East Australian marine abrasion surface

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Abstract: Almost one-third of the seabed off the coastline north and south of Sydney comprises a planated bedrock surface, evident from sidescan surveys over the inner continental shelf. In seismic records, this rock surface extends up to 23 km offshore from the sea cliffs along 300 km of the coast. The rock surface dips offshore to as much as 180 m below sea level, where it merges with a major unconformity in the shelf sediment wedge. The surface is eroded into Mesozoic and Palaeozoic rocks and is heavily dissected by sediment-filled, palaeo-valley incision and structural jointing. The sediment-fills comprise sand wedges that thicken landwards to form beaches and estuarine flood-tide deltas, respectively, in smaller and larger palaeo-valleys incised to below present sea level. At the base of the cliffs, the planated surface is buried by shelf sand bodies up to 30 m thick in places. The seaward edge of the surface is everywhere buried by the onlapping continental-shelf sediment wedge. The contiguity of the abrasion surface with the unconformity in the shelf sediment wedge suggests that marine planation began in the Mid-Oligocene, indicating time-average rates of gross cliff retreat at about 1 mm a^{-1}.

Coastal cliffs are one the most striking geomorphological features in southeastern Australia (Fig. 1a). The submarine abrasion surface created by retreat of these cliffs is even more striking (Fig. 1b). The cliffs are fringed by rock platforms and provide a scenic backdrop to the extensive headland and bay coastline of southeastern Australia. These cliffs range in height from 20 to 110 m above sea level and are cut into both horizontal and folded sedimentary rocks of Palaeozoic and Mesozoic age. Whereas considerable attention has been given to developing models for the evolution of Quaternary depositional systems and landform origins of embayments and offshore (Roy *et al.* 1994), there has been less effort in understanding the age and formation of the rocky coast and rock-bound offshore areas (Langford-Smith & Thom 1969). Over the last decade or so, seismic and other data have provided insights into the geological and geomorphological character of the continental shelf. These data offer new opportunities for deciphering the evolutionary history of the cliffs and offshore bedrock surface formed in rocks of varying lithology, structure and age that predate the formation of the continental margin.

Various studies have noted the division of the continental shelf of this region into an outer-shelf sediment wedge and an inner–middle shelf, which appears to have a veneer of mobile sediments over a rocky substrate (Davies 1975; Jones & Kudrass 1982; Jones *et al.* 1982; Roy *et al.* 1994). The shelf break off the Sydney coast occurs at depths of 150–160 m and is 30–50 km offshore. More detailed divisions of shelf morphologies and sediment features have been outlined by Boyd *et al.* (2004). However, the distinction between the outer prograding wedge and the inner and more gently sloping mid-shelf surfaces is fundamental to the focus of this paper.

In his recent textbook *Coasts*, Woodroffe (2002, p. 151) stated:

> Erosion of rocky coasts over sufficient time can form a near-horizontal submarine platform. For example, there is an abrasion surface, which is of the order of 1000 km long and 10 km wide along the east Australian coast, reflecting the concentration of wave energy along this coastline since the Miocene.

Thom and Cowell (2005, p. 252), in commenting further on this apparent feature, noted:

> On the east coast, the narrow continental shelf has been subjected to slow marginal subsidence. This has facilitated two geomorphic outcomes: shelf edge accretion of a sediment wedge ca. 500 m in thickness, and an inner-shelf abrasion surface ... (The East Australian Marine Abrasion Surface) ... [which] is now veneered with Late Quaternary sediments and is entrenched by infilled paleo-valleys carved by rivers draining to lower sea levels.

The abrasion surface referred to by these researchers has been revealed in sidescan sonar, multibeam and bathymetric surveys, together with some bottom sampling and shallow coring at selected locations (Fig. 2). The surveys show considerable geomorphological variability on the continental shelf, but include extensive evidence that a planar bedrock surface underlies or crops out on many parts of the inner shelf down to depths of generally more than

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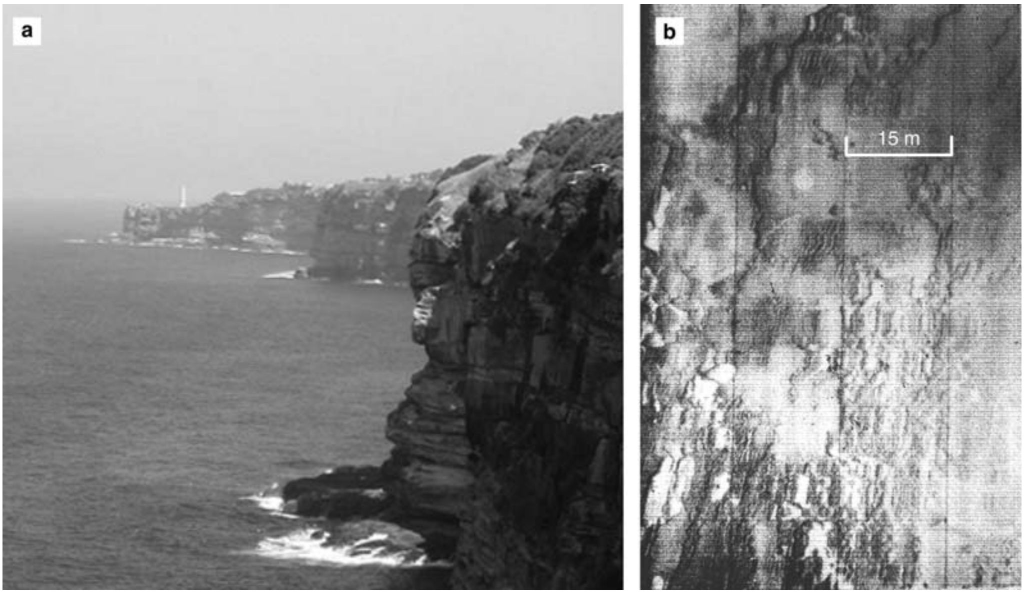

Fig. 1. Marine erosion features on the Sydney coast: (**a**) cliffs and modern rock platforms along the coast immediately south of Sydney Harbour; (**b**) sidescan-sonar image of abrasion surface cut into block jointed bedrock offshore from the cliffs shown in (**a**), in 40 m water depth.

120 m, and to almost 190 m in some places. This was tantalizingly suggested in a seismic section published by Roy (1998, fig. 25.12), but also indicated in earlier reports of the Bureau of Mineral Resources (see Davies 1975, 1979). The purpose of this paper is to show evidence for the abrasion surface that lies seaward of the cliffs and embayments of the coast of central NSW (Fig. 1) and to discuss its likely origin.

Continental margin and coastal setting

The principal geomorphological features in the east Australian margin of the Tasman Sea were formed during rifting and thinning of the continental crust in the Late Cretaceous between 110 and 80 Ma ago (Gaina *et al.* 1998; Persano *et al.* 2005). This was followed by a period of sea-floor spreading with the formation of new basaltic ocean crust, which continued until *c.* 52 Ma, as determined by magnetic anomalies (Ringis 1972; Hayes & Ringis 1973; Gaina *et al.* 1998). Sea-floor spreading created the Tasman Sea ocean basin and associated failed-rift troughs, ridges and plateaux. The basic first-order geomorphology of the present continental margin, including the development of drainage basins, shelf-edge sedimentation and shelf-slope erosion, began to develop after the cessation of sea-floor spreading and subsidence, although its progressive evolution has been punctuated by periodic intraplate volcanism (Keene *et al.* 2008). It is possible that the continental-shelf edge in its present configuration could be as young as early Eocene, although magnetic anomalies date the age of the oceanic–continental crust boundary, at the base of the continental slope, at 80–60 Ma offshore of southern and central New South Wales (Gaina *et al.* 1998).

The eastern Australian continental margin and the Lord Howe Rise can be regarded as passive margins, which, we hypothesize, have been subsiding to current depths since rifting ceased, perhaps since the early Eocene. The rates and timing of subsidence must be viewed in the context of global eustatic sea-level movements. Drilling on the Rise and dredging of sediments suggest open marine shelf conditions in deeper parts of these margins with little terrigenous input for the last 60 Ma or so (Burns *et al.* 1973; Quilty *et al.* 1997).

The terrestrial landscape of the eastern continental margin was once viewed as reflecting the imprint of river incision following uplift in the Late Tertiary (Browne 1969). Over the past 30 years detailed geomorphological studies complemented by thermochronometry and radiometric dating of basalts occupying valley floors have revealed a much more ancient landscape, which may be traced back to the Mesozoic (Bishop & Goldrick 2000; Persano *et al.* 2005). There should be a linkage between terrestrial tectonics, landform genesis, opening of the Tasman

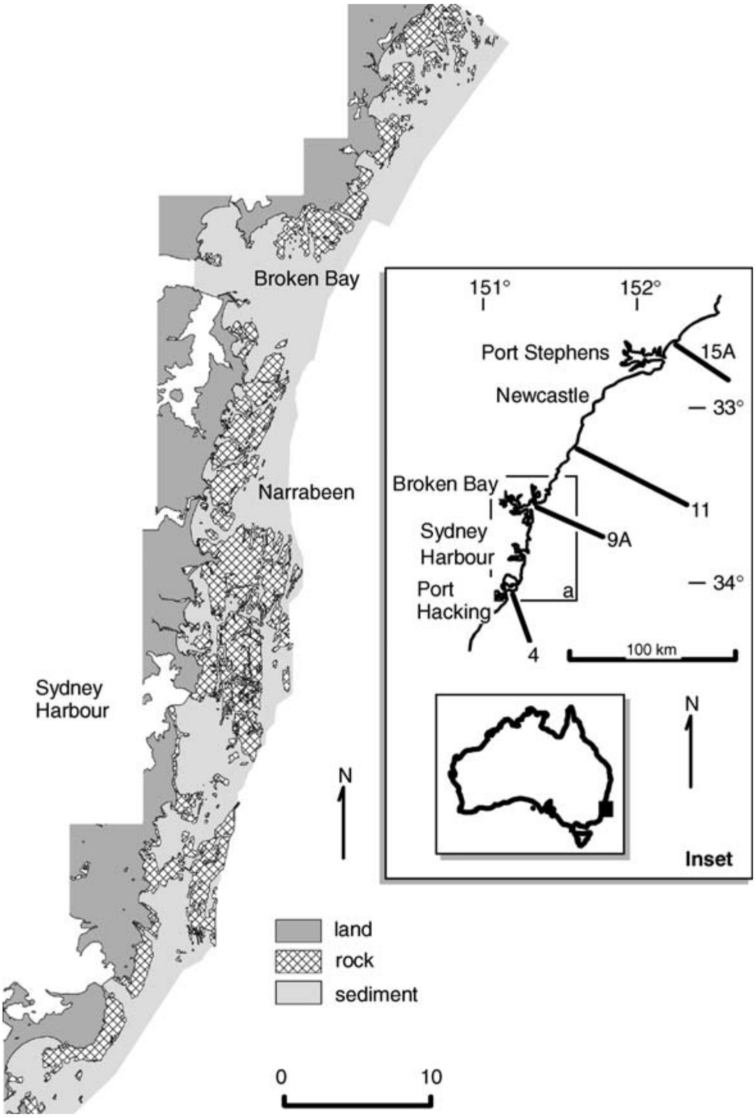

Fig. 2. Seabed rock and sediment surfaces in sidescan-sonar surveys (digitized from maps documented by Gordon & Hoffman 1986), locations of places referred to in the text, and (inset) seismic lines from surveys conducted by Geoscience Australia, The University of Sydney, and the NSW Department of Mineral Resources (Heggie *et al.* 1992).

Sea, asymmetric rifting processes, and subsequent volcanism, in relation to evolution of the continental shelf and slope (Roy & Thom 1991). We show below that incision of river valleys into this ancient landscape continues onto the continental shelf, with truncated and cliffed interfluves of ancient drainage lines forming many of the headlands and cliffs of this coast (Bishop & Cowell 1997). Is it possible to go one step further and demonstrate a continuum between fluvial denudation on the subaerially exposed rock surfaces of the eastern highlands, with the formation of valleys and ridges extending seawards, and the marine denudation of rock surfaces that are subjected to progressive submergence on the subsiding continental margin? This paper aims to answer that question.

Marine abrasion surfaces: an enigma?

The theory of marine planation resulting from processes of marine abrasion has a long and chequered history. Ramsay (1846) contested the marine-valley hypothesis of Lyell in his study of planation surfaces in Wales, and established a paradigm that was readily accepted by many coastal geomorphologists, especially in Great Britain (see Chorley *et al.* 1964, Chapter 16). Many of the classical studies in 19th and early 20th century geomorphology accepted marine planation as a powerful process in carving surfaces across rocks of different lithologies. Aspects of marine and subaerial denudation were discussed by Davis (1896), and various studies were reviewed by Cotton (1974*a*) and Dietz (1963). Woodroffe (2002, Chapter 4) has recently reviewed the literature on the polycyclic and polygenetic character of rocky coasts. Trenhaile (1989) more specifically reviewed ideas on marine planation in the context of models for polycyclic development of abrasion surfaces. He differentiated earlier theories as involving either submarine erosion or shore platform development near and at sea level. Significantly for our paper, Trenhaile's own work emphasized the diachronous formation of a residual surface as a polycyclic process during repeated fluctuations in relative sea level commensurate with Pleistocene eustatic cycles. Trenhaile's polycyclic processes relate to erosion of friable bedrock on the Pleistocene time scale (of the order of 10^5–10^6 years), whereas we consider the evidence for similar processes in southeastern Australia operating in more resistant sedimentary rocks on time scales of 10^7 years.

Arguably the most powerful proponent for marine planation in the classical literature was Johnson (1919). He developed theoretical models for submarine planation based on the concept of a profile of equilibrium under conditions of stable sea level. From his perspective, marine erosion, given sufficient time, will eventually destroy an island or even a land mass of considerable size (see Johnson 1919, figs 35 and 40; amended by Cotton 1974*a*). The result will be a submarine abraded surface little above local level of wave base. He stated that 'careful analysis of the process of marine erosion must lead to the conclusion that marine planation is possible without coastal subsidence' (Johnson 1919, p. 235). He cited examples where he thought this condition might apply. Cotton (1974*a*, *b*) was critical of Johnson's reasoning, especially in the light of what he considered to be the submergence history of submerged surfaces and sea-level oscillations.

Although some marine-planation surfaces on land have been reinterpreted as the product of subaerial processes, there remains the likelihood that rock-bound surfaces surrounding or capping basaltic tropical and subtropical islands are the result of marine abrasion (Woodroffe 2002, pp. 151–152). Along the Lord Howe Rise there are truncated seamounts forming flat-topped guyots and volcanic island peaks, remnants of once sizeable, subsiding island masses. Fraser Guyot in the northern Tasman Sea has significant terraces on its flanks formed in basalt now at depths of 1030 and 1350 m (Exon *et al.* 2005, 2006). There are also examples of apparently 'wave-cut' terraces on uplifted coasts (see Ota 1986). At higher latitudes, including areas of glacial rebound, there are many instances of shore platforms cutting across various rock types (Hansom 1983).

On passive continental margins, the existence of marine planation surfaces is less well established. Even Johnson (1925), in his regional study of the New England coast, was sceptical. However, Zenkovich (1967) and others have cited evidence from subsurface data. Widespread seismic and drilling programmes have subsequently given more emphasis to the constructional nature of shelves. Where a passive margin has received relatively little sediment in the Cenozoic, and is subsiding, it may be possible that, given sufficient time, marine abrasion processes may truncate bedrock. Oscillations of sea level should enhance these processes, as demonstrated numerically by Trenhaile (1989) for Pleistocene eustatic cycles (see Roy & Thom 1991, fig. 5, for sea-level oscillations during the Cenozoic in relation to different rates of margin subsidence). Also, where such processes are continuing to truncate submerging interfluves, the resulting coastal morphology of today will be the cliffed headlands and infilled embayments of the SE coast of Australia (Bishop & Cowell 1997).

SE coast inner and mid-continental shelf

Although inner and outer sections of the continental shelf of SE Australia have been subjected to seismic surveys over the last 30 years, very little of this information has been published. However, some reports have indicated the existence of a shallow basement surface underlying the inner shelf (Davies 1975; Jones *et al.* 1982; Albani *et al.* 1988; Heggie *et al.* 1992; Roy 1998). There is no deep drilling on the continental shelf between latitude 28 and 40 °S. For the purposes of this study, seismic and sidescan-sonar data on the inner shelf were analysed over a 300 km stretch of shelf from south of Sydney to north of Newcastle (Fig. 2). Over this stretch of coast considerable work has been done, and is continuing, on the sediment history of surficial 'drowned' barrier deposits and lobate shelf sand bodies (Albani *et al.* 1988; Roy *et al.* 1994; Boyd *et al.* 2004). These features are Late Quaternary in age and constitute a record of sea-level change through the glacial–interglacial cycles. They are being variously reworked by contemporary inner and mid-shelf wave and current processes.

In 1992 a cruise was conducted as a joint project with Geoscience Australia, The University of Sydney, and the NSW Department of Mineral Resources (Heggie *et al.* 1992). Several seismic lines from that cruise will be illustrated here. The seismic records were collected as single channel using a 120 cubic inch airgun. Detailed information is lacking on surficial sediments because of the resolution of the system.

Profile line 4 starts in 40 m of water offshore Port Hacking. It shows clearly that the outer-shelf sediment wedge thins landwards to 80 m water depth (Fig. 3). Bedrock with a thin veneer of sediment extends towards the shore with an average slope of 0.7° between −80 and −40 m. This forms the more steeply sloping inner shelf. Flat basement rocks are truncated to form an erosion surface that extends beneath the onlapping sediments at −80 m. Buried valleys exist seaward of this and beneath two prominent planar erosion surfaces. These surfaces are seen as reflectors in the profile and were called S1 (upper) and S2 (lower) by Davies (1975). The floor of the most seaward and largest valley is *c.* 250 m below present sea level.

Profile line 9A runs SE from Broken Bay (Fig. 4). It starts in a water depth of 40 m with a thin veneer of sediment overlying valley fills with at least 50 m relief. These are the palaeo-Hawkesbury channels, which extend seaward from the cliffed headlands at Broken Bay (see Albani *et al.* 1988) and include incised Late Pleistocene and, perhaps, Late Tertiary fill in the incised bedrock valley, as documented further upstream by Roy (1983). Figure 4 shows that fill in some of these channels has been truncated between 65 and 45 m water depths. On the mid-shelf, the basement-erosion surface is relatively flat and inclined seaward. The exact thickness of the sediment cover on the mid-shelf between 60 and 120 m is difficult to determine from the relatively low resolution of the airgun data. The outer shelf forms a prograding sediment wedge at −120 m below present sea level and extends over the shelf break at −150 m and wedges out between −1000 and −1500 m.

Profile line 11 starts at −38 m off Norah Head (Fig. 5). Landward tilted rocks of the Triassic–Permian Sydney Basin are truncated by a relatively flat unconformity that either crops out on the inner and mid-shelf or is covered with only a thin veneer of sediment. Here there are no valleys cut into this surface on the inner or mid-shelf, but they are present buried beneath the sediment wedge on the outer shelf below 120 m water depth.

Profile line 15A runs SE and shore normal to the headlands north of Port Stephens starting in 27 m of water (Fig. 6). The eroded basement surface has low relief of 10 m or less over a distance of *c.* 10 km along the length of the profile. It is seaward dipping until 100 m water depth, where it is onlapped by the outer shelf wedge. Beneath the wedge the basement reflector outlines eroded valleys. Off Newcastle and the Hunter River to the south of line 15A, other seismic data from Heggie *et al.* (1992) show the sediment wedge extending further onto the inner shelf but still overlying an eroded basement that slopes seaward. A major broad valley is buried beneath the sediment wedge at 122 m water depth. The floor of this valley is *c.* 250 m below present sea level.

Sidescan sonar, bathymetric, shallow-sampling and seismic data, collected by the then NSW Public Works Department (Gordon & Hoffman 1989) between Port Hacking in the south to Broken Bay (Fig. 2), reveal extensive outcrops of rock on the inner continental shelf. These outcrops extend to water depths of 50–80 m and are most pronounced and continuous off cliffed headlands (Gordon & Hoffman 1986; Albani *et al.* 1988; Albani & Rickwood 2000). The data were assembled into

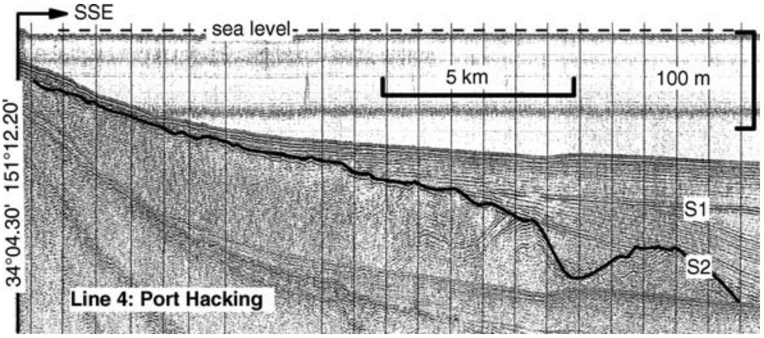

Fig. 3. Seismic profile off Port Hacking (part of Line 4, Fig. 2b).

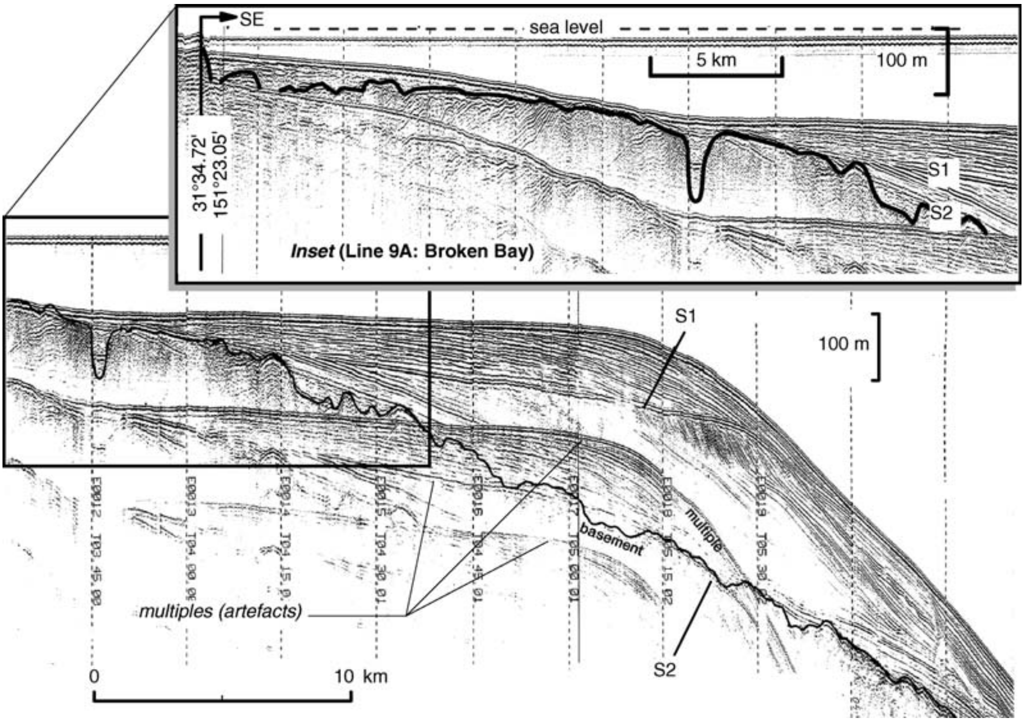

Fig. 4. Continental-shelf and continental-slope sediment wedge in seismic profile off Broken Bay (Line 9A, Fig. 2b).

a series of map sheets at a scale of 1:25 000 (Gordon & Hoffman 1989), which we digitized and integrated in ArcGIS (Fig. 2) for quantitative analysis. This analysis shows a total of 468 regions of rock outcrop on the inner shelf, collectively covering 150 km^2 within the region covered by the dataset. The sand surface is divided by the exposed rock into 251 separate compartments, with a combined coverage of 315 km^2. The rock outcrops thus make up 32% of the total area covered by the sidescan-sonar surveys. This proportion of rock is less than might be expected from the subaerial dominance of sea cliffs, which form roughly 70% of the coastline. The lower proportion of rock area on the inner shelf is attributable to the existence of overlying sand bodies off the headlands (Roy *et al.* 1994), especially along the south Sydney coast (Cowell 1986).

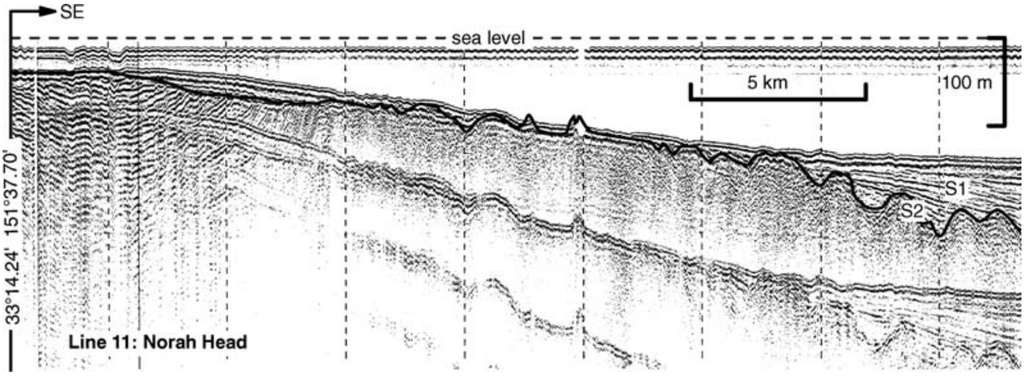

Fig. 5. Seismic profile off Norah Head (part of Line 11, Fig. 2b).

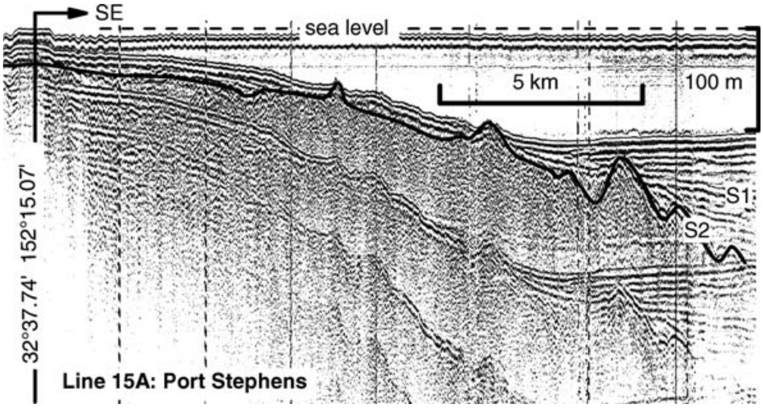

Fig. 6. Seismic profile off headlands north of Port Stephens (part of Line 15A, Fig. 2b).

Albani *et al.* (1988) used the data to define palaeo-drainage channels on the continental shelf as well as to describe the surface sediment characteristics (see also Gordon & Hoffman 1986). They also noted the existence of dissected plateaux carved into bedrock on the inner shelf, but did not discuss the geomorphological significance of these surfaces. These features are evident in the surface pattern of rock outcrops (Fig. 2), more clearly illustrated when focusing a more limited stretch of this coast (Fig. 7). The sediment fills evident in this illustration expand in proximity to the beaches, not because the width of the channels themselves increases, but because the sediment fill thickens to form bay barriers on which the beaches occur. Elsewhere, the landward thickening sand wedges form flood-tide deltas in entrance of the larger, drowned valley estuaries (Fig. 2). A network of palaeo-valley tributaries trending seaward is apparent between rock outcrops off Narrabeen Beach (Fig. 7). Connected sand filaments roughly perpendicular to the channel fills are probably indicative of joint planes enlarged through weathering and erosion during periods of subaerial exposure. Rectilinear structural patterns are typical of the regional lithology, and location of the palaeo-valleys is probably controlled by this structural grain (Bishop & Cowell 1997).

The depth contours derived from the sidescan-sonar dataset generally show a lack of marked deflection where they cross from regions of rock to sand, indicating that the rock is, like the sand, fairly planar in its surface geometry (see 40 m contour in Fig. 7). The general conformity of the sediment and rock surfaces is also evident in the presence of sand patches within the regions of rock outcrop (Fig. 1b). Patches of coarse sand are visible on the rock surface where wave-rippled bedforms are evident, and fine sand is evident in the regions of the image containing light homogeneous tones. These sand inclusions demonstrate that the rock outcrops are so low that inner shelf sand is transported over them without topographic impediment.

The general conformity between rock and sand surface elevations across the inner shelf is evident from analysis of depths in the entire sidescan-sonar dataset (Fig. 8). The dataset was partitioned into horizontal bands across the inner shelf, spaced at 100 m increments either side of the 40 m depth contour. Depth data were averaged separately for rock and sediment zones within each band. The difference between mean water depths over rock and sediment regions within each band is less than 3 m almost everywhere, as indicated by the dashed bands in Figure 8. In shallower water (toward the top left of the diagram), the rock regions tend to be higher because of proximity effects of the headlands. In deeper water (lower right), mean sand elevations are higher because of proximity of the onlapping shelf sediment wedge that buries the abrasion surface further offshore (Figs 3–6). These comparative elevations are put into perspective when considering that the abrasion surface is the residual topography left as a result of landward retreat of the eroding cliffs and associated features (e.g. shore platforms). Given that the relief associated with these cliffs is 30–100 m, variability in elevation of the order of 1 m along the inner shelf is negligible by comparison. This subdued relief demonstrates that the inner shelf can be regarded regionally as having a planar, seaward dipping morphology.

The rock surface on the inner shelf forms a seaward dipping surface ranging in width from more than 11 km to 23 km. The elevation of this surface ranges from 30 to 180 m below present sea level, where it passes into the S1 unconformity in

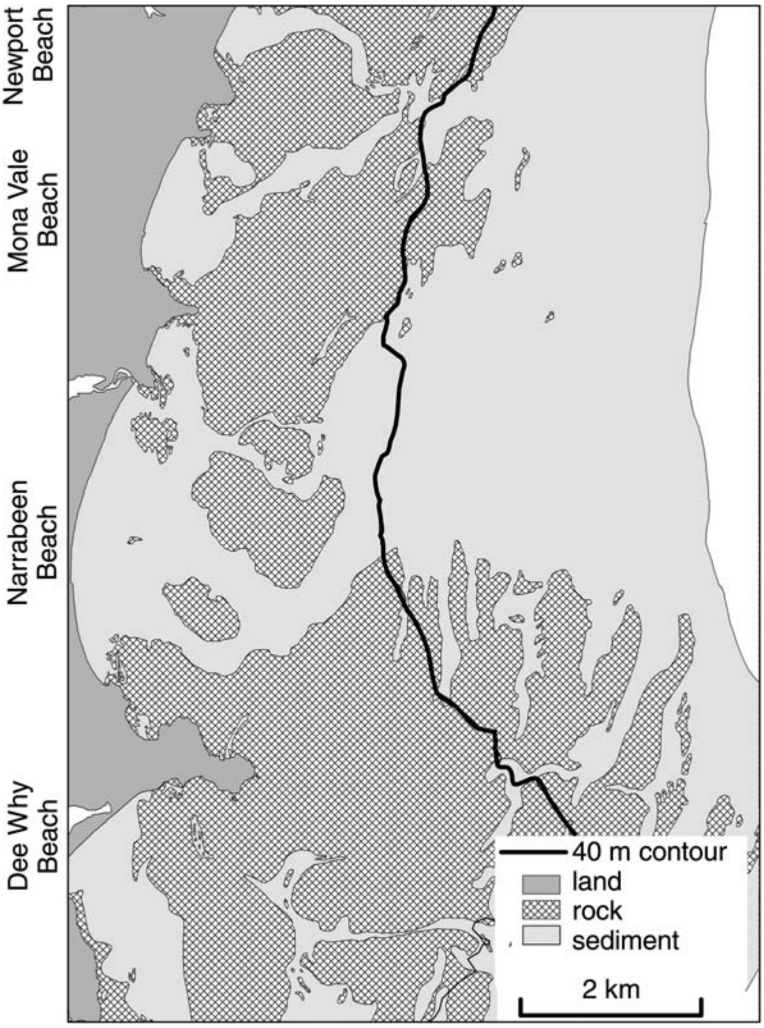

Fig. 7. Detail of sidescan-survey data off Narrabeen and adjacent beach, 10 km north of Sydney Harbour (Fig. 2), showing 40 m depth contour, and distribution of rock and sediments on the inner shelf, including the palaeo-valleys and structural depressions filled with sediments.

the shelf sediment wedge (Figs 3–6). The outer portion of the surface generally has the same slope as the unconformity. The seaward edge of the surface is everywhere buried by the onlapping continental-shelf sediment wedge.

The rock surface slope decreases landward, resulting in mild convexity in the across-shelf profile. At the base of the cliffs, shelf sand bodies, up to 30 m thick, bury the planated surface in parts of the region. Field and Roy (1984) and Ferland (1990) have described and discussed these remarkable lobate shelf sand bodies off the toe of cliffs along the south Sydney coast (also see Roy *et al.* 1994). These features are of Holocene age and together with the other more planar sediment veneers on the inner and mid-shelf sections provide a patchy cover over the Triassic rocks of this region. The mobility of the sand and gravel fractions of this veneer has been documented by Cowell (1986) and Gordon and Hoffman (1986). Terraces and nick-points are common down to 160 m and were formed by erosion during times of lower sea level (Jones *et al.* 1975).

Process implications and conclusions

Six key features of the southeastern Australia continental margin must be explained to provide a model

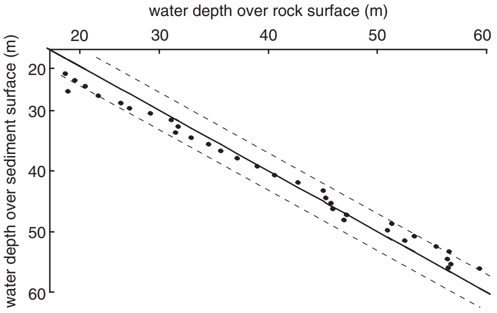

Fig. 8. Mean water depths over regions of rock (horizontal axis) and sediment (vertical axis) partitioned in horizontal bands at 100 m increments across the inner shelf. The continuous line is 1:1 correspondence between sand and rock elevations, and the dashed lines define the ±3 m envelope.

for marine planation: (1) an ancient terrestrial landscape with incised valleys extending offshore; (2) truncated interfluves of an embayed coast forming cliffs; (3) rock platforms at base of cliffs, with polycyclic and polygenetic origin; (4) division of the continental shelf into an outer sediment wedge and inner–mid-shelf in which basement rocks are at or near the sea floor; (5) an outer sediment wedge onlapping the truncated basement surface; (6) buried and infilled river valleys cut into inner, mid-, and outer shelf regions indicative of fluvial incision and fill on a subsiding margin.

Possibly two phases of ‘interidal’ marine abrasion exist, both associated with transgressive and fluctuating relative sea levels. The earlier, lower surface in seismic data of Davies (1975) and Jones *et al.* (1975) was described by Glenn *et al.* (2008) as being a flat seaward dipping surface underlying the entire sediment wedge of early Tertiary age off central NSW. Davies (1975) considered this S2 surface to be an extension offshore of a Cretaceous peneplain, but Jones *et al.* (1975) interpreted this surface as a possible marine abrasion platform formed during the initial transgression following the opening of the Tasman Sea. Dredge samples described by Quilty *et al.* (1997) that are of shallow marine origin and Palaeocene age may have been deposited on this surface.

The sediment wedge on the outer continental shelf extending over and forming the shelf break in central NSW has been interpreted as being post-Eocene in age. The younger portion of the wedge above the distinct S1 unconformity was regarded by Davies (1975) as Pliocene and younger, although Roy and Thom (1991) correlated the S1 erosion surface with relative changes in sea level during the Miocene. Based on the seismic data, continued sedimentation during the Late Cenozoic appears to have extended the sediment wedge landward as the margin subsided (Fig. 4).

The incised valleys can be traced across the shelf and beneath the sediment wedge and cut into the bedrock basement (Fig. 4; see also Roy & Thom 1991). These valleys are infilled with sediment and have been discussed in detail by Albani *et al.* (1988) where they occur on the inner and mid-sections of the shelf. Their seismic stratigraphy suggests that the valleys have been subjected to complex erosional and depositional episodes that have yet to be deciphered. However, on the inner and mid-shelf, their upper surfaces are truncated to levels generally comparable with the adjacent sea-floor bedrock, the dissected plateaux of Albani *et al.* (1988).

Rock platforms at the base of the cliffs along the central NSW coast have long been the subject of debate as to age and origin since first described by Dana (1863). He and others attributed them to wave erosion, although other marine processes have sometimes been invoked (Langford-Smith & Thom 1969; Stephenson 2000; Woodroffe 2002). Radiometric dating on surface crusts on the platforms has demonstrated that they are pre-Holocene (Young & Bryant 1993) and buried by 5000–6000 year old sediments, indicating an age older than the Holocene stillstand. This implies that the platforms are polycyclic and, by inference, so would be the cliffs that they front.

Overall the distinctive character of the cliffs, platforms, buried valleys, bedrock-bound inner–mid-shelf and the outer-shelf wedge can be best interpreted through a time-transgressive model of a subsiding margin dominated by polycyclic marine erosion. Trenhaile (1989) has simulated polycyclic shore platform retreat in weak rock with rising and falling sea levels during the Quaternary. On the NSW coast we have extended the time scale to include the effect of oscillating sea levels across basement surfaces formed in more resistant Palaeozoic and Mesozoic strata since the Eocene. These changes in levels should be combined with an uneven subsidence history of the continental margin (Roy & Thom 1991) giving rise to cyclic sweeping of the basement rocks leading to their planation. Subsidence has allowed for accommodation space on the outer shelf for a wedge of sediment to accumulate as a backstepping deposit that onlaps the truncated bedrock strata of the mid-shelf. Continued landward erosion, following concepts put forward by Dana, Davis, Johnson, Cotton, Trenhaile and others, highlights the capacity for marine abrasion processes to develop planation surfaces. The more prolonged exposure of the abrasion surface on the inner shelf, compared with further offshore where the surface has been buried by the onlapping deposits, is consistent with the inshore convexity of the surface referred to above.

An evolutionary model is proposed for the origin of the truncated bedrock of the shelf and the cliffs along the coast north and south of Sydney. Over a period of at least 30 Ma, the mid- and inner-shelf sections have been peeled landward. Figure 9 schematically shows how the shelf abrasion surface might have evolved. The contiguity of the abrasion surface with the unconformity in the shelf sediment wedge suggests that marine planation began in the Mid-Oligocene, based on previous speculation about the age of the unconformity; although these proposed ages range widely from Pliocene to Palaeocene. The reconstructed palaeo-land surface (dashed line) is hypothetical. Strata in the present-day cliffs tend to dip gently upward in the seaward direction, suggesting a higher palaeo-surface further to the east (Persano *et al.* 2005). Whatever the initial elevation and trend of this surface, subaerial lowering of the surface is likely to have continued. Although the initial surface in Figure 9 merely serves an illustrative purpose, the time lines of indicative retreat were computed from a uniform volume-rate of erosion (0.02 m^3 per m of coastline per year). For the hypothesized initial surface, rates of retreat decrease through time as the elevation of the initial land surface rises with distance from the sea. The need remains, however, to reconcile the erosion history of the dissected coastal plain seaward of the Eastern Highlands with the geomorphological evolution of the continental shelf and slope.

If margin subsidence is assumed to have brought sea level to a point where the bedrock was exposed landward of the shelf sediment wedge during the Mid-Oligocene, then the gross, time-average rate of cliff retreat can be estimated from the width of the abrasion surface evident today. The estimate also requires a hypothesized initial topography, which could be varied through sensitivity analysis. For the initial terrain shown in Figure 9, the gross, time-average rate of cliff retreat is estimated to be *c.* 1 mm a^{-1} (0.4–2 mm a^{-1}). These gross rates

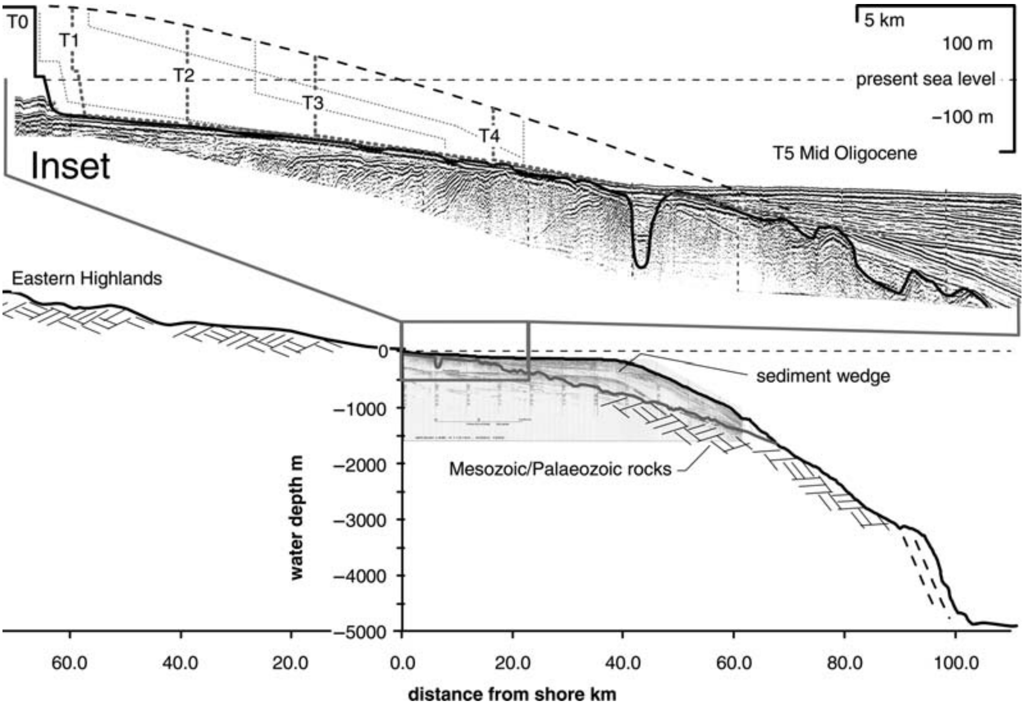

Fig. 9. Schematic representation (illustrated using stylized seismic section based on Fig. 4) showing disposition of the shelf sediment wedge relative to the continental margin. Inset shows detail of abrasion surface and its hypothesized evolution (bold dotted lines) initiated in the Mid-Oligocene (T5), then stepping landward to the start of the Miocene (T4), Mid-Miocene (T3), Early Pliocene (T2), and Early Pleistocene (T1), to the present (T0). The faint dotted lines schematically emphasize the likelihood of polycyclic back-cutting and lowering during successive irregular cycles of rising and falling sea level, rather than through the simplified representation of nick-point retreat along a single trajectory.

compare with published measurements of modern cliff retreat ranging from 9 to 20 mm a^{-1} in similar rock types (Sunamura 1992). The comparison supports the feasibility of gross marine planation rates inferred for the Sydney abrasion platform during the past 30 Ma ($\pm$20 Ma) through polycyclic platform lowering and cliff retreat. That is, the order of magnitude lower rates on the geological time scale seem feasible considering that the retreat is active at the landward-most cutting face during sea-level highstands.

Nevertheless, down- and back-cutting is not limited to the highest nick-point at any given time (Trenhaile 1989). Shore platform development is likely to have been working away at the rock mass to be removed at all times, except during periods of lowest sea levels. In this sense, the older shore platforms are effaced during subsequent eustatic cycles: shore-platform development can thereby be regarded simply as a transient, sub-grid process on the Cenozoic scale. The abrasion surface is a residual morphology, ultimately resulting from the aggregate process proposed by Trenhaile (1989) for a multitude of sea-level fluctuations through many tens of metres (polycyclic erosion). This point is illustrated by the faint timelines in Figure 9, which represent the irregular episodes of erosive retreat that ultimately result in the surface development plotted as the bold timelines (compare Trenhaile's figures 9.4 and 9.5).

The concepts underlying Figure 9 depart from Trenhaile's formalism in two respects. First, Trenahaile considered platform development in friable bedrock during Pleistocene sea-level fluctuations, whereas here abrasion-platform evolution involves harder sedimentary lithologies acted upon over a much longer time (i.e. throughout much of the Cenozoic). Second, it is necessary on this longer time scale to consider the erosion as a gross (lumped) process of polygenetic surface development. The gross evolution is the aggregate effect of intertidal weathering and physical erosion responsible for shore-platform growth and decay, consequent nick-point retreat that causes undermining and failure of cliffs, and, necessarily, removal of detritus produced by cliff failure and shore-platform disintegration. The Trenhaile model does not include this last aspect of the overall process.

Without this detritus removal, talus blanketing the bedrock impedes further erosion of the bedrock. For example, accumulation of the shelf sediment wedge (Fig. 4) isolated the S2 surface from erosion processes, preventing further planation. Conversely, the onset of wholesale erosion of the shelf that produced the S1 unconformity would have re-exposed the landward portion of the bedrock surface previously buried by the pre-S1 shelf-wedge onlap. This broad-scale detritus removal was therefore a fundamental requirement before development of the abrasion surface could proceed, just as was the case subsequently regarding removal of detritus produced during shore-platform development.

Detritus removal was likely to have involved weathering and abrasion, plus transport offshore, alongshore, and landward to form valley fills. Temporary burial even may have enhanced weathering through groundwater effects, at the base of cliffs on platform surfaces and within the detritus itself, during periods of subaerial exposure. Progressive breakdown of the detritus to sand, silt and clay would have served to make its removal possible through sediment-transport processes. Much of the detritus can be expected to have weathered and abraded to finer grades, which are readily removed by diffusive transport to the mid- and outer continental shelf, or to the adjacent ocean basin. Bedload transport of the sand fraction offshore to the shelf sediment wedge, although feasible, is likely to have been much less important than alongshore transport in the surf zone. Sand dispersed alongshore would have eventually been sequestered by drowned-valley fills to landward, under transgressive conditions, or in downdrift sinks, such as Fraser Island, or bypassed to the continental slope where the shelf is sufficiently narrow, immediately north of Fraser Island (Boyd *et al.* 2004).

The feasibility of sand-detritus removal through alongshore transport alone was evaluated by estimating the indicative capacity of erosive sand fluxes, assuming that the cliff-detritus volume was all sand (a maximum sand-volume assumption). Erosive fluxes require positive transport gradients along the entire coastal tract from which the detritus is to be removed. Net alongshore transport of sand in southeastern Australia is to the north, unless impeded by headlands, which were far less prominent at lower sea level than at present (Roy & Thom 1981). The long-term removal of sand detritus along some parts of the inner shelf may have required offshore transport (by streams) during periods of lower sea levels to allow the sand to enter the unimpeded littoral transport stream.

The length of the coastline from Sydney to Fraser Island is roughly 1000 km. The estimated net transport rate northward past Fraser Island is 500 000 $m^3 a^{-1}$ (Schröder-Adams *et al.* 2008). Assuming this transport rate increases progressively to the north from zero at Sydney, the transport gradient, and thus the potential capacity for detritus removal, is $+0.5\ m^3\ a^{-1}\ m^{-1}$ of coastline. Removal of detritus required an estimated gradient of only $+0.02\ m^3\ m^{-1}\ a^{-1}$ to maintain a bare abrasion surface, susceptible to continuing platform development. The actual requirement averaged along the coastal tract was less because a significant proportion of the total coastline consists of incised valleys. These are potential sinks for detritus, rather than a source.

The marine-abrasion surface may extend the full length of the coastal from Wilsons Promontory in the south to Fraser Island in the north. If so, the length of coastline from which removal of sand detritus was necessary increases by up to 1900 km, again ignoring the proportion of coastline consisting of incised valleys. In these circumstances, the potential alongshore-transport gradient averages *c.* $+0.26\ \mathrm{m}^3\ \mathrm{a}^{-1}$. Even this weaker gradient is an order of magnitude greater than that required for detritus removal, once talus is abraded to sand (i.e. at the time-averaged rate of roughly $0.02\ \mathrm{m}^3\ \mathrm{a}^{-1}\ \mathrm{m}^{-1}$ of coastline). Therefore, erosion and transport processes are more than sufficient to allow formation of an abrasion surface, 20 km wide, after the continental shelf was flooded, while the margin subsided relative to sea level.

Overall, the data seem to support the general conclusion that, on the Cenozoic time scale, the non-friable bedrock forming the cliffs along the Sydney–Newcastle coast was peeled back with no more resistance than inherent in the unconsolidated shelf sediment wedge located immediately offshore. This conclusion can be inferred from the coplanar disposition of the bedrock abrasion surface, the S1 unconformity in the shelf sediment wedge, and the truncated surface of valley fills immediately offshore the present coast. The aggregate processes tend to plane off high points, and fill low points with sediments, along a diachronous shoreline trajectory that probably reflects the long-term transgressive trend associated with combined passive-margin subsidence and slow eustatic rise throughout the Cenozoic, regardless of superimposed eustatic fluctuations. These fluctuations are, however, responsible for the submarine terraces and nick-points that occur down to 160 m below present sea level. The scale of these features, and other higher residuals, seems negligible compared with that of the marine-abrasion surface and retreating sea cliffs.

References

Albani, A. D & Rickwood, P. C. 2000. Marine aggregates near Sydney. *In*: McNally, G. H. & Franklin, B. J. (eds) *Sandstone City—Sydney's Dimension Stone and other Sandstone Geomaterials*. Geological Society of Australia, EEHSG Monograph, **5**, 260–266.

Albani, A. D., Tayton, J. W., Rickwood, P. C., Gordon, A. D. & Hoffman, J. G. 1988. Cainozoic morphology of the inner continental shelf near Sydney. *Journal and Proceedings of the Royal Society of NSW*, **121**, 11–28.

Bishop, P. & Cowell, P. J. 1997. Lithological and drainage network determinants of the character of drowned, embayed coastlines. *Journal of Geology*, **105**, 685–699.

Bishop, P. & Goldrick, G. 2000. Geomorphological evolution of the East Australian continental margin. *In*: Summerfield, M. A. (ed.) *Geomorphology and Global Tectonics*. Wiley, New York, 227–235.

Boyd, R., Ruming, K. & Roberts, J. J. 2004. Geomorphology and surficial sediments on the southeast Australian continental margin. *Australian Journal of Earth Sciences*, **51**, 743–764.

Browne, W. R. 1969. Geomorphology. *Journal of the Geological Society of Australia*, **16**, 559–569.

Burns, R. E., Andrews, J. E. & Shipboard Scientists. 1973. *Initial Reports of the Deep Sea Drilling Project, 21*. US Government Printing Office, Washington, DC.

Chorley, R. J., Dunn, A. J. & Beckinsale, R. P. 1964. *The History of the Study of Landforms. Volume 1, Geomorphology before Davis*. Methuen, London.

Cotton, C. 1974*a*. The theory of secular marine planation. *In*: Collins, B. W. (ed.) *Bold Coasts*. Reed, Wellington (republished from *American Journal of Science*, **253**, 1955), 164–174.

Cotton, C. 1974*b*. Plunging cliffs and Pleistocene coastal cliffing in the southern hemisphere. *In*: Collins, B. W. (ed.) *Bold Coasts*. Reed, Wellington, 245–266.

Cowell, P. J. 1986. Wave-induced sand mobility and deposition on the south Sydney inner-continental shelf. *In*: Frankel, E., Keene, J. B. & Waltho, A. E. (eds) *Recent Sediments in Eastern Australia – Marine Through Terrestrial*. Geological Society of Australia Special Publication, **2**, 1–28.

Dana, J. D. 1863. *Manual of Geology*. 1st edn. Bliss, Philadelphia, PA.

Davies, P. J. 1975. Shallow seismic structure of the continental shelf, southeast Australia. *Journal of the Geological Society of Australia*, **22**, 345–359.

Davies, P. J. 1979. *Marine geology of the continental shelf off southeastern Australia*. Bureau of Mineral Resources Bulletin, **195**.

Davis, W. M. 1896. Plains of marine and sub-aerial denudation. *Geological Society of America Bulletin*, **7**, 377–398.

Dietz, R. S. 1963. Wave base, marine profile of equilibrium, and wave-built terraces: a critical appraisal. *Geological Society of America Bulletin*, **74**, 971–990.

Exon, N., Hill, P. et al. 2005. *The geology of the Kenn Plateau off northeast Australia: results of* Southern Surveyor *Cruise SS5/2004 (Geoscience Australia Cruise 270)*. Geoscience Australia Record, 2005/04.

Exon, N., Hill, P., Lafoy, Y., Heine, C. & Bernardel, G. 2006. Kenn Plateau off northeast Australia: a continental fragment in the southwest Pacific jigsaw. *Australian Journal of Earth Sciences*, **53**, 541–564.

Ferland, M. A. 1990. *Shelf Sand Bodies in Southeastern Australia*. PhD thesis, University of Sydney, Sydney.

Field, M. E. & Roy, P. S. 1984. Offshore transport and sand body formation: evidence from a steep, high energy shoreface, southeastern Australia. *Journal of Sedimentary Petrology*, **54**, 1292–1302.

Gaina, C., Muller, D. R., Royer, J.-Y., Stock, J., Hardebeck, J. & Symonds, P. 1998. The tectonic history of the Tasman Sea: a puzzle with 13 pieces. *Journal of Geophysical Research*, **103**, 12413– 12433.

Glenn, K. C., Post, A. et al. 2008. *Geoscience Australia Marine Survey Post-Cruise Report—NSW Continental Slope Survey*. Geoscience Australia, Record, **2008/14**.

Gordon, A. D. & Hoffman, J. G. 1986. Sediment features and processes of the Sydney continental shelf. *In*: Frankel, E., Keene, J. B. & Waltho, A. E. (eds) *Recent Sediments in Eastern Australia – Marine Through Terrestrial*. Geological Society of Australia Special Publication, **2**, 29–51.

Gordon, A. D. & Hoffman, J. G. 1989. *Seabed Information, 1:25,000 Sheets: Bate Bay, Sydney Heads, Broken Bay, Gosford*. Public Works Department New South Wales Coast and Rivers Branch, Sydney.

Hansom, J. 1983. Shore platform development in the South Shetland Islands, Antarctica. *Marine Geology*, **53**, 211–229.

Hayes, D. E. & Ringis, J. 1973. Seafloor spreading in the Tasman Sea. *Nature*, **243**, 454–458.

Heggie, D. & Shipboard Scientists. 1992. *Preliminary results of AGSO RV* Rig *Seismic Survey 112: Offshore Sydney Basin continental shelf and slope geochemistry, sedimentology and geology*. Australian Geological Survey Organisation Record, **1993/5**.

Johnson, D. W. 1919. *Shore Processes and Shoreline Development*. Wiley, New York (reprinted Hafner, New York, 1965).

Johnson, D. W. 1925. *The New England–Arcadian Shoreline*. John Wiley, New York.

Jones, H. A., Davies, P. J. & Marshall, J. M. 1975. Origin of the shelf-break off southeast Australia. *Journal of the Geological Society of Australia*, **22**, 71–78.

Jones, H. A. & Kudrass, H. R. 1982. *Sonne* cruise (SO-15 1980) off the east coast of Australia bathymetry and sea floor morphology. *Geologisches Jahrbuch*, **Reihe D56**, 55–68.

Jones, H. A., Lean, J. & Schlüter, H.-U. 1982. Seismic reflection profiling off the east coast of Australia, Newcastle to Cape Hawke. *Geologisches Jahrbuch*, **Reihe D56**, 69–75.

Keene, J., Baker, C., Tran, M. & Potter, A. 2008. *Sedimentology and Geomorphology of the East Marine region of Australia: A spatial analysis*. Geoscience Australia Record, **2008/10**.

Langford-Smith, T. & Thom, B. G. 1969. New South Wales coastal morphology. *Journal of the Geological Society of Australia*, **16**, 572–580.

Ota, Y. 1986. Marine terraces as reference surfaces in late Quaternary tectonics studies: examples from the Pacific Rim. *Bulletin of the Royal Society of New Zealand*, **24**, 357–375.

Persano, C., Stuart, F. M., Bishop, P. & Dempster, T. J. 2005. Deciphering continental breakup in Eastern Australia using low-temperature thermochronometers. *Journal of Geophsyical Research*, **110**, B12405.

Quilty, P. G., Shafik, S., Jenkins, C. J. & Keene, J. B. 1997. An Early Cainozoic (Paleocene) foraminiferal fauna with *Fabiania* from offshore eastern Australia. *Alcheringa*, **21**, 299–315.

Ramsay, A. C. 1846. *The Denudation of South Wales*. Memoir of the Geological Survey of Great Britain, 1. HMSO, London, 297–335.

Ringis, J. 1972. *The Structure and History of the Tasman Sea and Southwest Australian Margin*. PhD thesis, University of NSW, Sydney.

Roy, P. S. 1983. Quaternary geology. *In*: Herbert, C. (ed.) *Geology of the Sydney 1:100,000 Sheet 9130*. Geological Survey of New South Wales, Sydney, 41–91.

Roy, P. S. 1998. Cainozoic geology of the New South Wales coast and shelf. *In*: Scheibner, E. & Basden, H. (eds) *Geology of New South Wales: Synthesis, Volume 2 Geological Evolution*. Geological Survey of New South Wales, Memoir, **13**, 361–385.

Roy, P. S. & Thom, B. G. 1981. Late Quaternary marine deposition in New South Wales and southern Queensland—an evolutionary model. *Journal of the Geological Society of Australia*, **28**, 471–189.

Roy, P. S. & Thom, B. G. 1991. Cainozoic shelf sedimentation model for the Tasman Sea margin of southeastern Australia. *In*: Williams, M. A. J., Kershaw, A. P. & De Deckker, P. (eds) *The Cainozoic in Australia: A Reappraisal of the Evidence*. Geological Society of Australia, Special Publication, **18**, 119–136.

Roy, P. S., Cowell, P. J., Ferland, M. A. & Thom, B. G. 1994. Wave-dominated coasts. *In*: Carter, R. W. G. & Woodroffe, C. D. (eds) *Coastal Evolution*. Cambridge University Press, Cambridge, 121–186.

Schröder-Adams, C. J., Boyd, R., Ruming, K. & Sandstrom, M. 2008. Influence of sediment transport dynamics and ocean floor morphology on benthic foraminifera, offshore Fraser Island, Australia. *Marine Geology*, **254**, 47–61.

Stephenson, W. J. 2000. Shore platforms: remain a neglected coastal feature? *Progress in Physical Geography*, **23**, 311–327.

Sunamura, T. 1992. *Geomorphology of Rocky Coasts*. Wiley, Chichester.

Thom, B. G. & Cowell, P. J. 2005. Coastal changes, gradual. *In*: Schwartz, M. L. (ed.) *Encyclopedia of Coastal Science*. Springer, Dordrecht, 251–253.

Trenhaile, A. S. 1989. Sea level oscillations and the development of rock coasts. *In*: Laknan, V. C. & Trenhaile, A. S. (eds) *Applications in Coastal Modelling*. Elsevier Oceanography Series, **49**, 271–295.

Woodroffe, C. D. 2002. *Coasts*. Cambridge University Press, Cambridge.

Young, R. W. & Bryant, E. A. 1993. Coastal rock platforms and ramps Pleistocene and Tertiary age, southern New South Wales, Australia. *Zeitschrift für Geomorphologie*, **37**, 257–272.

Zenkovich, V. P. 1967. *Processes of Coastal Development*. Oliver & Boyd, Edinburgh.