. In some locations, slab slides have coalesced so that entire depositional packages are missing for distances along slope of 20 km. Several slab slides have linear furrows preserved on their base. These furrows, or grooves, are up to 5 km long, 50 m deep and 300 m wide. Seismic data across slab slides show the sediment is made up of well stratified beds that failed on a bedding plane surface. Five cores that penetrated the basal slide surface had accumulated between 0.6–2.5 m of pelagic carbonate mud since the slide occurred. At average sediment rates for the margin of 0.1 m/1,000 years (Troedson and Davies 2001) these slides appear to have occurred between 6–25 ka.

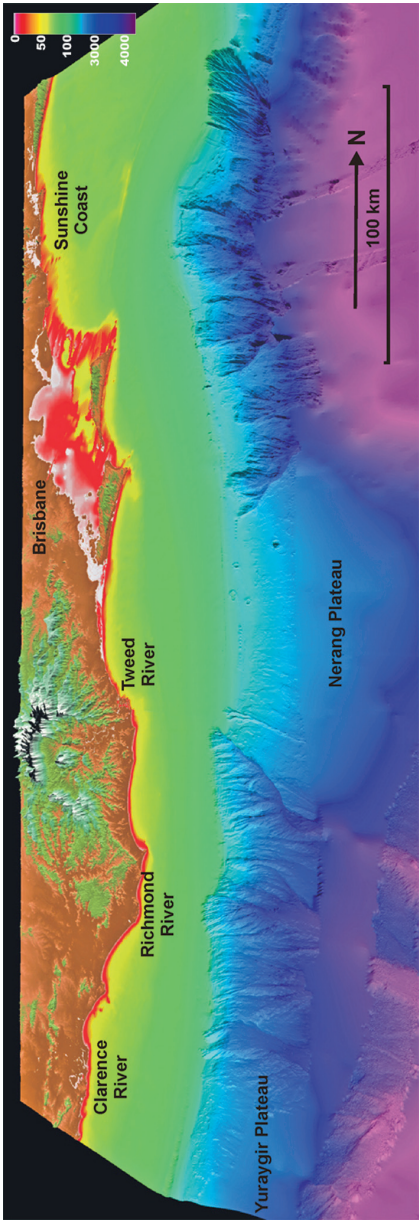


Fig. 2 The SE Queensland margin displays alternation between marginal plateaus (Nerang and Yuraygir Plateau) and steep rifted margin segments. The steep rifted margin segments are dominated by box canyons, while they are absent on the lower gradient plateaus. Box shows location of plunge pools in Fig. 5. Depth key in upper right in m

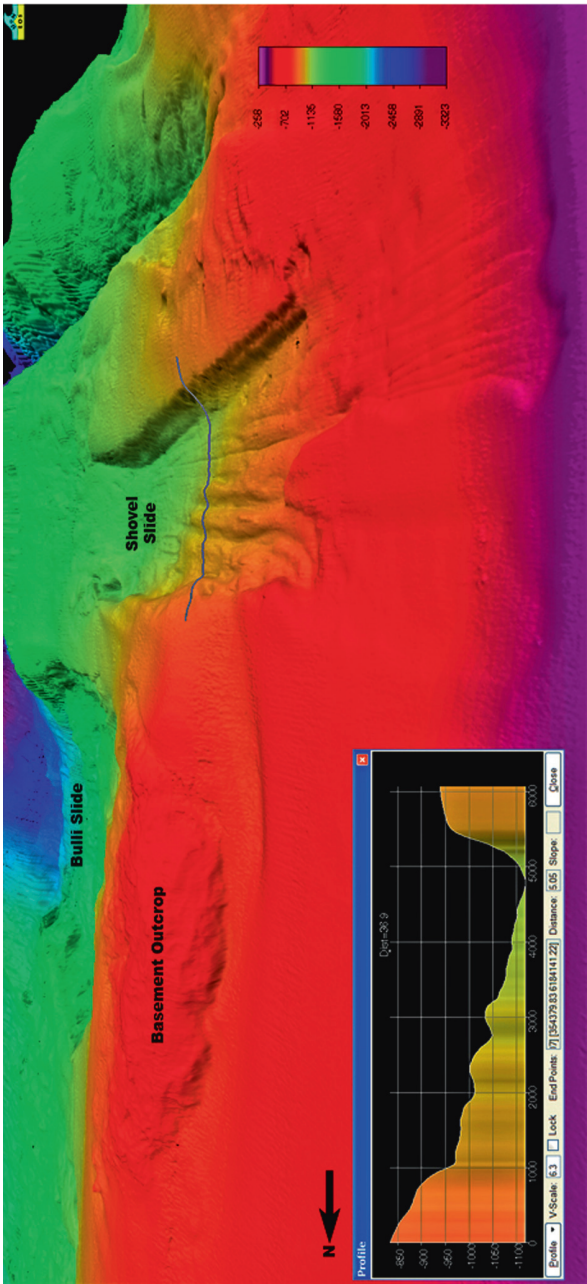


Fig. 3 View looking downslope of two slab slides (*the Shovel Slide, left; and the Bulli Slide, right*). The color bar shows water depth and the cross section shows scale. Note the grooves on the base of the Shovel Slide, the steep linear margin of the slide, and the basement outcrop above the Bulli Slide

3.2 *Debris Flows*

In most locations, slab slides have no sediment derived from the slide visible further down slope, and it appears as if the materials derived from the slide have been transferred to the abyssal plain. However, in a small number of locations, the slides are localized on the upper slope, and their sedimentary deposits are located immediately downslope. In these cases, the slide deposits occur as massive debris flow fields over 10 km² in area. The debris flow deposits spread out in a radial pattern and contain blocks up to 350 m wide and 50 m high. Slopes on which the slab slides deposited debris flows down slope were less steep and averaged 2.5°.

3.3 *Box Canyons*

Box Canyons (Figs. 1 and 4) are large erosional chasms on the lower to middle continental slope that extend to the base of the slope but do not connect upslope to feeder canyons or sediment supply systems. They consist of multiple erosional events, branch upslope into tributary box canyons, usually involve pre-rift basement and synrift basin rocks and may extend retrogressively upslope into the toe of the Tertiary sediment wedge. In terms of volume and extent, box canyons are the dominant erosional feature on the SE Australian margin. The box canyons are abundant along steep rifted margin segments, but poorly developed to absent on the continental plateau segments. Between Bass Strait and the Great Barrier Reef, there are around 46 box canyons, averaging 32 km apart. These erosional mass-movement features average 14 km wide and 680 m deep at the 1,500 m isobath, and frequently have slopes up to 17° on the walls. Box canyons stretch from the middle slope to the abyssal plain and average over 20 km long. Individual canyons have excavated as much as 690 km³ of slope volume and average 220 km³. In local examples, box canyons have coalesced along sections of steep rifted margin such as off Queensland's Sunshine Coast, leaving isolated remnants of mid to lower continental slope bedrock exposed. One example of these remnants occurs off Moreton Island, has a prominent crown crack and a volume of over 100 km³.

3.4 *Linear Canyons*

In a limited number of locations along the margin, mainly low gradient segments of the upper slope and off major river systems such as the Shoalhaven, Hunter and Tweed, are located a set of narrow, linear erosional furrows incised into the Tertiary sediment wedge (e.g. Figs. 1 and 4). There are over 30 linear canyons along the margin, most located in central NSW or off Fraser Island. These linear canyons penetrate up slope to 200 m water depth, just below the shelf break off Newcastle

(Fig. 4). Well developed examples are 800–1,900m wide, 120–320m deep and extend downslope for 14–22 km. Canyon wall slopes are 18–34°, the steepest developed in sediment found on this margin. Linear canyons are only found where slopes are less than 4.5°, and often display tributary rills. Off the Clarence and Richmond Rivers, the tributary rills have coalesced to form a large canyon, suggesting that isolated linear canyons are the early stage of larger, merged canyons.

3.5 Carbonate Platform Slides

The upper continental slope, north from the Clarence River in northern NSW to the Great Barrier Reef, is made up of series of backstepping Tertiary carbonate platforms with steep seaward margins. These steep lithified platform fronts have frequently failed and resulted in rock slides at the seaward margin. In some cases the slides are flanked by regions of the carbonate platform that can be observed to have crown cracks, or to have incipient slides that have partly separated from the platform front, but not yet moved down slope. The lower carbonate platform front is over 250m high seaward of Fraser Island and has slopes of 43° over distances of 500m.

3.6 Plunge Pools

Several of the canyon-channel systems (e.g. Sydney Canyon and off the Richmond River) have features that resemble plunge pools in their distal reaches. The plunge pools are large erosional bowl-shaped depressions and occur at abrupt drop-offs (>35°) with >200m of relief. These depressions are 500 to 1,000m wide in the down-channel direction and are as much as 100m deeper than the adjacent down-channel reach. Several of the plunge pools have a depositional bar across the down-channel side of the depression. The bars are <50m high and typically extend only partway across the channel. In a location seaward of the Richmond River in northern NSW (Fig. 5), multiple plunge pools can be seen, often in the same valley system. These plunge pools appear to be migrating upslope like a waterfall or fluvial knick points.

3.7 Pockmarks

Circular to elongate depressions occur on the upper continental slope, often isolated from other erosional and mass transport features. These depressions are mainly off central NSW and occur as groups on slide surfaces between the tributaries of the Hunter Canyon complex. The largest of the pockmarks is 1 km in diameter and 70m deep (Fig. 4), and they appear to overlie faulting in the underlying basement above Sydney Basin coal measures.

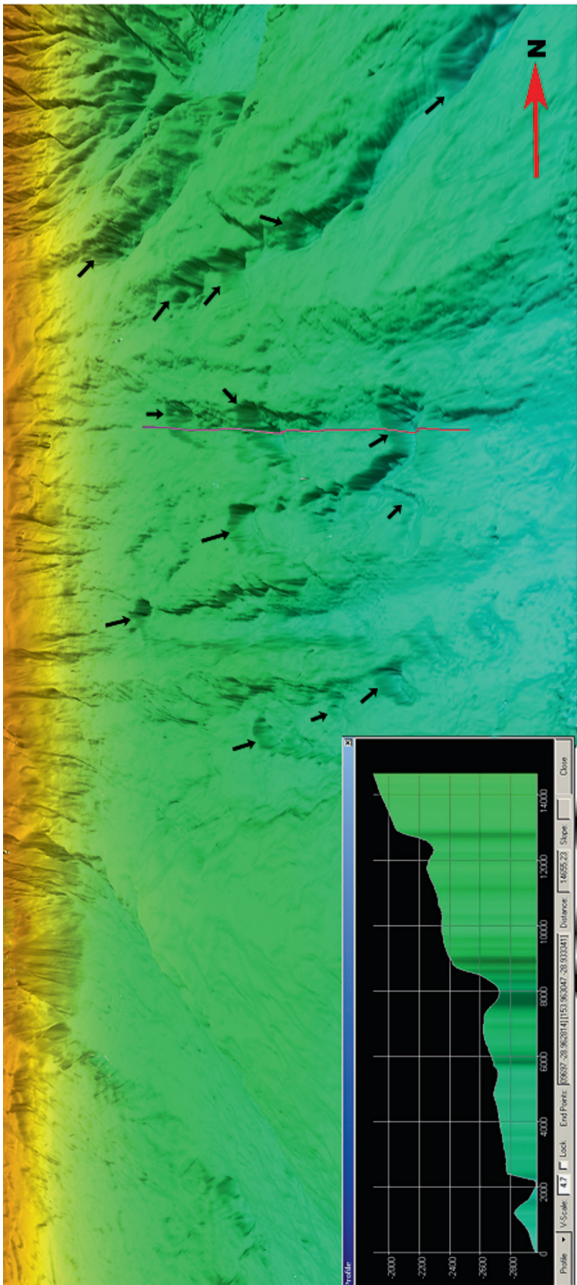


Fig. 5 Middle continental slope between 2,000 and 3,000 m depth off the Richmond River showing extensive development of plunge pools (*arrowed*). A cross section (*scales in m*) shows three plunge pools up to 200 m deep, apparently migrating up slope in the same canyon

4 Discussion

Mass movements on the SE Australian margin are in part due to the steep nature of the margin and its thin sediment cover. Rifting models interpret the SE Australian margin as an upper plate segment buttressed by igneous underplating. The dryness of the Australian continent, the relatively subdued highlands and small rivers combined to allow accumulation of only a minimal sediment cover over the slowly subsiding margin. This combination resulted in the outer shelf and upper slope being covered by a thin sediment wedge, but pre-rift and syn-rift rocks cropping out on the inner shelf and mid to lower slope. These exposed rocks are frequently located on steep slopes, cut by down-to-the-basin normal faults and often expose fault scarps on the lower slope. Over time, these unstable slopes have failed, initiating box canyons that have continued to retrogress up slope and undercut the toe of the Tertiary sediment wedge. This undercutting in turn has made the wedge unstable and initiated slab slides along bedding planes in the wedge. Another long-lasting tectonic influence on the SE Australian margin is shown by the bathymetry at the base of the continental slope conforming to the strike-slip pattern and oblique spreading of the Tasman Sea defined by Gaina et al. (1998). Offsets in the base of slope coincide with fracture zones (e.g. Hill 1992) and the location of major rectilinear canyons (e.g. Sydney and Tweed Canyons). This pattern of offset rifting also produced alternate narrow and steep rifted segments separated by wider marginal plateaus and basins (Fig. 2). Examples of wider margins are off the Queensland Gold Coast (the Nerang Plateau) and off the southern Clarence Moreton Basin (the Yuraygir Plateau). In these locations, the lower slopes of 1–2.5° inhibited the formation of box canyons. The result is a wide zone of thin slab slides generating a morphology of “creepy topography” formed from the coalescence of small slab slides for distances of up to 110 km along the margin without intervening canyons.

Gravity-driven mass transport processes are intensified in locations where slopes are over-steepened (e.g. Fig. 3). This often occurs seaward of igneous intrusives that are common along the margin, and exposed faulted basement blocks (Glenn et al. 2008). Other areas of steeper slopes combined with more recent local sedimentation are on the upper slope, seaward of major river systems. These locations are not steep enough to initiate slab slides but instead generate linear canyons that retrogress upslope through prodelta and delta front deposits. The causes of these retrogressive canyon heads in the delta deposits, currently occurring at 200–300 m water depth, are unlikely to be related to Late Quaternary sea-level lowstands, and therefore relatively little terrigenous clastic sediment has been transported to the shelf edge in recent times.

Another location of increased slopes occurs at the front of the sub-tropical carbonate platforms. Unsupported on slopes as great as 45°, the front of these platforms has failed along much of the margin where it is not buried by more recent sediment. Although relatively young, and occurring at shallow depths of 200–400 m, the carbonate platforms are lithified and fail as large blocks, sliding down onto the mid slope.

Plunge pools along continental margins have been described from multibeam data from the California and New Jersey continental margins (Lee et al. 2002), the Gulf of Alaska continental margin (Mayer et al. 2005) and the West Florida Escarpment (Gardner, J., unpublished). In all the cases, plunge pools occur where there has been an abrupt decrease in slope, suggesting excavation by a high-momentum, sediment-laden density flow. The bars suggest deposition downstream from a hydraulic jump within a sediment-laden density flow. These are presumably eroded by sediment-loaded flows as they cascade over a nick point similar to waterfalls on land. This indicates the erosive power of intermittent catastrophic flows in shaping canyons on the lower slope. Pockmarks on the central NSW coast are best explained by gas or fluid escape from gas-prone source rocks in the underlying Permian coal measures.

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