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Cliffed coasts of New Zealand: perspectives and future directions

David M. Kennedy[1] and Mark E. Dickson[2]

Abstract About one-quarter of New Zealand's shoreline is composed of cliffs. In some areas erosion rates are sufficiently rapid to be of concern to planners, whereas other cliffs have eroded imperceptibly slowly over human timescales. This paper reviews work conducted on New Zealand's cliffed coasts, from the pioneering studies of Sir Charles Cotton, who used Davisian theoretical methods to elucidate the evolution of hard-rock coasts, to Jeremy Gibb's nationwide benchmark measurements of historical erosion rates. This review is augmented with a description of state-of-the art methods in use globally for investigating processes of cliff evolution. Key methods identified include detailed measurements using the micro-erosion meter as well as novel geophysical methods of studying cliff movement under wave loading. Such process-based studies build on previous research that has been largely confined to explanatory description and observation. It is recognised that the combined impact of such studies has been relatively muted, owing particularly to the difficulty of unravelling ambiguous process-form interactions. However, the increasingly widespread availability of terrestrial and aerial remote laser scanning systems now provides an opportunity to re-invigorate such studies by extending the scale from local to regional. The paper concludes by outlining prospects within New Zealand for further research. In particular, the development and use of numerical models is seen as an important avenue both for clarifying some basic behaviours observed on cliffed coasts, and for studying the likely response of eroding cliffs to future climate change.

Keywords cliff; erosion; slope; shore platform; shoreline

INTRODUCTION

New Zealand straddles the convergent boundary of the Indo-Australian and Pacific plates. Over millions of years, shearing and collision along this plate boundary have uplifted and deformed rocks of varied lithology and age, and marine and subaerial processes have shaped the landscape producing a diverse suite of New Zealand coastal landforms. Cliffed coasts account for approximately 23% of the shoreline (Gibb 1984), but the form of these cliffs differs markedly from location to location, reflecting local tectonics, lithology and the varied process environment. Geology represents the principal control on local cliff erosion rates.

[1]School of Geography, Environment and Earth Sciences, Victoria University of Wellington, PO Box 600 Wellington 6140, New Zealand.
[2]National Institute of Water and Atmospheric Research, PO Box 8602, Riccarton, Christchurch 8440, New Zealand.

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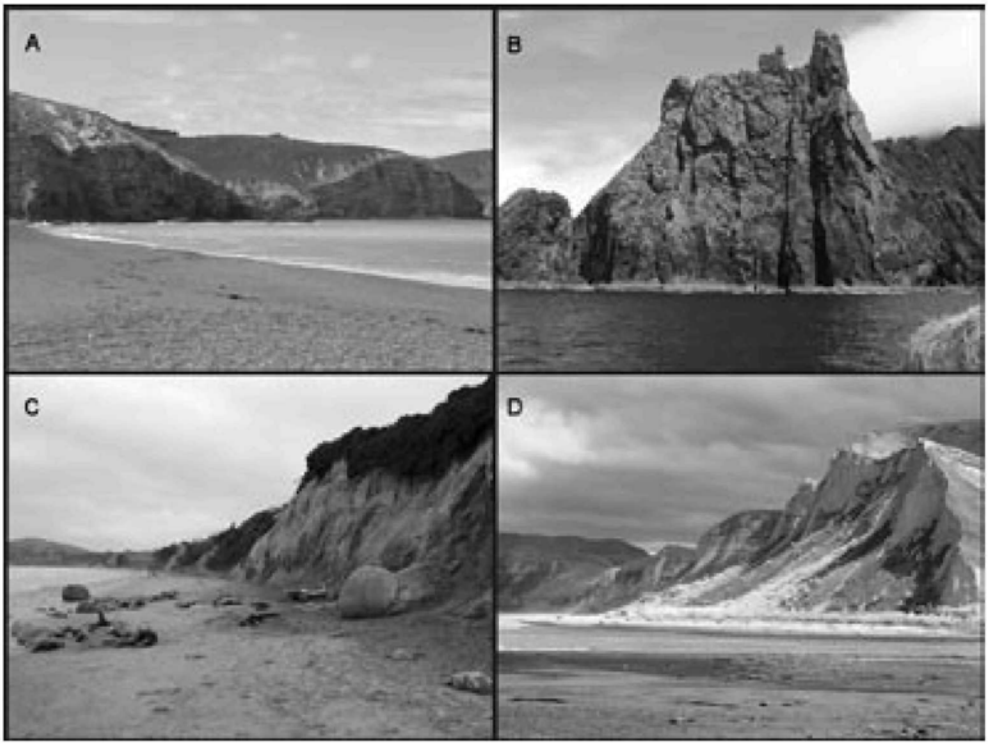

Fig. 1 Basaltic cliffs along **A**, southern side of Banks Peninsula and **B**, the entrance to Whangarei Harbour. Cliffs composed of soft Tertiary and Quaternary sediments at **C**, Moeraki, Otago and **D**, Mohaka, northern Hawke's Bay.

For instance, the volcanic rocks which comprise Banks and Otago Peninsulas (Fig. 1), and the resistant schistose lithologies of southeastern Fiordland, have eroded almost imperceptibly over thousands of years. Hence, while sea level has been high for the last 6500 years (Gibb 1986; Pirazzoli 1991), for most of the last 2 million years it has been many tens of metres lower (Imbrie et al. 1984) such that these hard-rock landscapes have formed primarily through the action of subaerial processes, such as glacial advance and retreat in Fiordland. During the Holocene high sea level, marine processes have flooded valleys rather than eroding cliffs. By contrast, long stretches of New Zealand's shoreline are composed of softer Tertiary and Quaternary sediments that offer relatively little resistance to marine processes (Fig. 1). This means that erosion during the current period of high sea level may have obliterated evidence of past subaerial processes, forming relatively straight cliffed shorelines, such as those that occur in outwash gravels between Banks Peninsula and Oamaru, as well as siltstones and sandstones along much of the east coast of the North Island. In these areas, erosion rates are measured in centimetres or even metres per year. Such erosion rates are clearly of concern to coastal managers and property owners, particularly in the context of recent increased urban development.

Globally, the amount of research on cliffs and the processes driving their evolution has increased in recent decades. This paper sets out to review the work conducted on New Zealand's cliffed coasts and outlines prospects for future research in light of recent international advances. New data is also presented building on a benchmark study of shoreline change in New Zealand.

Morphology and processes

Sir Charles Cotton (1885–1970), Professor of Geology at Victoria University of Wellington, extensively researched the cliffed coasts of New Zealand and his writings through the period 1916–69 continue to provide a basis for understanding many hard-rock landscapes. Much of Cotton's work was framed in the Davisian concepts of landscape youth and maturity, with coastal landforms undergoing cycles of erosion, and their form being related to the rate of marine erosion, recent tectonics and sediment accumulation at the cliff base (Cotton 1951a,b). Cotton's thinking was framed by the debates of the time, and his writings show increasing realisation of the role of sea-level oscillations in the ongoing erosion of hard-rock cliffs (Cotton 1974). Throughout the 19th century and for the first half of the 20th century most investigators thought that wave action could abrade the seabed to great depths (about 180 m), thereby providing a mechanism for continual cliff retreat. Charles Darwin (1844) observed, however, that the seabed adjacent to high cliffs around the island of Saint Helena is composed of fine sediment, and questioned how marine processes could possibly have eroded such large volumes of rock while simultaneously depositing a bed of fine sediment. The notion of wave abrasion at great depths was eventually dispelled (Dietz & Menard 1951), and Cotton (1969a) and others gradually realised that repeated sea-level oscillations have provided the mechanism necessary for ongoing erosion of many of the hard-rock cliffs observed around New Zealand and worldwide.

It has since been understood that the morphological imprint of changes in land and sea level can be inherited from previous glacial/interglacial cycles on slowly eroding coastlines. Multi-storied cliffs occur where marine cliff erosion has re-activated cliffs previously modified by subaerial processes, as vertical faces formed by marine processes are separated by subaerially modified angled slopes (Arber 1949; Cotton 1951a; Te Punga 1957), such as on the Auckland Islands in the Southern Ocean (Fleming 1965) or the Waitakere Ranges near Auckland (Cotton 1951a). Such forms are often also termed composite or bevelled cliffs (Trenhaile 1987; Griggs & Trenhaile 1994). In some cases, however, such as around Banks Peninsula and Wellington, sea cliffs plunge into deep water and therefore reflect incident wave energy rather than being eroded by it. Moreover, such cliffs generally lack basal shore platforms, which further imply an absence of erosion at current sea level. Cotton recognised that the morphology of such plunging cliffs must be largely inherited from lower sea levels (Cotton 1951a,b, 1952a,b, 1968). This is not to say that plunging cliffs are completely resistant to modern wave erosion. Indeed, the development of sea caves around the Auckland Islands (Fleming 1965) and Banks Peninsula (Bal 1997) may be attributable to localised erosion of weaker bedrock through hydraulic action and pressure exerted by air trapped by wave action. However, such features present minor perturbations in otherwise continuous plunging cliff faces. In order for sustained and widespread cliff retreat to occur, Cotton recognised that shallowing of the foreshore is required, either by a base level change (e.g., sea-level change) or the accumulation of subaerially eroded debris.

In a classic summary of the form of sea cliffs, Emery & Kuhn (1982) attributed cliff form to the relative efficacy of marine and subaerial process in weathering and eroding coastal bedrock (Fig. 2). Typically, near-vertical profiles occur where marine processes are dominant, whereas subaerial erosion tends to smooth and lower the cliff slope. This can be seen, for instance, along the late Pleistocene conglomerate cliffs of the east coast of Canterbury and Otago (Fig. 3): where beaches are narrow the loosely consolidated gravel cliffs are steep owing to rapid erosion of the cliff toe during storm events. By contrast, wide beaches sometimes occur adjacent to river mouths (owing to the supply of river sediment) and protect the cliff from repeated wave erosion, whereas subaerial erosion continues unabated thereby building a talus slope at the cliff toe. Eventually, the talus slope may reach the cliff top, at which point

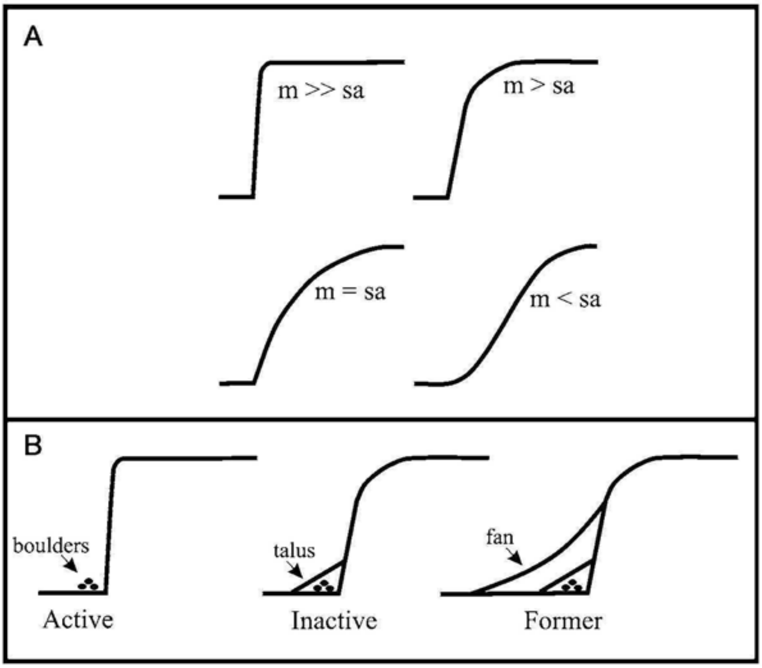

Fig. 2 **A**, A classification of cliff profiles based on the relative efficiency of erosive processes (m = marine erosion, sa = subaerial erosion); **B**, cliff profile development through increasing abandonment by the sea. Modified from Emery & Kuhn (1982).

Fig. 3 Late Pleistocene fluvial gravel cliffs: **A**, fronted by wide gravel beaches at the mouth of the Waitaki River; **B**, fronted by narrow beaches just south of the river mouth.

the cliff becomes effectively "inactive" (Fig. 2). Reactivation of the cliff occurs only when the wide beach and talus have been removed. Cotton (1951a) described such accumulations as temporary interruptions to the cycle of marine erosion.

In adopting a long-term perspective on cliff evolution it is typically thought that marine energy is the primary determinant of cliff form. However, such inferences have been criticised by New Zealand researchers, especially when referring to the development of shore platforms, which are nearly horizontal rock surfaces that occur at the base of sea cliffs and which result from their retreat. Around New Zealand the form of shore platforms can vary significantly over short distances related to a single change in platform hardness or structure (e.g., Kaikoura—Kirk 1977; Wellington—Kennedy & Beban 2005; Otago—Kennedy & Dickson 2006). However, much of New Zealand's coast has a relatively small tidal range and most shore platforms are near horizontal with a steep outer seaward edge, rather than gently sloping as is the case in many macro-tidal areas (Trenhaile 1987). It has been hypothesised that during the formation of near horizontal platforms, the outside edge of the platforms do not retreat (Sunamura 1992). While difficult to confirm and not universally applicable (e.g., Kennedy & Paulik in press), this hypothesis has been supported by several studies (e.g., Dickson 2006; Stephenson 2001), and on this basis de Lange & Moon (2005) used the width of the shore platforms around Auckland to calculate cliff retreat rates of about 14 mm/yr.

The debate on the relative efficacy of processes that contribute to the form of shore platforms is long-standing, with early discussion centred on the "Old Hat" islands of the Bay of Islands (e.g., Bartrum 1916, 1924). More recently, micro-erosion metre measurements on platforms around Kaikoura Peninsula led Stephenson & Kirk (2000a,b) to conclude that non-marine weathering processes are the primary mechanism of shore platform formation. The implications of such findings have yet to be fully incorporated within a longer-term perspective of cliff retreat and platform formation, although numerical modelling supports the hypothesis that platforms are largely wave-cut, with weathering processes becoming increasingly important as platforms widen (e.g., Trenhaile 2005).

It is clear that soft Tertiary rocks around much of New Zealand's shoreline succumb rapidly under both weathering processes and wave action. Additionally, large-scale landsliding can result in rapid shoreline retreat over annual to decadal periods. For instance, on Omokora Promontory in Tauranga Harbour, the base of the cliff lies within the high tide zone and rates of retreat under marine processes are estimated at 0.15 m/yr. However, in August 1979 a single landslide caused 30 m of cliff top retreat (Gibb 1979). In contrast to this instantaneous event, along the Otago coast eroding cliffs 10–20 m high between Blueskin Bay and Karitane are formed in the base of an active landslide (Puketeraki Landslide) some 1.4 km long and 1 km wide at its seaward edge, which is sliding in a seaward direction at rates of up to 0.15 m/yr (Glassey 1994) (Fig. 4A).

The rate and nature of cliff retreat is fundamentally influenced by structural weaknesses (e.g., bedding orientation, stratigraphic variation, etc) that are inherent within the lithology in which the cliff is formed. Terzaghi (1962) demonstrated theoretically that cliffs without structural defects, formed in even very weak rocks, could hold vertical faces over 1200 m height, whereas hard rocks such as granite and basalt could have much greater heights. In nature, a range of mass movement processes, from block toppling to mudflows, result from subaerial processes acting on structural weaknesses and so affect the ability of the bedrock to hold up a vertical edifice (Allison 1989; Allison & Brunsden 1990; Goodman & Bray 1977). Hence, generalisations of how a single section of coastline will evolve are difficult (Trenhaile 1987). However, around the Auckland region, Moon & Healy (1994) have described the effect of wedge failures associated with angular bedding planes in flysche coastal cliffs which are eroding at rates of around 0.06 m/yr.

Hutchinson (1973) classified the clay cliffs of south-east England based on the relative rates of marine erosion and subaerial weathering. Parallel retreat of the slope occurs when both processes are in balance, while deep-seated failures occur when marine erosion is dominant. Where the sea has abandoned the cliff, a steep upper slope develops where landsliding dominates, whereas talus accumulates at the cliff base. These processes are particularly prevalent along New Zealand's coast, especially where late Tertiary and Quaternary marine sediments occur. Much of this young geology is massive in structure with large rotational slumps being common, such as along the Ngawi-Cape Palliser Bay road (Fig. 4B). Wedge-type failures may

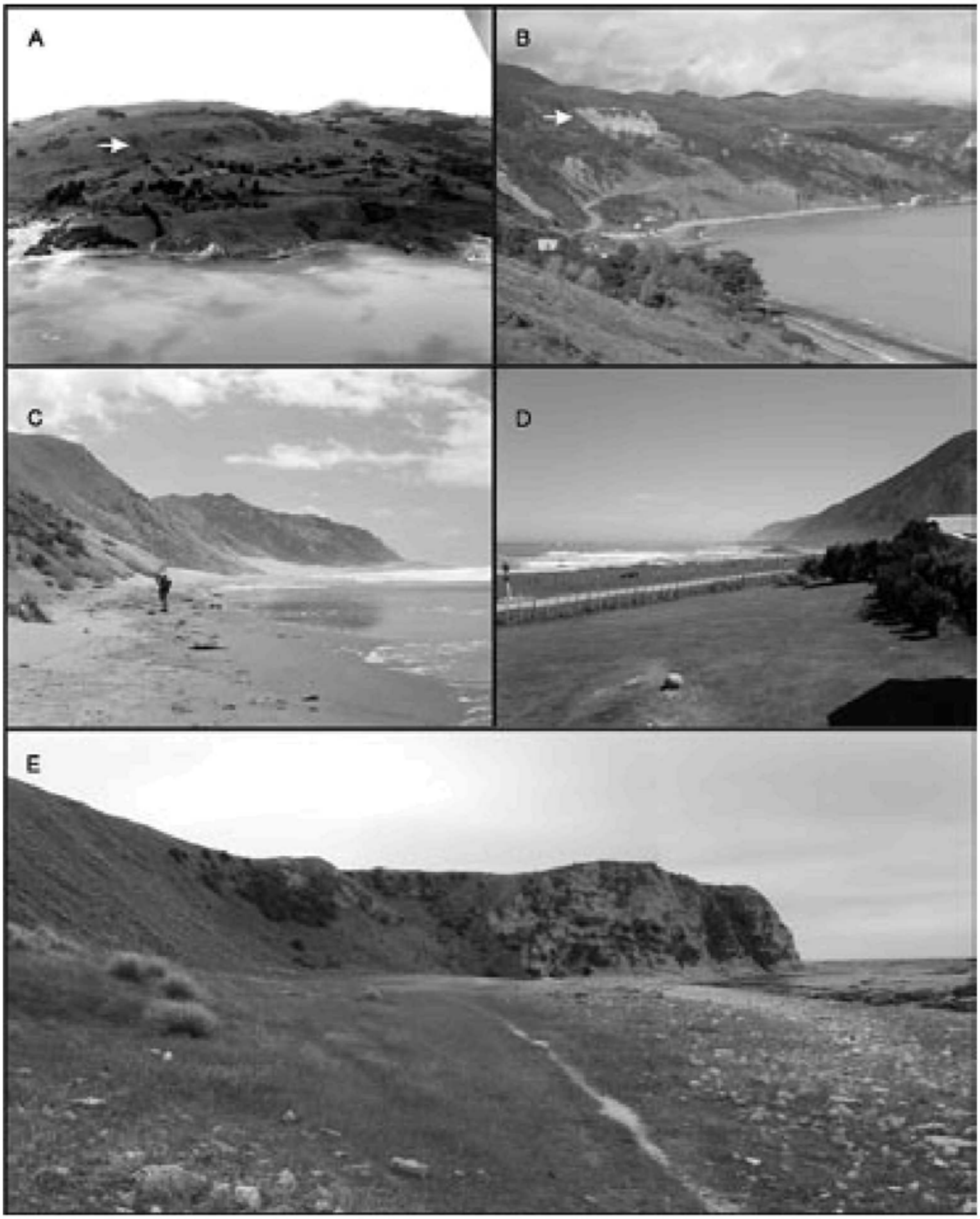

Fig. 4 **A**, A large wedge type landslide north of Blueskin Bay, and **B**, rotational failure along the Ngawi-Cape Palliser Rd *(Photo: Mike Henry)*. The steep vertical faces (arrowed) represent the rear of these mass movements. Holocene sea cliffs fronted by: **C**, dunes just south of Cape Turnagain; **D**, a raised coastal plain at Tora, south-east Wairarapa, and **E**, raised gravel beach on the Kaikoura Peninsula. Note the contrast between the steep profile backing the shore platform to the lower angle slopes behind the beach at Kaikoura.

also be large such as in the Puketeraki landslide, Otago, where failure is estimated to occur at a depth of up to 50 m (Glassey 1994) (Fig. 4A). In these situations the cliff toe is destabilised and moves seaward. This can cause difficulties in estimating the rate of shoreline change. While the toe may advance seaward, the head scarp at the back of the slump indicates a larger landward retreat of the cliff top. While such slumps can be triggered by marine truncation of the cliff base, and therefore over steepening of the profile, continued slumping will often occur without the toe necessarily being within the marine environment.

Marine terraces

Much of New Zealand's shoreline is highly active tectonically. In the Wellington region and elsewhere uplift occurs very rapidly, particularly during earthquakes, which has the effect of stranding the cliff line above marine processes (Wellman 1967; Cotton 1969b). Cotton (1952c) initially thought this to be only a temporary interruption to the marine erosion cycle, but recent investigations of the Turakerai coastal plain indicate a series of co-seismically uplifted gravel beach ridges dating back to 6 ka (Moore 1987) which have stranded the sea-cliff beyond the reach of marine processes for most of the current sea-level highstand. Similarly, on the south coast of Wellington, uplifted shore platforms occur and despite lateral erosion rates of up to 0.15 m/yr the sea cliff is also inactive (Kennedy & Beban 2005).

Within New Zealand uplift rates vary up to 4 mm yr^{-1} along the Hikurangi subduction margin with subsidence of 4 mm/yr occurring in the Marlborough Sounds (Berryman & Hull 2003). Numerical modelling of tectonically active rocky coasts over Quaternary eustatic cycles has indicated that highstand terraces are best preserved on uplifting shorelines, whereas subsiding shores tend to preserve lowstand terraces (Trenhaile 2001, 2002). This can be observed in the uplifting northern Wanganui Basin where there are 12 marine terraces dating back to 680 ka and up to 300 m above sea level (Pillans 1983). These terraces unconformably overlie the Plio-Pleistocene Wanganui Basin, representing some of the world's best preserved eustatic sedimentary sequences for this period (Naish 2005; Naish et al. 2005a,b). Although not as extensive, the east coast on both the North and South Islands also has well developed terraces (Kaikoura–Malborough, Ota et al. 1996; and northern East Cape, Yoshikawa et al. 1980), each representing various high eustatic stages along uplifting coasts. Around Mahia Peninsula late Pleistocene marine terraces are preserved (Berryman 1993a), and along parts of this shoreline a sequence of uplifted shore platforms also occur, each recording Holocene earthquake events (Berryman 1993b). Drowned marine terraces are less well studied, partly due to logistical difficulties. Holocene subsidence has been occurring in both Napier (Berryman 1988) and the Rangitaikei Plains (Nairn & Beanland 1989), with drowned terraces of late Quaternary age described in the Malborough Sounds (Singh 2001).

During formation of marine terraces, each coseismic uplift or eustatic event results in the sea cliff being raised beyond the action of waves. Hence, cliff form subsequently becomes dependant solely on subaerial processes. Fluvial dissection of cliffs often occurs rapidly after abandonment by the sea, while terrestrial sedimentation tends to be slower. In the Wanganui region accumulation rates of 6 m/100 ka (Pillans 1985) occur on terrace surfaces while valleys are initiated almost immediately after abandonment by the sea with streams eroding headward at rates of approximately 2 mm/yr (Pillans 1988). Pillans (1988) identified the period of maximum profile change as occurring within the first 10 ka (little variation occurs after 300 ka), which is coincident with the length of the Holocene period, implying that the maximum rate of profile change presumably occurs on recently uplifted cliffs rather than those which may be inherited from older highstands. Hence, even though cliffs may have their toe protected by sediment and rarely, if ever, be linked into the contemporary marine system (e.g., east coast of North Island, Fig. 4C,D), retreat may still occur. Such an example can be observed on the well studied Kaikoura Peninsula. Holocene uplift is estimated at around 1.5 m/ka (Ota et al. 1996) with raised gravel beaches on the southeastern portions of the peninsula protecting the cliff base from wave erosion. The debris-mantled cliff contrasts markedly in steepness with cliffs which are fronted by shore platforms. Platform downwearing at these locations has meant

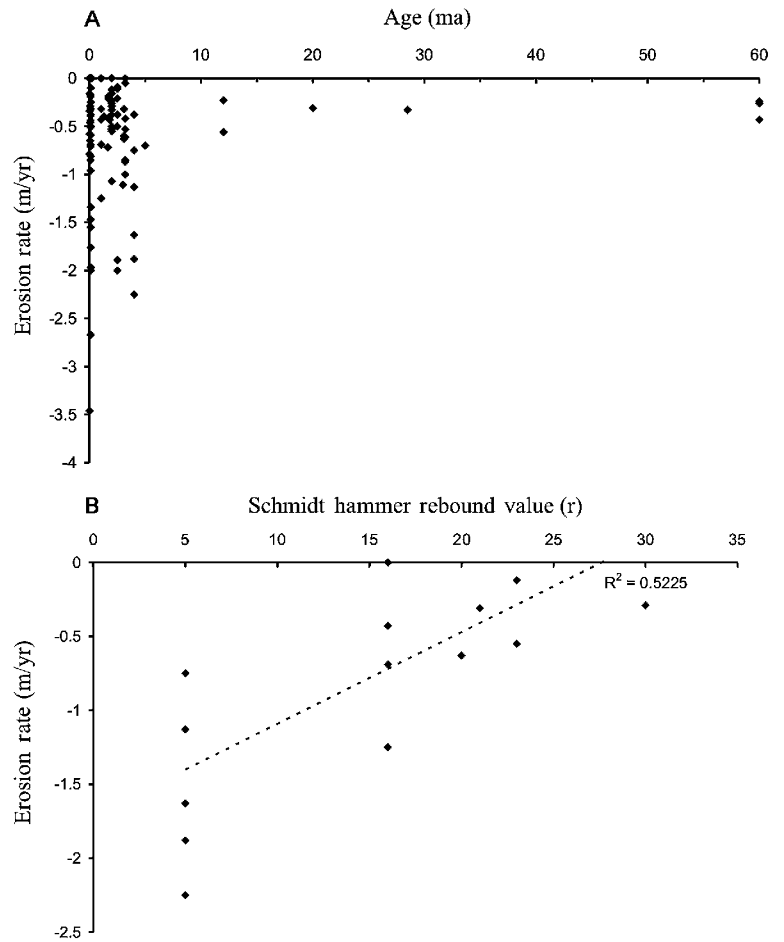

Fig. 5 The relationship between erosion rates derived by Gibb (1978) and **A**, lithological age and **B**, rock hardness. Lithological age is determined by the latest geological mapping and rock hardness from field strength testing as part of this investigation. See Table 1 for details.

the landward cliff has remained active (Kirk 1977; Stephenson & Kirk 2000b, 2001) with a resulting near vertical profile (Fig. 4E).

Historic erosion rates within New Zealand

The benchmark study for historical erosion rates around New Zealand's coast was conducted by Jeremy Gibb in 1978 and several regional authorities continue to use this data in their coastal management planning. Gibb's study was primarily based upon a time-series analysis of historical aerial photographs and cadastral maps. He showed that along New Zealand's 10 000 km shoreline, 25% is eroding, 19% is accreting, and the remainder shows no discernible trend of advance or retreat. With respect to the cliffed shoreline, the maximum erosion rate occurs on the southeastern Wairarapa coast at Ngapotiki where 9.5 m/yr of retreat was recorded between 1944 and 1973 (Gibb 1978, 1984). The majority of erosion rates along cliffed shores ranged from 0.02–0.5 m/yr comprising 44% of the cliffed shoreline length. For the entire country,

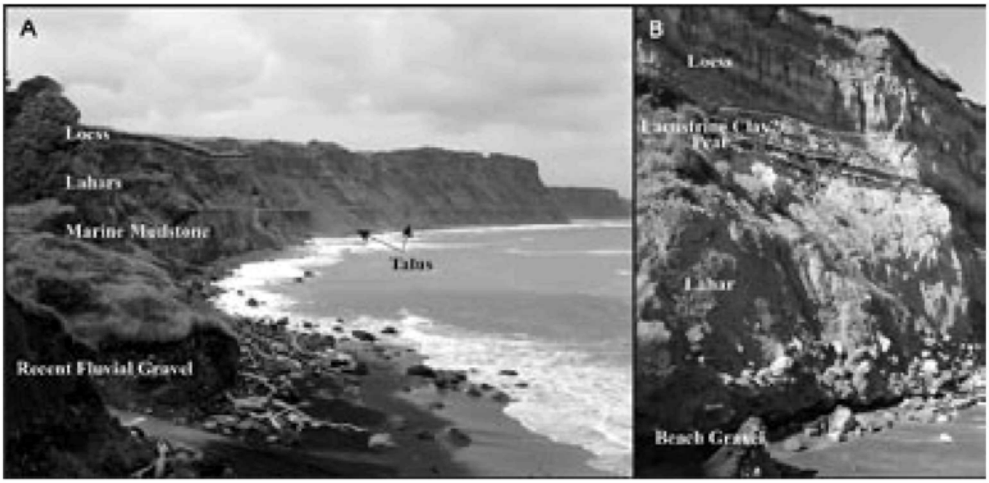

Fig. 6 **A**, Cliff line at Ohawe, South Taranaki. Marine units form the vertical face at the base of the cliff while volcanic sediments in the centre and upper parts of the cliff are reclined and subjected only to subaerial processs. These volcanic units are also the source of the talus at the cliff base. **B**, Cliff profile at the Willis Rd end, east New Plymouth. Beach gravels are incorporated into the base of the cliff profile which is dominated by lahars with loess at the cliff top.

eroding and stationary cliffed shorelines account for 20% and 3% respectively of the entire coast (Gibb 1984).

Gibb (1984, p. 145) noted that erosion rates for sea cliffs are largely determined by the resistance to erosion (subaerial and marine) of the rock from which they are formed; those lithologies with many structural weaknesses have the greatest susceptibility. This is well observed along East Cape where extensively deformed late Cretaceous–early Tertiary sediments are highly susceptible to erosion (retreat rates of 0.92 m/yr), while those shorelines composed of the Matakaoa Volcanic Group are essentially static with erosion rates of 0.01–0.02 m/yr (Gibb 1981). A re-assessment of the erosion rates published by Gibb in the light of more recent geological mapping of the sites indicates that shoreline retreat is greatest in those lithologies younger than 5 ma (erosion rates <0.6 m/yr) (Fig. 5A), which reflects the greater induration of the older units.

On the basis of field survey and rock-strength testing (using both N- and L-type Schmidt hammers in accordance with the recommendations of Day & Goudie (1977) and Selby (1980) and using Chauvenet's criterion to remove outliers as described by Göktan & Ayday (1993) and Dickson et al. (2004)) along the entire rocky coast of the lower North Island in 2005, it is possible to highlight some of the local controls on high erosion rates. One of the main areas of cliffed shoreline retreat occurs along the Taranaki coast as well as the eastern Wairarapa. Nearly all these lithologies are Tertiary or younger in age, and composed of either marine or volcanic units. In general, erosion rates are higher in softer rocks ($R^2 = 0.52$) as measured with the Schmidt hammer (Fig. 5B, Table 1), however, several critical factors affect this. First, a high degree of variation in local lithology is observed and often those units in direct contact with the sea account for only a minor proportion of the entire cliff edifice (Fig. 6). Second, many of the units are essentially structureless, partly due to their young age and lack of lithification, joint planes, foliation, and other such lineations. This allows many cliff lines to stand tens of metres high despite low overall hardness (Schmidt hammer rebound <10) (Fig. 7A,B).

As Cotton noted early in the 20th century, nearshore water depth plays a major role in cliff evolution. In particular, the extent to which sediment accumulates at the cliff toe is important. Where there are large beaches at the cliff toe the sediment acts as a buffer against further erosion, whereas thin beaches provide material that acts as an abrasive and may actually exacerbate erosion rates (Robinson 1977). Around the coast of Taranaki the proportion of cliff sediment of beach grade imparts a direct control on erosion rates. For instance, where siltstones from the Wanganui Basin outcrop, cliffs tend to be near-vertical (Fig. 7A,B) as fronting beaches are narrow and offer little protection from wave erosion. By contrast, in other areas volcanic and laharic sediments have accumulated at the cliff toe and provide a greater level of protection against further cliff retreat (Fig. 7C,D).

Prospects

Methods of studying cliffed coasts can be broadly separated into those that focus on soft and hard lithologies. For soft-rock cliffs, rates of recession are sufficiently high to be measured from historical photographs and cadastral maps (provided that sufficient care is taken, as erosion rates of centimetres per year may fall within the error bounds of photogrammetric methods). Such techniques form important baseline datasets, such as Gibb (1978, 1984), for forward-looking coastal management. On the other hand, such practices do not take account

Table 1 Age and Schmidt hammer rebound values for those lithologies surveyed in the field where historical erosion rates have been established.

Location no.*	Location	Lithology†	Erosion rate (m/yr)*	Mean R (L type)†	Mean R (N type)†	Age (ma)‡	Source
119	Kai iwi Beach	Siltstone	1.25	16 ± 1.0	20 ± 0.4	1.05	Naish et al. (2005b)
119	Kai iwi Beach	Siltstone	0.43	16 ± 1.0	20 ± 0.4	1.05	Naish et al. (2005b)
119	Kai iwi Beach	Siltstone	0.69	16 ± 1.0	20 ± 0.4	1.05	Naish et al. (2005b)
131	Ohawe Beach	Fine Sandstone	0.63	20 ± 1.1	<10	3.10	Naish et al. (2005a)
164	South Onaero	Siltstone	0.55	23 ± 0.7	18 ± 0.9	2.00	Edbrooke (2005)
165	South Onaero	Siltstone	0.12	23 ± 0.7	18 ± 0.9	2.00	Edbrooke (2005)
175	Pukearuhe Road	Siltstone	0.29	30 ± 2.0	28 ± 1.8	2.00	Edbrooke (2005)
340	Castlepoint	Mudstone	0.31	21 ± 3.1	19 ± 1.6	20.00	Lee & Begg (2002)
342	Cape Turnagain	Mudstone	2.25	<10	<10	4.00	Lee & Begg (2002)
343	Cape Turnagain	Mudstone	0.75	<10	<10	4.00	Lee & Begg (2002)
344	Cape Turnagain	Mudstone	1.63	<10	<10	4.00	Lee & Begg (2002)
345	Cape Turnagain	Mudstone	1.88	<10	<10	4.00	Lee & Begg (2002)
346	Cape Turnagain	Mudstone	1.13	<10	<10	4.00	Lee & Begg (2002)

*Gibb (1978).
†This study.
‡Age from published mapping.

Fig. 7 Cliff profiles in the massive marine mudstones at **A**, Kaiwi, north Wanganui and **B**, Patea, south Taranaki. Sloping cliff top profile in the laharic sediment at **C**, Manaia, South Taranaki and **D**, basaltic boulder beach at the base of the cliff.

of potential impacts of future climate change (Dickson et al. 2007) or the possible control of antecedent topography (Dillenburg et al. 2000). On hard-rock coasts retreat rates are so slow as to be beyond the bound of modern process-based geomorphology in which measurements are key. Accordingly, observation-based approaches have been necessary, often employing classical geomorphological methods such as the space-time substitution used in the observations of Savigear (1952) in South Wales.

The predominantly descriptive international literature on hard-rock coasts has yielded some insights into formative processes (e.g., shore platforms tend to be higher where there are harder rocks). More often, however, results from site studies have been difficult to transfer to other locations (e.g., in some locations shore platforms are wider where wave exposure is greater, but in other settings the reverse is true). One prospect for reducing such ambiguity may be to extend traditional morphometric studies from local to regional scale using automated data extraction from airborne laser scan information, as described by Palamara et al. (2007). However, it is also important that researchers take up the challenge of fundamental process-based studies on rocky coasts. Some advances have already been made. For instance, on the Kaikoura Peninsula there is now a 30+ year record of rates of change (millimetres per year) on shore platforms recorded from micro-erosion meter bolt sites (Kirk 1977; Stephenson & Kirk 2000a,b; Stephenson 2001; Stephenson et al. 2004); in Europe, laser-based scanning has been used to intricately map erosion surfaces in order to identify the nature of weathering processes (e.g., Goméz-Pujol et al. 2006; Swantesson et al. 2006); and in the United Kingdom, automatic terrestrial laser scanning systems have been used to repeat-scan cliff faces yielding new information on failure modes (Lim et al. 2005). Such methods are generating new understanding, particularly of the role of subaerial weathering processes. By contrast, aside from some laboratory experiments a number of decades ago (e.g., Sanders 1968; Sunamura 1992), relatively little work has been conducted on the ability of waves to erode hard-rock cliffs. An interesting recent study in this respect utilised seismometer measurements to show that cliffs shake in response to direct wave impact, and flex in response to water load on the shore platform. It was hypothesised that this movement of the sea cliff fatigues cliff rock by micro-cracking, which lowers the bedrock strength and makes the cliff subject to failure under direct wave attack (Adams et al. 2005).

For both soft- and hard-rock coasts, numerical modelling appears to hold particular promise for advancing both our general understanding of coastal evolution, and our ability to predict the future response of rocky shorelines to changing boundary conditions. The paucity of previous process-based studies means that many mechanisms of cliff erosion are poorly understood, which clearly imparts a major restriction on efforts to develop numerical process-based models. Additionally, in contrast to morphodynamic models available for use over short timescales (hours, days), the rate of change on rocky coasts requires that models simulate tens, hundreds, and even thousands of years. Hence, rocky coast models must represent processes and interactions using quite abstracted numerical descriptions. A third difficulty facing the cliff modeller is that traditional model verification (comparing model results to measured results) is restricted to locations where historical data are available. Despite these difficulties, several models have been developed.

On hard-rock coasts, models have employed simple descriptions in order to investigate some fundamental principles of rocky coast evolution. For instance, Sapoval et al. (2004) developed a simple model to investigate why it is that the geometry of rocky sea coasts often evolves toward fractal morphology. A scheme was developed in which a lattice of cells is provided with values to represent rock lithology and rock resistance. Rock lithology is variable, and rock resistance takes on a value depending both on its lithology and also its exposure to sea. At each timestep, if the force of waves (represented by wave height) exceeds the cell resistance, then the cell is eroded. Hence, some cells are eroded because they represent a weak lithology, whereas others are eroded because of their exposure to the sea. Beginning with a smooth coast, the shoreline progressively roughens, forming islands. As the length of the coast increases, wave power becomes increasingly attenuated and eventually the model stabilises when wave power is less than the weakest cell. At this point the coastal morphology is fractal. This minimal model provides one explanation for the fractal geometry of rocky coasts; while erosion of rocky coasts may spontaneously create irregular shorelines, this geometrical irregularity damps wave power, such that there may exist a mutual self-stabilisation of the wave height with the irregular morphology of the coast.

In several studies it has been suggested that in the case of a shoreline composed of less resistant rocks, or where the fraction of fine material within bedrock is higher, the local shoreline retreat rate should be higher than in adjacent areas of coast. Over the long-term such a hypothesis would result in an increasingly jagged coastline, as described by Sapoval et al. (2004). By contrast, on sandy coasts backed by rock, the shoreline actually tends to be quite smooth. To explain this apparent paradox, Valvo et al. (2006) developed a simple model comprised of a lattice of cells containing proportions of sea water, sediment and rock. Sediment is transported between cells using a well known equation for longshore sediment transport, while a weathering function converts rock to mobile sediment at a rate that is controlled by the thickness of sediment overlying the rock. The model algorithm tracks the boundary between water and sediment, and between sediment and rock. Model behaviour showed that rock is more protected from weathering where sediment accumulates, and that alongshore sediment transport causes sediment to accumulate if the properties of the rock cause accelerated shoreline erosion. Hence, the apparent paradox is explained in the model behaviour in which over time relatively smooth shoreline shapes emerge with alongshore-uniform recession rates.

In contrast to the aforementioned models, which explicate contrasting examples of alongshore shoreline evolution, Dickson et al. (in press) developed a simple cross-shore profile evolution model to investigate the evolution of rapidly eroding alluvial fan shorelines. The model defines a critical threshold between fair weather and storm conditions (under which cliff erosion occurs), and erodes a profile into an initially gently sloping alluvial fan on the basis of bottom shear stress under incident wave action. The rate of abrasion of coarse sediment is identified as a key variable, ultimately controlling rates of shore recession as well as emergent beach volumes.

The aforementioned models have focused on answering qualitative questions about morphological evolution. It is also possible, however, to use simplified numerical models to address quantitative questions, such as the extent to which future sea-level rise may accelerate cliff erosion rates. Walkden & Hall (2005) developed a model to predict the rate of cliff retreat on eroding soft-rock glacial till shorelines. Describing cross-shore profile evolution, the model describes a series of horizontally stacked cells that erode landward due to wave force. Differential erosion of these cells (due to the distribution of wave energy) produces a profile shape, which through time begins to retreat parallel to itself. The primary negative feedback path which ensures model stability over long time periods is that a steeply sloping profile promotes an aggressive wave breaking shape, which leads to greater erosion, which leads to a more gentle profile shape, which causes less erosion. The model is extended alongshore using a sediment transport model and multiple cross-shore profiles. In this form, and because the model is process-based, the impacts of climate change and management can be explored. Dickson et al. (2007) used the model in such a capacity. Firstly verifying model predictions against more than 100 years of historical recession data, the model was used to provide predictions between 2000 and 2100 of future management and climate change on recession rates. For the scenarios evaluated the model showed that cliff retreat rates are likely to increase in response to sea-level rise, but that alongshore patterns of cliff retreat are variable due to changes in sediment transport patterns (and associated beach build up). In fact, the model predicted that due to alongshore effects on some sectors of coast, sea level rise actually resulted in a decrease in cliff erosion rates. Such a result is non-intuitive, but logical when considered in the light of the model results, and underpins the value of such modelling studies in comparison to simplified extrapolations of historical recession rates or applications of the modified version of the Bruun-rule (e.g., Bray & Hooke 1997).

In summary, within New Zealand there has been and continues to be only a small body of researchers focused on the evolution of cliffed coasts. As in other parts of the world, much of the previous research in New Zealand has employed descriptive field survey of cliff and platform morphology. While there is value in this type of study, it is also generally the case that there are major difficulties detangling ambiguous process-form relationships using such methods, particularly in respect to understanding shore platform morphology. In this respect, one prospect in the morphometric study of platforms may be to extend local studies to regional scale using remote data gathering technologies coupled with automated data extraction methods. Particular advances in our understanding of cliffed coasts will likely occur through a new emphasis on process-based studies, together with the continued prolification in numerical modelling methods of the type described above. Such models will remain relatively simplistic in terms of the level of amount of detail afforded to numerical description of processes, because many mechanisms of change remain poorly understood. However, numerical modelling holds a key both in science terms for generating new understanding, and in management terms for providing useful quantified estimates (with inbuilt estimates of model uncertainty) of future shoreline change under various scenarios.

CONCLUSIONS

The cliffed coasts of New Zealand are evolving at varied rates in response to local geology and forcing. High rates of cliff retreat are related to the young (Tertiary and Quaternary) lithologies that comprise much of the eastern coastlines of both islands. Such rates contrast with resistant lithologies in various areas where retreat rates are measured over millennial rather than decadal timescales. Despite a relatively long history of study, the length and variability of New Zealand's shore means that descriptive studies will remain a major research theme in upcoming years. However, automatic ground-based survey systems as well as airbone laser scanning technology provide an exciting opportunity to extend traditional laborious field study. The increase in scale permitted by such studies will re-invigorate the difficult task of disentangling ambiguous process-form inter-relationships in the field. Process-based studies remain difficult on rocky coasts, but further measurement of erosion rates at the bolt sites installed on Kaikoura Peninsula will continue to provide an important record of the efficacy of the weathering process in rock coast environments. Further developments in the field of process studies require novel methods, such as those relating wave loading to cliff shaking. Modelling will continue to be limited by a lack of understanding on detailed process mechanics, but even with simplified process representations, models have been shown to be useful for understanding some basic system behaviours. At present, management of eroding cliffed coasts rests on, at best, a study of past trends and their extrapolation into the future. Changing global climate as well as human land use means that passed trends may not provide a realistic picture of future erosion rates. Continued development in numerical modelling combined with more detailed quantification of New Zealand's coastal systems represents the best prospect for improving on such predictions, as well as understanding the sensitivity of trends to climate change, particularly sea-level rise, and other perturbations.

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