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Engineering Geology and Coastal Cliff Erosion at Takapuna, Auckland, New Zealand

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Summary: Actively eroding cliffs at Takapuna on Auckland's north shore support prime residential properties and consist mainly of very weak to weak alternating sandstones and mudstones of the Miocene Waitemata Group. Stronger limonitic sandstone and Parnell Grit form headlands and reefs. Weathering to extremely weak soil these beds are overlain in places by Quaternary alluvium and slope debris. The sandstone and mudstone are porous, low-density materials, which slake. The mudstone readily disintegrates into small chips, which erode, undercutting the sandstone. This fails by block fall on two mutually perpendicular fracture sets. Folding changes the dip direction. Failures in the weathered rock and residual soil take place on bedding planes between 30^0 and 60^0 dip. Fractures and faults with gouge trend both into the cliff and parallel to it. Toe erosion and erosion of fault gouge perpetuates instability in the form of slabbing, block falls, slides and wedge failure along defects. Failure on defects presents the greatest slope hazard. Erosion rates from 2.6m to greater than 12.7m per 100 years are recorded from observation of fixed points along the cliffs.

INTRODUCTION

The actively eroding cliffs at Takapuna (Figures 1, 2 and 3) are typical of Auckland's coastline. Urban expansion and demand for cliff top properties have resulted in engineering challenges and expensive remedial measures along this interface of urban development and cliff recession. Management of the cliffs and protection of properties are facilitated by a good understanding of the geology and erosion processes.

At Takapuna gently sloping hills around 10-30m above sea level terminate in steep (60" to 80°) coastal cliffs. These expose weak, highly weathered sandstones and mudstones and residual soils of the Waitemata Group, with lenses of stronger volcaniclastic Parnell Grit

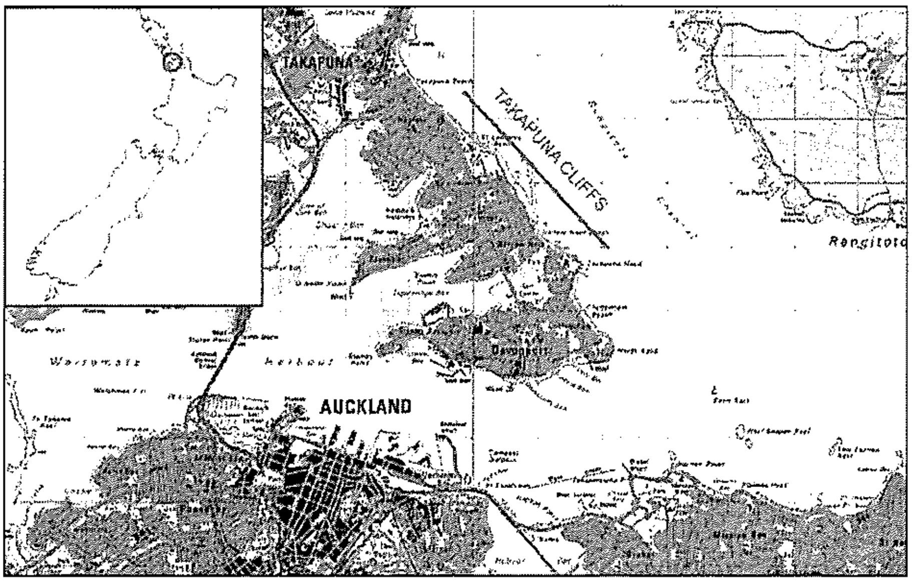

Figure 1. Locality Map

GEOLOGY

Deposited in a marine basin by turbidity currents during the Miocene, the sediments of the Waitemata Group derive mainly from the erosion of andesitic volcanoes on the western margin of the basin (Ballance 1974). Turbidite sands are interbedded with silt, mud and fine sand from suspended material. The Waitemata Group can be referred to as flysch and represents the distal deposits from erosion of the volcanic arc (Ballance et al 1977).

Large debris flows into the basin deposited Parnell Grit, a sandy volcanigenic conglomerate, which is interbedded with the flysch sequence. Burial and diagenesis consolidated the sediment into very weak to moderately strong rock. Typically the flysch is flat or gently dipping, but there are zones of complex folding.

Subsequent uplift, weathering and erosion of the Waitemata Group was followed by deposition of Quaternary material in topographic lows, unconformably on exposed and weathered Waitemata Group strata. Weathering has reduced the strength of the rock mass. Much of it is now residual soil to very weak rock.

EAST COAST BAYS FORMATION

The rocks are mostly well-bedded sandstones and mudstones (or siltstones) of the East Coast Bays Formation, part of the Waitemata Group. These rock masses and their residual soils are found in the cliffs along Auckland's coastline. The soils typically consist of silts and a lesser clay content with mudstones producing a more clayey soil than sandstones. Extremely to highly weathered material may extend 5-10 metres deep. Unweathered rock is found only at a few tens of metres depth in deep boreholes, excavations and tunnels (e.g. Wylie 1989).

Table 1. Properties of the East Coast Bays Formation

Lithology	Strength (UCS)	Weathering Grade	Saturated Density	Porosity (%)	Slaking (jar index)
Sandstone	1 to 3.6	EW-HW	1.89	31	3
Mudstone	1 to 5	EW-HW	2.42	37	2
Limonitic Sst	9*	HW	1.97	27	5

Sandstones

The sandstone is mainly an extremely to highly weathered, extremely weak residual soil to weak rock, which spans the rock/soil boundary of 1 MPa u.c.s (Table 1). It is light grey to light brown. An increase in limonite creates an orange tint and a rise in field strength from R1 to R2 (i.e. from very weak to weak).

Individual beds are massive, homogenous, muddy and poorly sorted although some beds exhibit normal grading with coarser material at the base, fining upwards. Occasional rounded mudstone clasts (typically less than 10cm) are found parallel to bedding. Bed thickness ranges from ~10cm up to ~2m, with the majority of beds being between 0.3m and 1.0m thick. The basal contacts are sharp. Contact with the overlying mudstone is gradational.

Grain size varies from coarse sand (0.06-2.0mm) to clay particles in the matrix (0.002mm). Thin section and SEM work showed that the greater the degree of weathering the higher the percentage of finer grained material, both in the matrix and within the decaying grains. The sand grains are sub-rounded to well rounded and set in a porous clay-rich matrix, which is mainly smectite. Hence the sandstones are matrix supported. The grains are mainly quartz, feldspar and fragments of penecontemporaneous siltstone, subordinate argillite and andesite with rare glauconite, biotite and zeolites (identified as clinoptilite under XRD). Opaque grains of limonite and organic rich material (including foraminifera) were also prevalent.

Sandstone is slightly more resistant to slaking than mudstone and sandstone beds are observed protruding from the cliff face, overhanging the mudstone beds.

Mudstone (siltstone)

The mudstones are mainly a highly weathered 'soft' weak rock. They are light to dark grey depending on moisture and grain content. The rock is mostly massive and homogenous with some beds exhibiting normal grading (fining upwards) and some very fine sandy grains. Occasional sandy laminae can include specks of carbonaceous material. Bed thicknesses can be over 1m but typically do not exceed 0.5m. Abrupt contacts occur at the top of the beds against the base of the overlying sandstone. Basal contacts are more gradational.

The mudstone consists of silt-sized quartz, feldspars and lithics in a clay matrix. Glauconite and organic material also occur. The grains are very well sorted and tend to be parallel to bedding. The clay was identified by XRD and SEM as smectite, kaolinite and illite.

Unconfmed strength of mudstone is 1-2 Mpa, with tests on small *dry* mudstone fragments averaging around 5Mpa (Table 1). Field strength is very weak (R1). bordering on the rock/soil boundary.

Mudstone slakes quicker than sandstone. However, this difference is not thought to be the cause for its faster erosion rate in the cliffs, where mudstone is always seen undercutting sandstone. It is believed to be more a result of the way it slakes, forming small curved fragments, usually < 1 cm in length, which are easily removed.

Limonitic Sandstone

Limonitic sandstones are sandstones cemented with limonite (hydrated iron oxide) and have different engineering geological properties. They are exposed on the shore platform of headlands and are foundjust above or below the high tide mark. Like the sandstone these beds are highly weathered but stronger (Table 1 and field strength R3-R4). Schmidt hammer readings do not appear to give a true estimate of their overall strength and the results were variable. Rock block interlock strength is tight requiring 2-3 hammer blows to dislodge a jointed block.

The mineralogy is very similar to that of sandstone (rounded quartz, feldspar and lithic fragments) but there is a much greater concentration of limonite grains. Glauconite also appears to be more common. The amount of limonite varies with colour. Smaller amounts are found in the light brown zones.

Parnell Grit

This is a coarse volcanic conglomerate consisting of angular fragments tightly bound in a matrix. Clast size is typically <10mm with some larger rip-up fragments of the sandstone/mudstone flysch. The fragments are very poorly sorted and are set in a variable light grey clayey matrix, which is rich in smectite. Limonite staining in some places can give an orange tint.

Mineralogy of the clasts includes andesitic and basaltic volcanic lithic fragments, sedimentary clasts, feldspars, altered glass (palagonite?) and traces of glauconite, biotite, and zeolites. No quartz was identified. Large black clinopyroxene crystals (up to 2mm) are visible. Very coarse feldspar crystals are highly altered and the basaltic clasts have vesicles infilled with clays. Occasional forams, bryozoans and echinoid fragments were identified.

Field strength is moderately strong to strong (R3-R4) requiring several firm hammer blows to break. Schmidt hammer readings give an unconfined compressive strength of 14 Mpa (Table 1). The material chips through the matrix and clasts rather than breaking off. The Parnell Grit is also the most erosion resistant rock and can be seen forming reefs both in the shore platform and further offshore. Its strength is similar to that of some limonitic sandstones meaning slaking may be more important than strength in erosion of rocks in the study area. Overall the unit is slightly weathered with some clasts being moderately to highly weathered.

QUATERNARY DEPOSITS

A mantle of recent soil debris is found in the upper part of the cliffs and on gentler slopes. Soil debris is often bound together by roots of trees, especially pohutukawas. Alluvial material of the Tauranga Group overlies large areas of the Takapuna cliff section. This is unusual as it is more common for alluvium to fill valleys eroded into the Waitemata Group. In the cliff face it is difficult to distinguish alluvium from residual soils of the flysch.

DEFECTS

Even in very weak rock and residual soil of the East Coast Bays Formation, defects influence slope failure, such as in the Southern Landslide Zone and the North Shore (Prebble 1995 and 2001, Buckeridge 1995).

The sandstone is dissected by two perpendicular joint sets (Figure *2)*, which increase in spacing with bed thickness. The mudstone has an extremely closely spaced fractured surface (Figure *2)* that is easily dislodged causing comparatively rapid erosion.

Very narrow (–1 mm aperture) fractures are continuous throughout the sandstone beds, regularly spaced at intervals ranging from 10mm up to 1m and in some places several meters. Most of the joints are limonite filled and perpendicular to bedding, varying only –20" off vertical. Two sets of joints strike approximately at right angles to each other, creating tabular blocks, which tend to break off when undercut. One dominant fracture set in the sandstone strikes north or northeast approximately at right angles to the coastline and another set usually more or less parallel to the coast. The dip of 60-70° is similar to the cliff slope angle. Steeply dipping faults also strike into the cliffs with another set running parallel to the cliffs. Several continuous faults can be seen parallel to the cliffs in the shore platform.

When dried out completely, an extremely closely fractured and tightly interlocked zone forms on the surface of the mudstone (Figue *2)*. It produces curved chips approximately 1cm in length. This is a result of slaking by swelling clays, which change volume during wetting and drying of the cliff face. This disintegration of the mudstone only extends a few centimetres (<10cm) into the rock. Deeper than this the mudstone is moist, malleable, dark grey and massive.

Parnell Grit has no well-developed fracture sets. Joint spacing is variable, ranging from a few centimetres up to several metres with variable orientation. Limonite filled joints are also prevalent.

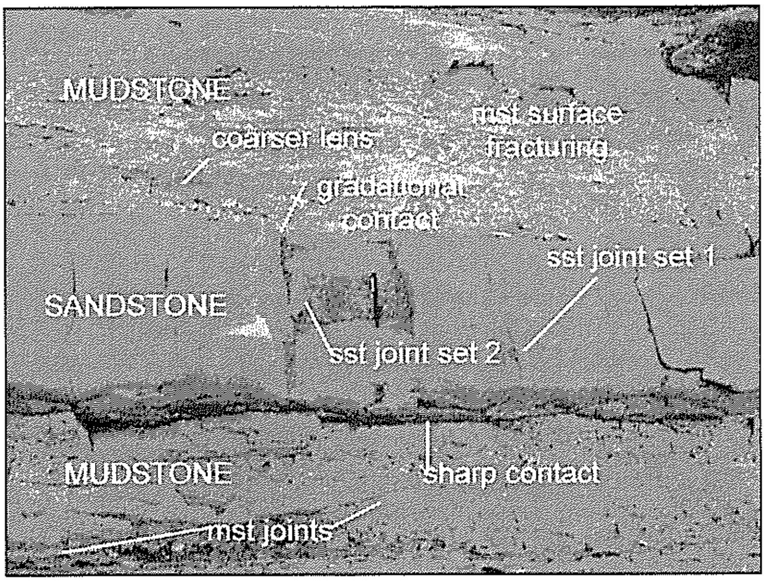

Figure *2*. Sandstone and mudstone beds showing contacts and joint sets.

EROSION PROCESSES AND CLIFF INSTABILITY

Local folding has produced varying dip direction, which has a significant control on slope stability, with failures occurring in extremely weathered rock or residual soil on bedding planes dipping between 30" and 60". Failure occurs at the sharp contact between sandstone and mudstone.

Faults running perpendicular to the cliff face form narrow coves, gullies and caves as the fractured fault gouge is loosened and eroded. Joint fractures erode in a similar way to faults but there is no gouge so failure is in the form of block fall in combination with bedding planes.

Gradual erosion of the cliffs by wave action forming a notch at the base is ongoing. This destabilises the cliff and promotes falls, slabbing and slides or wedge failures along intersecting defects.

Frittering

Disintegration of the extremely closely fractured surface of *dry* mudstone produces fragments, which are removed by rainwater, waves and wind. These fritter away, resulting in undercutting of the overlying sandstone beds. Mudstone frittering is ubiquitous.

Block fall and Slabbing

Block fall refers to blocks bounded by joints. Slabbing is the exfoliation of slabs on defects, which form parallel to the cliff face often as a result of relaxation of the cliff. The two processes are very similar and difficult to tell apart in the field. Frittering mudstone layers undercut sandstone blocks which then fail by block fall. This is responsible for most cliff face erosion.

Slabbing is observed in coastal cliffs of Auckland (Simpson 1988), in tunnels in the East Coast Bays Formation (Wylie 1989) and in high, steep cliffs of the central North Island (Prebble 1995). Large block fall or slabbing failures occur when notches have sufficiently undercut a cliff face or when it has been over-steepened by smaller block falls.

Jointed block fall is the most dominant cliff failure mechanism eroding Waitemata Group cliffs with 60% of the displaying some form of block fall (Roy 1997). It is also considered to be responsible for the average retreat rates in the cliffs with very high proportions of mudstone speeding up the mechanism (Moon and Healy 1994).

Wedge Failure

These involve two defects that intersect allowing a wedge shaped rock and/or soil mass to pull away. This is the cause of most of the large failures observed in the Takapuna cliffs. As discussed earlier, failures are observed on defects dipping between 30-60". These include faults and joints (Figure 3) and bedding planes.

Wedge failures are particularly hazardous to cliff top properties. This is because the dip of the failure plane means the head scarp of the slide will be set back from the cliff face, allowing a considerable volume to slide out.

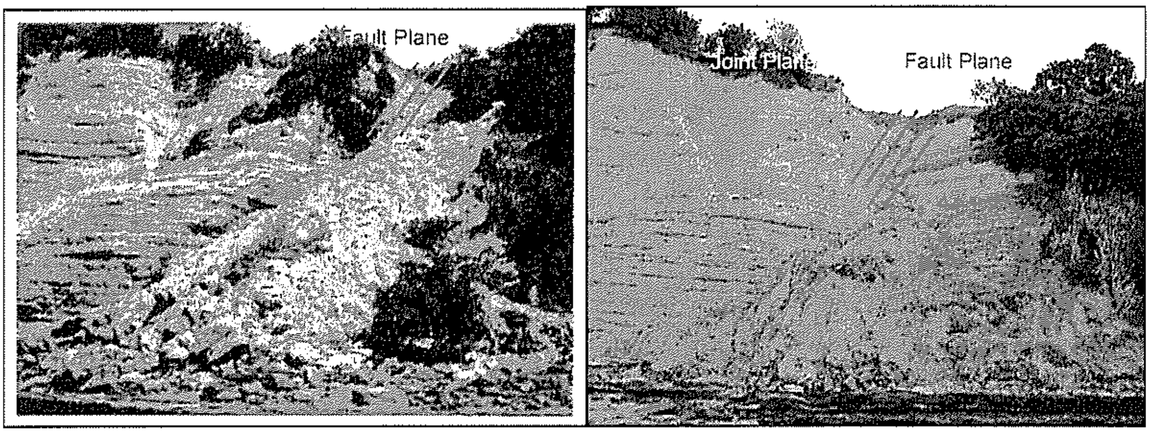

Figure 3. Large wedge failure at Takapuna Grammar fields. Initial failure was along a fault plane (dipping at 42°) as seen in the photo on the left hand side (photo from Simpson, 1988). Subsequent failures along an intersecting joint (photo taken by author, 2002).

Residual soil failures

Residual soil failures can be both translational and rotational with deep curved failure planes. They pose the greatest immediate risk to cliff top property. The overlying soils typically slope down at a stable angle to the cliff top. Retreat of the cliff face oversteepens the soil profile which eventually fails - usually in saturated conditions. This keeps the cliff in a delicate equilibrium. Vegetation (particularly pohutukawa trees) and moisture content (rainfall events) affect this equilibrium which, when unbalanced, leads to soil failures. These failures can occur on defects masked by weathering. Another common failure is a translational slide of the soil along the underlying rock. Failure is attributed to excess water at an abrupt soil/rock interface. Failure also occurs at the contact of alluvium and weathered East Coast Bays Formation (Price 1997). This is observed frequently along Seacliffe Ave. Continual gradual movement of the soil mass down slope is thought to produce tension cracks, which are observed at some locations along the cliff top. This soil 'creep' is exacerbated in the Waitemata Group by the swelling clays.

Contributing processes

Water

Water is involved in all the failures observed. In 1995 and 1996 approximately 20 failures occurred along the cliffs in the study area. This coincided with above average rainfall for some months in North Shore City. It is thought a large proportion of the failures were in alluvium, which is more likely to fail in wet conditions.

Vegetation

The most dominant vegetation is the pohutukawa tree, which can be found along the cliff tops throughout the region and are effective at binding the overlying residual soil and taking water from the soils. The pohutukawa tree temporarily stabilises the top of the cliff. This causes over-steepening as the cliff face retreats underneath. In time this will be undone as the tree will eventually fall, taking the soil bound in its extensive root structure with it. It may be a case of continual gradual retreat of the cliff top in the form of small residual soil failures where pohutukawas are absent, and occasional larger scale mass movement where they do line the cliff. In this regard, the affect of the pohutukawa tree can be seen as buying time between failures. This problem has come around as the forest of trees has been removed back from the cliff, typically leaving just one row of pohutukawas meaning when one falls there isn't another behind to take its place.

EROSION RATES

Further development on the cliff top properties requires official consents that take into account the likely cliff retreat over a 50 or 100 year period. Therefore, the erosion rates of cliffs are important for planning and for the design of structures. Erosion rates determined in this study are given below in Table *2*. Accurate laser monitoring of the cliffs is currently being looked at to provide a more definitive assessment of erosion. In combination with geological mapping this would provide a detailed means of zoning hazard potential of the cliffs and the risk to cliff top properties.

Table *2*. Erosion Rates in the Waitemata Group obtained in this study

	Structure and Location	Year Built	Observed Erosion Distance	Calculated Erosion Rate (m/100yrs)
1	Sewer, St Leonards	1926	1m (1963), 2m (2002)	2.6 and 2.7m
2	Survey MHWS, Seacliffe Ave	1926	3m (1995)	4.2m
3	Pipe and tower, Seacliffe Ave	1940's	3.5m (2002)	6.1m
4	Pipe and tower, Seacliffe Ave	1940's	5.3m (2002)	9.3m
5	Pipe, Lake Rd cliffs	1947	>7m (2002)	>12.7m
6	*Ancient Waitemata River*	*18,000 years ago*	*~2km*	*11.1m*
7	*Outer Shore Platforms*	*6,500 years ago*	*>~200m*	*3.1m*

In Table *2*, above, Locations 6 and 7 are late Quaternary geomorphic features, which were identified on aerial photographs and nautical charts. Their age has been assessed and the distance from them to the present cliffs measured to provide an estimate of long- term erosion over the last approximately 18,000 years and 6,500 years respectively.

SUMMARY AND DISCUSSION

The coastal cliffs at Takapuna consist mainly of interbedded sandstone and siltstone of the East Coast Bays Formation. These very weak to weak muddy rocks weather to extremely weak residual soils. Measured strength indicates that these materials are close to the rock/soil boundary. The low density and high porosity reflect the degree of weathering. The clayey matrix of the rocks and the abundance of smectite, a swelling clay, arise from the source of the original sediment on andesite volcanoes along the margins of the Waitemata basin. Background sedimentation and turbidite deposition ensured widespread distribution of andesitic detritus and mud, the main constituents of the formation. The sandstone and mudstone both slake readily with the mudstone being more reactive and disintegrating by body slaking into small chips. In the cliffs this has the effect of undercutting the sandstone beds, which protrude as unsupported ledges. These eventually fall off as blocks along mutually perpendicular fractures, which intersect the bedding planes. Lenses of Parnell Grit and the cemented cap to the limonitic sandstones are stronger and markedly more resistant to slaking than the sandstone and mudstone beds. This contributes to their ability to form reefs and headlands. Wave action forms a notch at the base of the cliffs, promoting instability above such as block fall, slabbing and wedge failures.

Defects control the majority of slope failures, even in the residual soils in the top part of the cliffs. Frittering of mudstones, block fall from the overhanging sandstones, and slabbing on defects together account for most of the cliff erosion. Wedge failures on intersecting, steeply dipping defects account for the large slope failures at Takapuna. These are hazardous because the wedge can extend several metres back into the cliff, creating a large set–back to the head scarp at the top of the cliff and causing the removal of large volumes of rock and soil. Pohutukawa trees temporarily stabilise the cliff top but eventually fall with a larger mass of residual soil attached to the root mat.

Erosion rates of 2.6m to 12.7m per 100 years have been obtained from fixed features of recent historic origin. These compare with the rates of 2 to 6 m suggested by Moon and Healy (1994). The lower end of this rate is also of the same order as the rate indicated from our geomorphic assessment of cliff retreat over the last 6,500 years, the period known as the Holocene Still-stand. There will always be areas of more rapid erosion as a result of wedge failures, very soft zones of fault gouge or soft soils. However it is suggested that the rates reflect the erosion attributable to slabbing, frittering and block fall under the existing conditions.

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