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Report on

MAUAO STABILITY ASSESSMENT
MOUNT MAUNGANUI, TAURANGA

Submitted to

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1. INTRODUCTION

Further to a request from the Tauranga District Council, the writer has carried out an overview of the stability of the slopes of Mauao – Mount Maunganui. The Council's Project and Contract Numbers for this work are 6482-39 and 1880-10-99 respectively.

The purpose of the project was defined as follows:

> *To undertake an overview of the north-eastern to south-eastern slopes of Mount Maunganui to ascertain their present stability, assess the risk they may present to the hot pool and camping ground complexes and walkway networks and recommend a short to long-term management strategy for on going remediation of the slopes and/or additional investigation to be undertaken.*

The Brief set out the requirements and aims of the study as being:

- *a review of the present state of the existing slopes*
- *a review of the stability of the rock outcrops above the lower slopes*
- *a summation of the geological processes involved with the formation of Mount Maunganui and the effects that the elements will have on the Mount over time*
- *a summary of the short and long-term risks posed by the present geology and topography as they relate to the camping ground, hot pools and general public using the track network*
- *recommendations for the mitigation of these short or long-term risks through remediation works, further investigations and public education and communication*
- *recommendations for any further investigative studies*
- *recommendations for any on going monitoring programmes and who should undertake these*
- *outline a long-term management strategy plan for the Mount in light of the findings of the review above*
- *provide indicative costs associated with any recommended remedial works, monitoring programmes and additional studies if required.*

The programme for this study comprised the following:

Sunday 7 March	*Travel from Christchurch to Tauranga*
Monday 8 March	*Discuss project with Mr Baunton & Mr Watson (TDC)* *Review documents, photos and other data at Tauranga District Council and Public Library (morning only – Accreditation Panel interviews in the afternoon)*
Tuesday 9 March	*Walkover survey of the camping ground and Base Track*
Wednesday 10 March	*Walkover survey of the upper slopes. Discuss project with Mr Scott (TDC). Visit camping ground site with Mr Hughes (Shrimpton & Lipinski)*
Thursday 11 March	*Collate notes and commence report. Return from Tauranga to Christchurch*

A draft report was submitted to TDC on 17 March 1999. Detailed comments were received back from TDC in various forms, notably Mr Baunton's letter of 22 April which also included comments by Messrs Scott and Watson. Specialist engineering geology input to the study was provided by Mr David Bell, Senior Lecturer in Engineering Geology, University of Canterbury whose review of the first draft and TDC's comments is contained in Appendix C. Mr Bell's comments have been incorporated into the text of this final report. The valuable contribution to this study made by TDC's reviewers is gratefully acknowledged.

2. SITE DESCRIPTION

2.1 Geological history

The 232m high rhyolite dome of Mauao (Mount Maunganui) is a major feature of the Tauranga landscape. Figure 1 is a plan of Mauao showing its main physical features together with the present network of roads, paths and fences. A vertical aerial photograph (1998) and two views of the mountain from the roof of the Oceanside Tower Block are shown in Figures 2 and 3. Figures 4 and 5 show details of two sections through Mauao in a south-north and west-east direction. The eastern and northern slopes of Mauao are significantly steeper than the other sides, probably as a result of wave undercutting on the flanks more exposed to ocean storms.

The volcanic geology of the area has recently been assessed by Hall[1] who describes the setting of Mount Maunganui as follows:

> *The general morphology of Mount Maunganui is of a steep-sided flat-topped dome reaching 252m in height. At the top of the dome steep bluffs and flow foliations are sub-vertical to vertical which is characteristic of flow structure at the vent. The middle section of the dome is steeply sloped and obscured by grass, rhyolite talus and tephra. At the base of the middle section the surface becomes less inclined which represents the top of a small terrace. This area of the dome is farmed. At the very base of the dome, highly eroded lava flows extend out into the sea. Their flow foliations vary from moderately to steeply inclined which represents the lava flowing away from the vent as more lava was squeezed up and extruded through the vent.*
>
> *Lithology of the Mt Maunganui rhyolite is varied. . . . The predominant lithology is flow-banded spherulitic rhyolite which is highly devitrified. A coherent breccia form is also common which is seen as dark grey clasts embedded in a reddish pink oxidised matrix.*
>
> (Note that the height of Mauao is consistently given as 252m in References 1 & 2 although elsewhere it is indicated as being either 231m or 232m. The survey data used in this report indicate a height of 232m).

Hall also notes that Pahoia Tephras outcrop along the base of Mauao.

The Mount Maunganui rhyolites are a formation within the Minden Rhyolite Subgroup[2]. When unweathered, the rock is dense, very strong to extremely strong (100 to >250 MPa uniaxial compressive strength) but weathers readily to a very weak rock or firm clay. The rhyolites exhibit a well-developed flow banding which imparts a strongly foliated structure often with flow folds on a small scale.

The development of the Tauranga Harbour area has been described by Davis and Healy[3]. In the early Holocene, the shoreline was a few kilometres offshore of its present position as sea levels were about 130m lower than present. Sea level stabilised about 6500 years ago and the barrier spit or tombolo now attached to Mauao began to grow from that time. The coast in this area achieved its present geomorphological character about 3000 to 4000 years ago.

The present topography of Mauao, with the boulder-littered colluvial apron below the rocky summit, attained its present configuration about the same time as the above, with little subsequent modification. The gullies on the north-east face of Mauao may relate to erosion occurring at slightly higher sea levels (≤ 1m above present level) during the period from about 3000 years ago, although they may also simply reflect increased wave heights from north-east storms. The slopes of Mauao are littered with numerous boulders, most of which are deeply embedded in the colluvium. These boulder fields are considered to have resulted from episodic accumulation over the last few thousand years rather than from any single event.

Six springs on the southern and eastern slopes have been recorded on a TDC plan of Historic Sites included in their Management Plan[4]. These generally seem to be in the vicinity of about RL30m. Despite the limited catchment area on Mauao, at least one of these springs, Wai Patukakahu, was noted as being a large spring and important water source.

2.2 Recent history

The importance of Mauao to the three iwi of the area is emphasised in the current Tauranga District Council Management Plans. Stafford[5] provides a description of the fortifications on Mauao in recent times:

> *Maunganui pa, situated on the symmetrical mount of that name, must at the time of these events have presented one of the most heavily defended positions in New Zealand. Covering about a*

hundred acres the fortifications crossed the top of the hill and ran down each side, where, circling around the base towards the south, they met. Waitaha lived on the eastern slopes of the mount and Ngati Ranginui held the west side, which overlooked the Tauranga harbour, and their total numbers were such that large though the pa was, there were more than enough fighting men to defend it. There was, however, one weakness in the defences and that was a point on the northern side which was so steep and difficult of access that it was considered unnecessary to defend it. This steep part was flanked on both sides by boulders, so that it would need only a handful of men to hold it against any number of invaders.

The pa was sacked and reduced to ruins by Ngaiterangi in the early 19th century. According to information in the Tauranga Public Library[6], there have been no Maori settlements on Mauao since 1819. The south-eastern side of Mauao retains evidence of this early history, being heavily terraced with massive middens mainly comprising pipi shells.

Prior to 1925, the site was devoid of vegetation[7] but has been covered in pines since 1925. A description of the present vegetation is given in the Tauranga Management Plans. The upper slopes are mainly clad in scrub and trees and the lower slopes are mainly grazed pasture with extensive kikuyu grass. Fires have caused extensive damage to the vegetation, notably in 1986 and 1997. Most of the pine trees have been removed over the last decade.

Mauao is predominantly used as an open space recreational area (picnicking, fishing, camping, walking) and for active sports such as paragliding. Other amenities include:

- The camping ground occupying 0.88 hectares across the base of Mauao adjacent to Adams Avenue
- The Hot Salt Water Pools complex on the reserve in the middle of the two camping areas and which is designed to cater for 300,000 people per year
- Sheep grazing on the lower slopes
- Services on the summit comprising a navigational beacon, communications repeaters, trig station and beacon, peace monument, picnic tables
- Unused reservoir at RL42.7m and operational 1 million gallon reservoir at RL61m
- Navigation lights and beacons for Port of Tauranga

2.3 Previous history of stability problems

The extensive colluvial slopes that are draped around Mauao would have been formed at an earlier time when the geometry of Mauao and sea levels were significantly different to the conditions that exist today. There have been extensive rockfalls from the steep bluffs on the summit as can be seen from the boulder fields around the mountain.

According to the lessee of the camping ground (Mrs Marie Cox, reported in a letter from Shrimpton & Lipinski[8]), there have been no instances of boulders entering the camp ground, apart from one dislodged by children. A brief search through archival material in the Tauranga Library did not reveal any instances of rockfall problems. Although further enquiries might be made from the Department of Conservation and the track maintenance crew, it appears that rockfalls have not caused any problems to date either to the walking tracks or the facilities at the toe of the mountain.

Within the colluvial slopes and mainly on the north to eastern side, there are large landslide features (see Section 3). As far as the writer is aware, there has been no evidence of further large scale movement within these old landslides.

TDC staff advised that there have been some localised stability problems at a few places associated with the oversteepened cuts in colluvium above the Base Track. These are also described in Section 3.

On the afternoon of 11 July 1998 after a period of intense rainfall, a small debris flow entered the northern end of the camp. This was initiated by a concentrated flow of water from a natural "pipe" above the walking track in this area. A report on the incident was submitted to TDC[9] and caravans were removed from the area while surface water drainage was improved and some small retaining structures were installed. Figures 6 to 8 show photographs of the area of the debris flow. The size of the debris flow is not known but it appears to have been a small volume of no more than several cubic metres.

Several years prior to the incident, the area of the debris flow was planted with trees and shrubs and it is possible that the debris flow occurred because of the high intensity rainfall on the previously disturbed soil cover. Photographs provided by TDC indicate that the area may have been sprayed with herbicide prior to or after planting – this may also have been a factor in the debris flow event.

The rainfall that initiated the debris flow was an unusually heavy event. The effect of rainfall on the stability of slopes can be quantified by considering the total rainfall on the day of the event together with the cumulative rainfall over a previous number of days[10]. TDC have supplied rainfall data for the Chapel Street Treatment Plant from 1977 to 1998 and Figure 9 is a plot of the daily rainfall versus the cumulative previous 14 days rainfall. It can be seen that the 10-11 July 1998 rainfall is significant for both the intensity of the rain on those dates and the antecedent 14 day rainfall. – being exceeded only about 15 times in the previous 21 years. Also plotted on the same graph is the data point for 1 August 1979, a period of heavy rain that resulted in seven landslides along the cliffs of Omokoroa[11]. The Omokoroa and Mauao events plot quite close to each other indicating that this level of rainfall and antecedent is likely to trigger slope stability problems.

There has been no detailed study of rainfall events that will lead to slope problems in the Tauranga area. Earlier New Zealand work by Crozier[12] used a similar approach to that of Lumb above and correlated a 10-day antecedent rainfall index with stability problems (although, unlike the Lumb method, the previous rainfall was decayed by an exponential function so that past rainfall exerted less influence on the index as time elapsed). A recent paper by Brand[13] disputes the relevance of antecedent rainfall and suggests that for Hong Kong

- Most landslides are induced by short-duration high-intensity rainfall and the slides take place at about the same time as the peak hourly rainfall
- Antecedent rainfall of any duration is not a significant factor in landslides
- A rainfall intensity of about 70 mm/hour is the threshold above which landslides occur
- 24 hourly rainfall usually reflects short-duration high-intensity rainfall and can be used as an indicator of landslides

The importance of the daily rainfall has recently been further studied by Evans[14] who established three possible thresholds for landslide incidence related to the normalised rainfall (ratio of 24 hour rainfall to the annual average rainfall at the site):

Normalised rainfall	*Landslide frequency*
0.03	Landsliding starts
0.09	Rate of landsliding increases
0.19	Rate of landsliding increases again

The average annual rainfall at Chapel Street is about 1250mm and the thresholds of 0.03/0.09/0.19 would correspond to daily rainfall figures of 38/112/238 mm respectively. The Hong Kong thresholds do not therefore appear to be valid for Tauranga. A likely reason for this is that the permeabilities in Hong Kong's tropical soils are relatively high compared with those of Tauranga as well as the fact that Hong Kong's rainfall is about 1m higher than that of Tauranga.

3. WALKOVER SURVEY

During the course of this review, the slopes on the eastern side of Mauao were inspected. In particular, the slopes above the camping ground were assessed for any signs of distress or instability and the boulder fields were surveyed for any signs of recent movement or rockfalls. This inspection was carried out over two days (with rain on the second day) and was intended only to check for signs of distress or instability. It was not intended to be a comprehensive geomorphological survey of the slopes (which would take some considerable time and require more accurate baseline survey data). The following descriptions summarise the observations on:

- the aerial photographs
- the rock bluffs at the summit with their associated rockfall problems
- the major landslide features, and
- the frontal lobes of the landslides.

3.1 Aerial photographs

TDC provided the writer with four aerial photographs taken on the following dates:

- 21 October 1953
- 11 February 1979
- 3 April 1988
- 9 January 1998

1953 photograph

The 1953 photograph is black and white and of poor quality. It is difficult to distinguish much detail on this photograph but the following points were noted:

1. There are few permanent buildings on the camp site and hot pools complex compared with the present
2. The Oruahine Path to the summit is quite visible through the scrub on the upper parts of the slope but barely defined on the lower grass slopes. It appears to follow the same route as at present.
3. The geometry of the landslide scarps on the eastern side of Mauao appears to be quite similar to the present condition
4. There are no signs of rock or boulder falls through the bush or across the talus slopes
5. There are two significant areas of slumping of the lower parts of the colluvial slope above the Base Track about 150 to 200m north of the main track leading to the Old Stone Steps. Two smaller areas can be seen above the Base Track at the north end of the camp.

1979 photograph

This is also black and white but of much better quality than 1953.

1. The camp site and hot pools complex are much more developed and the camp site appears to be fully occupied
2. The path network is well defined and the same as at present
3. The landslide scarps are the same as 1953
4. There are no signs of rock or boulder falls
5. The slumped areas above the Base Track are the same as 1953

1988 photograph

This is black and white, good quality but the scale is too small for any useful interpretation.

1998 photograph

This is a good quality colour photograph with very clear detail on the landslide scarps and the boulders on the colluvial slopes. There are no discernible changes from the 1953 or 1979 photographs except that the area of the 1998 debris flow has had the grass cover removed and there are areas of bare soil showing in various places.

Figure 10 shows the 1988 photograph with the top of the landslide scarps marked in red (for the eastern side of Mauao only – the terracing and middens on the southern end may have obscured any old landslide features). The landslide feature directly above the Ocean Camp is more or less contiguous with that above the Old Stone Steps and forms the single largest landslide feature on Mauao. The landslide extends back about 125m from the edge of the camp and approaches close to the fence encircling the bush on the upper parts of the slope.

3.2 Summit bluffs and rockfalls

The dome of Mauao is characterised by steep sub-vertically jointed columns of rock forming a wall above the flatter colluvial slopes. The recent fire has exposed the full length of the wall running north-west to south-east across the summit (see Figure 2). The rock cliffs directly above the camp site can be seen in Figure 11.

The summit rocks on Mauao include large columns of rock which are up to 5m square in plan and 15m in height (see Figure 12 taken on the north side of Mauao). The vertical joints are often open or filled with colluvial material – the aperture of these joints can be 1m or more. Although the rock mass is blocky and open, the individual blocks are mostly defined by subhorizontal jointing. Figure 13 (taken by Mr Scott on a sunny day in November 1998) shows clearly the openness of many of the joints in the rock mass and the large size of the individual rock blocks. As can be seen from the boulders on the surface of the colluvial slopes, the rocks are generally slabby in shape and will not roll far on flatter slopes after they have detached from the rock mass above. Most of the boulders in the colluvial slopes are embedded in the soil and have clearly been there for some time (Figure 14).

The fence lines around the summit bush and above the camp site were inspected for damage from falling rocks. There was no evidence of recent falls from the cliffs from either scarring in the bush or damage to the fences. No signs could be seen of fresh boulders from the summit cliffs on the grassed slopes below the fence line.

There are a number of local hazards directly around the western edge of the camping sites 93-98 to the south of the Hot Pools complex. The wire fence above this area shows signs of having been hit by boulders and there are a number of small boulders resting against the wires. At site 98, two boulders have come to rest at the fence line, one having broken through the sheep netting; two smaller boulders have travelled on to the caravan/tent site (see Figure 15). The area above the fence has many boulders in amongst the trees and the boulders may have been dislodged by children or animals.

Above site 63 in the same area of the camp, a large tree and boulder are located on the edge of a small but steep soil; either or both of these could readily fall on to the site beneath (Figure 16).

3.3 Old landslide features in colluvial slopes

The landslide scarps essentially cover all of the side of Mauao exposed to the ocean and would have formed in response to erosion of the toe of the colluvial slopes by rising sea levels. The lower parts of the talus slopes would, in any event, have been less stable because of the water seepage from springs around the 30m elevation on Mauao.

The old landslide surface directly above the Ocean Camp site was inspected (Figure 17). There was no evidence that the landslide was moving at greater than normal creep rates for soil – in particular there were no observable tension cracks or active scarps. The lack of activity in the major landslide zones could also be confirmed from examination of the aerial photographs (Section 3.1).

Despite the lack of any significant signs of mass movement, two observations of the slide area were of concern:

- Sinkholes or depressions could be seen in a number of locations (e.g. in the Old Stone Steps gully - Figure 18) indicating that piping channels may be eroding through the colluvium and may give rise to blowouts near the toe of the landslide
- The sides of the landslide gullies are often very steep and small failures of the sides would not directly affect the camp site. However during periods of heavy rain, these failures could block the surface runoff and subsequently fail creating high-speed debris flows down into the camp area.

The susceptibility of the remnant landslide features slopes to debris flows when the ground has been disturbed has been noted in Section 2.3 above. The slopes are closely grazed by sheep and bare ground is evident in a number of locations.

3.4 Frontal lobes of landslide

The gross stability of landslides is often very sensitive to small changes in the stability of the frontal lobes. Examination of the aerial photographs has indicated that a number of small slumps directly above the Base Track have been active since at least 1953. Examples of these are shown in Figure 19. These are slow-moving features and are not considered to present any significant hazard to users of the Base Track.

Caravan sites in the Ocean Camp from near the entrance to the Base Track to about site 109 are located directly in front of an oversteepened, undercut section of the landslide (Figure 20). The height of the undercut area is up to 3m, is very steep and is likely to be continually saturated with seepage from the slopes above.

The nature of the colluvial material (heterogeneous and poorly sorted) is such that assessment of the mass parameters is very difficult and, with the available information, there is little point in carrying out conventional slope stability analyses. However, based purely on the nature of the site and its geomorphological setting, the siting of caravans and other forms of holiday accommodation in this area is considered to be imprudent with respect to potential failure of the frontal lobe and the likelihood of further debris flows.

The risks of injury or fatality from slope failures to sleeping persons in fragile accommodation (tents/caravans) is quite high and the owners/operators of such facilities would have a duty of care to ensure their safety. It is likely that there might be a much higher requirement for duty of care to occupiers of camp facilities than to those walking or jogging around the mountain.

4. STABILITY ASSESSMENT

4.1 Rockfalls from summit cliffs

Historical and anecdotal evidence indicates that rockfalls have not caused any injuries or accidents to date. Examination of the mountain slopes has not shown any signs of recent boulder movements, either from travel paths through the bush or from damage to fences.

The behaviour of falling rocks can be modelled by computer simulation programs. The writer carried out a review of rockfall problems some years ago[15]. Following on from some serious rockfall problems in Hong Kong, the writer is currently working on a project for the Geotechnical Engineering Office which includes a requirement to evaluate all the currently available methods for rockfall simulations.

The input for rockfall simulations consists of a definition of the slope geometry, the irregularities on the slope surface, the damping (or rebound) characteristics of the slope material and the size and shape of the falling boulder. The programs generally use probability distributions for the rebound characteristics and slope surface and the output consists of statistical distributions for the endpoints of the boulders, the trajectory envelopes and the height, velocity and energy of the boulders along the slope profile.

RocFall is the most recently developed rockfall simulation program[16] and has a convenient Windows set-up and good graphics. It is particularly suitable for situations where the slope profiles are not accurately known since the program allows a standard deviation value to be associated with the co-ordinates for each vertex on the slope.

Simulations have been carried out for the North Slope, East Slope and the section above the Hot Pools complex. The parameters used have been conservatively assessed as in Table 1.

Table 1: Parameters used for rockfall simulations

	Best estimate		Pessimistic estimate	
	Mean	Standard deviation	Mean	Standard deviation.
Normal coefficient of restitution, r_n	0.2	0.05	0.3	0.05
Tangential coefficient of restitution, r_t	0.6	0.05	0.8	0.05
Standard deviation of slope vertex, x		2m		
Standard deviation of slope vertex, y		2m		

The coefficients of restitution are the ratio of a particle velocity before and after impact with a surface of a particular type. The normal and tangential coefficients of restitution are applicable to the directions normal and parallel to the surface, respectively. The standard deviation is a measure of the variation from an average value. The program allows a standard deviation to be applied to the vertex of each slope segment and therefore introduces a probabilistic roughness and variation to the slope surface.

250 simulations were done for each case considered. In order to model the worst possible situation, the analysis has involved the following assumptions:

- the boulder is modelled as a sphere whereas the real boulders are columnar and would not travel anywhere near as far as a sphere
- the analysis does not take account of the trees and scrub on the upper part of the slope which would significantly impede the boulders
- the slope profile has been arbitrarily steepened at the top with a 20m high vertical "cliff" above the colluvial slope
- the boulders have been given an initial vertical and horizontal velocity of 3 ± 0.5 m/sec
- the analysis does not allow for the effect of the falling boulders becoming embedded in the soil

The results will therefore be rather pessimistic and will overestimate the distance that the boulders can travel. For example, the initial velocity imparted to the boulders would be applicable only to locations within a very short distance of fault rupture in a large magnitude earthquake such as Murchison or Edgecumbe (in which case, boulder falls from Mauao would be one of the smaller problems affecting the district).

The results of the analyses are given in Appendix A which gives details of the slope profile and a histogram for the endpoints of the boulder travel. The results show that most of the boulders come to rest on the middle part of the slopes and that none of the boulders will reach the Base Track, Camp Ground or Hot Pools complex. A summary of the modal (most frequent) and maximum travel distance for the boulders is given in Figure 21.

4.2 Risk analysis for rockfalls

The risk of boulders hitting visitors on Mauao has been assessed using a method developed by Bunce[17] and Bunce et al.[18] The theoretical basis for this and the data used for the analysis are summarised in Appendix B.

The probability of an accident from a rockfall on Mauao has been assessed for the following cases:

- Rockfall on to stationary person on Base Track
- Rockfall on to moving person on Base Track, and
- Rockfall on to moving person on the tracks on the upper slopes

The rockfall analyses have been used to provide the basic assumption that 75% of the boulders falling from the cliffs will cross the upper tracks and that 1% of these will reach the Base track or lower areas of Mauao. The other assumptions for the analysis are set out in Appendix B.

The probability of an accident arising from a rockfall is summarised in Table 2 below.

Table 2: Probability of an accident on Mauao assuming different rockfall frequencies

Type of accident	0.1 rockfall per year	1 rockfall per year	10 rockfalls per year	100 rockfalls per year
Stationary people – lower tracks				
P(A) (per 0.5 hr stop)	5.68×10^{-10}	5.68×10^{-9}	5.68×10^{-8}	5.67×10^{-7}
PAI (per 0.5 hr stop)	5.71×10^{-11}	5.71×10^{-10}	5.71×10^{-9}	5.71×10^{-8}
Moving people – upper tracks				
P(A) (per year)	1.07×10^{-4}	1.07×10^{-3}	1.07×10^{-2}	1.02×10^{-1}
PAI (per year)	2.14×10^{-9}	2.14×10^{-8}	2.14×10^{-7}	2.14×10^{-6}
Moving people – lower tracks				
P(A) (per year)	4.29×10^{-6}	4.29×10^{-5}	4.29×10^{-4}	4.29×10^{-3}
PAI (per year)	2.85×10^{-11}	2.85×10^{-10}	2.85×10^{-9}	2.85×10^{-8}

P(A) is the probability of a rock hitting a person. A probability of $1.07x10^{-4}$ per year means that the event will occur about once every $1 \div 1.07x10^{-4}$ years, i.e. every 9346 years on average.

PAI is the probability of a rock hitting an individual person. For $1.07x10^{-4}$ annual probability of a rock hitting a person and 50,000 people at risk in the same period, the probability of an accident to an individual is $1.07x10^{-4} \div 50{,}000 = 2.14x10^{-9}$.

The vulnerability (probability of death) of a person in open space struck by a rockfall has been assessed at 0.1 to 0.7 based on references to historical data[19]. For the case of moving persons on the upper or lower tracks, the vulnerability has been assumed to be only 0.1 (because of the possibility of being able to take evasive action) and 0.5 when stationary. The probability of a fatality resulting from the rockfall is then set out in Table 3 for the probability of death in a year, the probability of death to an individual per trip and per 500 trips in a year.

Table 3: Probability of fatality on Mauao due to rockfall frequency of 0.1 per year

Type of accident	*P(L:T)*	*P(D)* per year	Return period in years	*PDI* per trip	*PDI* per 500 trips
Stationary person on lower track	0.5	$2.84x10^{-10}$	-	$2.86x10^{-11}$	$1.43x10^{-8}$
Moving person – upper track	0.1	$1.07x10^{-5}$	93,458	$2.14x10^{-10}$	$1.07x10^{-7}$
Moving person – lower track	0.1	$4.29x10^{-7}$	2,331,00	$2.85x10^{-12}$	$1.43x10^{-9}$

P(L:T) is the vulnerability or probability of loss of life to an individual hit by a rockfall.

P(D) is the probability of one or more deaths per year. This is equal to P(L:T) x P(A). If P(L:T) = 0.1 and P(A) = $1.07x10^{-4}$, then P(D) = $1.07x10^{-5}$

The return period is the average interval between rockfall deaths = $1 \div P(D)$. If P(D) = $1.07x10^{-5}$, the return period - $1 \div 1.07x10^{-5}$ = 93,458 years.

PDI is the probability of death on an individual trip = P(L:T)xPAI where PAI is the probability of an accident on a single trip. PAI = P(A) ÷ total number of trips per year. If P(L:T) = 0.1, P(A) = $1.07x10^{-4}$, and number of trips = 50,000, then PDI = $0.1 \times 1.07x10^{-4} \div 50{,}000 = 2.14x10^{-10}$

Based on the current understanding of a low frequency of rockfalls per year (< 0.1 per year at present), the probability of a death per year is about $1x10^{-5}$ for the most dangerous situation (i.e. one death is probable about every 100,000 years) and the risk to an individual on a single trip is about $2x10^{-10}$.

Acceptable levels of risk have been defined by a number of organisations. The NSW Department of Environment and Planning[20] specify an individual risk criteria of $1x10^{-5}$ and $5x10^{-6}$ for passive and active open space land use respectively. Other criteria for risk are set out on Figure 22 which summarises the Mauao risk in relation to boundaries defined by UK Health & Safety Executive, BC Hydro, Netherlands and Hong Kong Governments. The present risk at Mauao falls well below any relevant risk criteria of which the writer if aware.

Table 4 shows that even if the rockfall frequency increases 100 fold to 10 rockfalls per year, the return period for a fatality would still be of the order of 1000 years. It is concluded that the risk to the public at Mauao falls within acceptable levels and that no engineering works are required to mitigate the hazard.

Table 4: Probability of fatality on Mauao due to rockfall frequency of 10 per year

Type of accident	*P(L:T)*	*P(D)* per year	Return period in years	*PDI* per trip	*PDI* per 500 trips
Stationary person on lower track	0.5	$2.84x10^{-8}$	-	$2.86x10^{-9}$	$1.43x10^{-6}$
Moving person – upper track	0.1	$1.07x10^{-3}$	930	$2.14x10^{-8}$	$1.07x10^{-5}$
Moving person – lower track	0.1	$4.24x10^{-5}$	23,500	$2.85x10^{-10}$	$1.43x10^{-7}$

The implications of undertaking any remedial works on Mauao would be considerable. The cost of carrying out works to produce a meaningful improvement in the stability of the summit outcrop would be veryhigh. Access to the area would need to be prohibited during the time of the works and the intrusion of the works on Mauao would probably be unacceptable to many of the parties concerned with the administration of the area. Similarly, the cost of rockfall fences would be very high (about $2000 per metre run) and would be able to stop only the smaller type of block that might fall from the summit. There is, however, no indication that any such works are warranted at present.

4.3 Large scale mass movements

The aerial photograph assessment and walkover survey did not give cause for any concern that either the colluvial slopes or the existing landslides had moved recently or were likely to fail suddenly.

Conventional stability analyses for slopes require detailed information on the subsurface conditions, the groundwater pressures and the soil/rock properties –and these data are not available for the present study. A methodology for assessing the risks associated with sites close to steep hillsides has been developed by Hungr et al[21] as part of a programme to meet Hong Kong Housing Authorities' target of delivering 50,000 housing units to the public each year. This is an empirical method which can be used with the information that is available at the moment.

The landslide runout model which forms a key component of the above method has the following characteristics:

- The runout is controlled by a travel angle
- The travel angle decreases with increasing volume of event
- The total horizontal distance, L, traversed by the slide has an upper limit despite the angle of the slope profile
- Runout occurs within a limiting distance, D, from the toe of the slope irrespective of other constraints

The method classifies slopes as either confined or unconfined depending on whether the landslide is contained within a confining channel Landslide types and their runout characteristics are listed in the following table (see Figure 23 for a definition sketch of the terms)

Table 5: Landslide types and runout characteristics

Slide type	*Typical H/L*	*Maximum L (m)*	*Maximum D (m)*
Small unconfined (<500 m^3)	0.75	200	40
Medium unconfined (500 to 2000 m^3)	0.5	300	60
Large unconfined (> 2000 m^3)	0.35	350	120
Small confined (<500 m^3)	0.75	300	40
Medium confined (500 to 2000 m^3)	0.5	500	60
Large unconfined (> 2000 m^3)	0.35	1000	120

Figure 24 is a section through the landslide at the location where the small debris flow occurred in July 1998 (see Figure 4 for location of section). The gradient of the slope above Site 107 is about 16.5° and the upper part of this section (the landslide scarp) is about 32.5°. The information for this section was obtained from a contour plan provided by TDC and produced from the March 1997 aerial photography. This is understood to be the most detailed ground information available for this area.

The most pessimistic value of Hungr's recommendations for travel angle is for an H/L value of 0.35 for a large (> 2000 m^3) confined landslide. This angle of approximately 19° is steeper than the angle of the slope and therefore significant runout from a further large-scale movement of the landslide material would not be expected (see Figure 24).

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The conclusions from this review of the stability of Mauao are as follows:

1. The frequency of rockfalls from the summit cliffs has been low in recent years and there have been no instances of rockfall accidents as far as the writer is aware.

2. There is no evidence of boulder movements in recent years (at least since 1953) and all the boulders on the colluvial apron are quite deeply embedded and unlikely to move any further.

3. Both geomorphological evidence and computer simulations indicate that the probability of boulders from the summit cliffs reaching the camping ground or the Hot Pools complex is extremely low.

4. With the present frequency of rockfalls from the summit cliffs, the risk of accidents to users of Mauao is at an acceptable level according to international criteria.

5. There are no geomorphological indications of distress or significant activity in the landslide features above the Ocean Camp.

6. At a number of locations above the camp, there are signs of sinkholes indicating that piping may have developed at some stage through the colluvium although there seems to be no present activity at these features.

7. The grass slopes above the camping ground are closely grazed with minimal vegetative cover in some areas.

8. The geometry of the slide area above the July 1998 debris flow location is such that further mass movement and a major runout would not be expected

9. There are a number of failures in the frontal lobes of the landslides along the Base Track which indicate that these are prone to failure when oversteepened

10. A number of caravan sites are imprudently located directly adjacent to oversteepened, undercut segments of a landslide feature in an area prone to drainage problems

11. Other sites in the camping ground are at risk from adjacent boulders and trees.

5.2 Recommendations

Recommendations arising from this review are as follows:

1. There is no present requirement to undertake any major investigations or remedial works on the slopes of Mauao

2. As a matter of routine (not urgency), produce a detailed topographical and geomorphological plan of the slopes above the Camping Ground and Hot Pools complex. (This could be done as a postgraduate student research project).

3. Use the above information as a basis for a regular annual walkover survey of the slopes to check that conditions are not changing. (This would be done on a similar basis to the walkover surveys on the landslides above Lake Dunstan).

4. Install some survey control points on the slope that would provide a basis for more accurate monitoring if this was indicated as being necessary from future inspections.

5. Remove caravans from the area of Sites 101-109 at the Ocean Camp and maintain a horizontal clear area beside any steep cut of 3 times the cut height

6. Caravans should not be returned to this area unless the cut slopes are stabilised. Likely remedial works could include gabion walls along the affected length with horizontal drainage holes into the slope. The walls should project above the slope to allow deflection of any surface debris flows.

7. The camp grounds should be inspected in detail and a hazard plan prepared showing the nature and location of any potentially dangerous features which may compromise safety in these areas. Based on the brief survey described in this report, several locations of unacceptable hazard have already been noted. Affected camp sites should be vacated until the hazard is eliminated. In particular, any boulders in the immediate vicinity of the camp which could be dislodged by children should be removed.

8. Warning signs should be erected at the entrance to Mauao stating that this is a natural environment with potentially hazardous features, warning people to be aware of rockfalls, tree collapses or path subsidence, and warning against dislodging boulders from the cliffs. DOC may be able to advise on suitable wording.

9. The camp site should provide camp registrants with a brief safety note along the same lines as above.

10. The slopes above the camping ground should be retired from grazing and planted with shrubs and trees that would provide root reinforcement and buttressing to the superficial soils. This would make the slopes less liable to erosion and debris flow activity.

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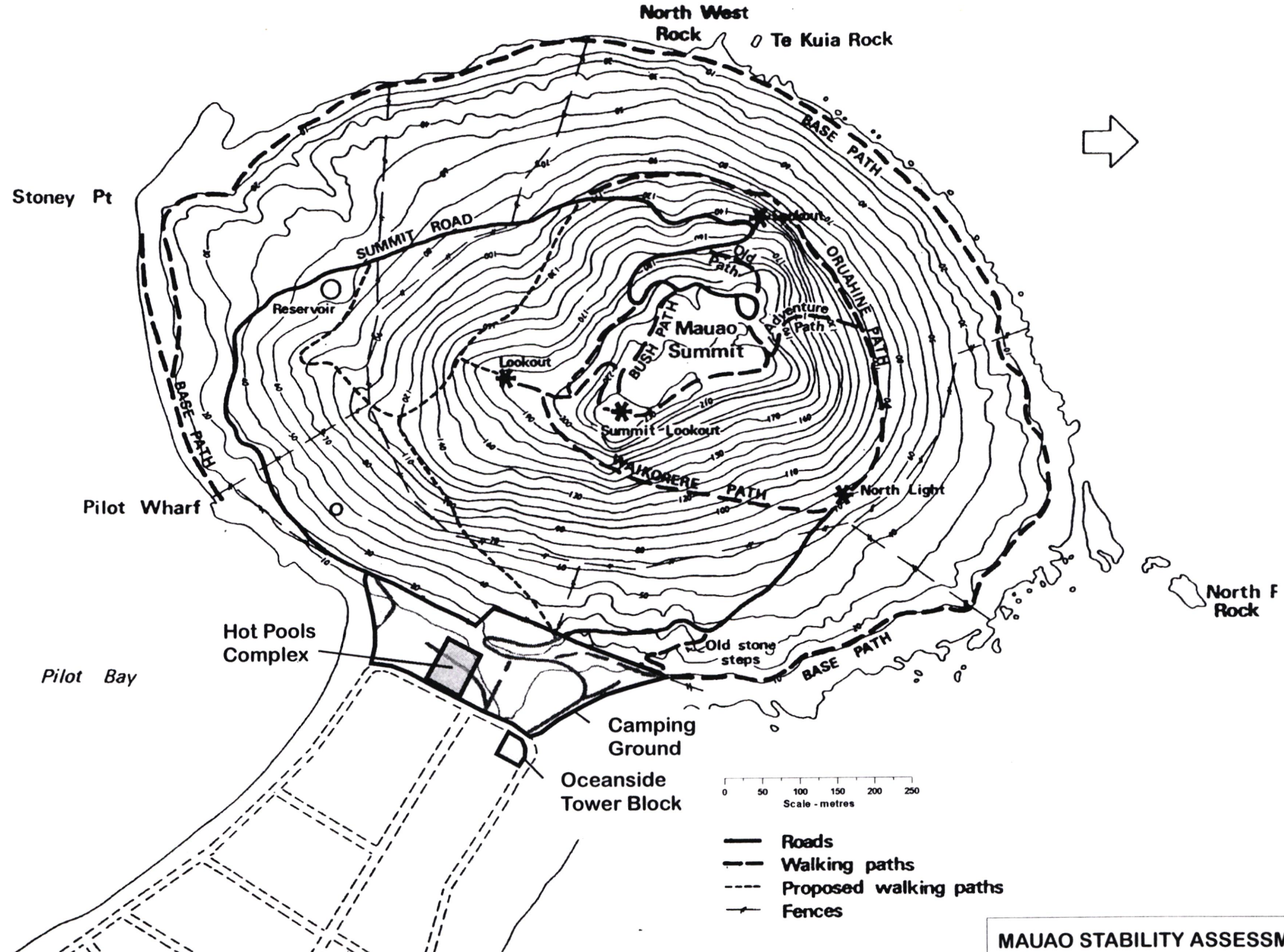
Figure 1



MAUAO STABILITY ASSESSMENT
Plan of Mauao showing main features

Figure 2

MAUAO STABILITY ASSESSMENT

1998 aerial photograph

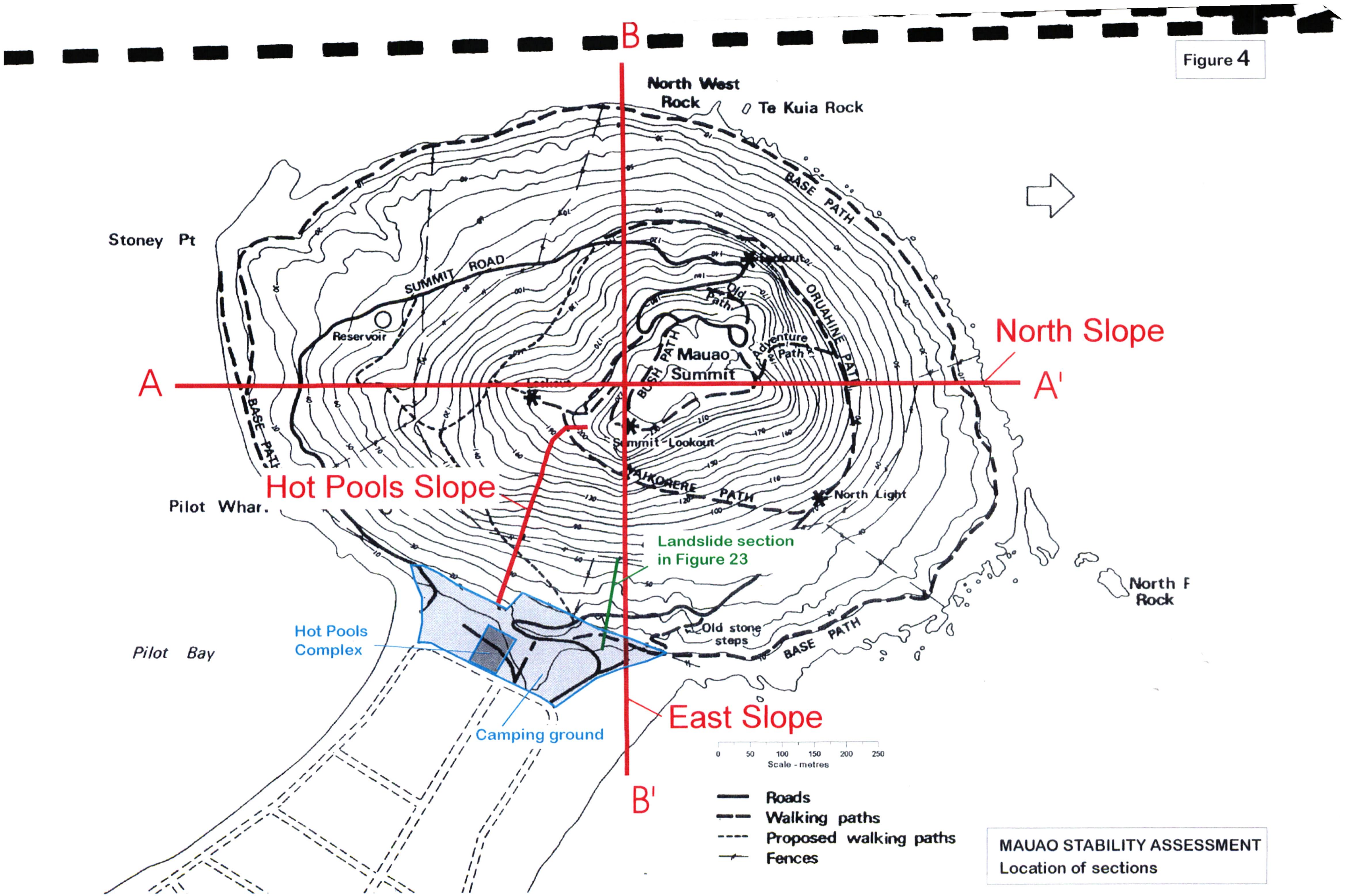
Figure 3

North-eastern side of Mauao above camping ground

Eastern side of Mauao above Hot Pools complex

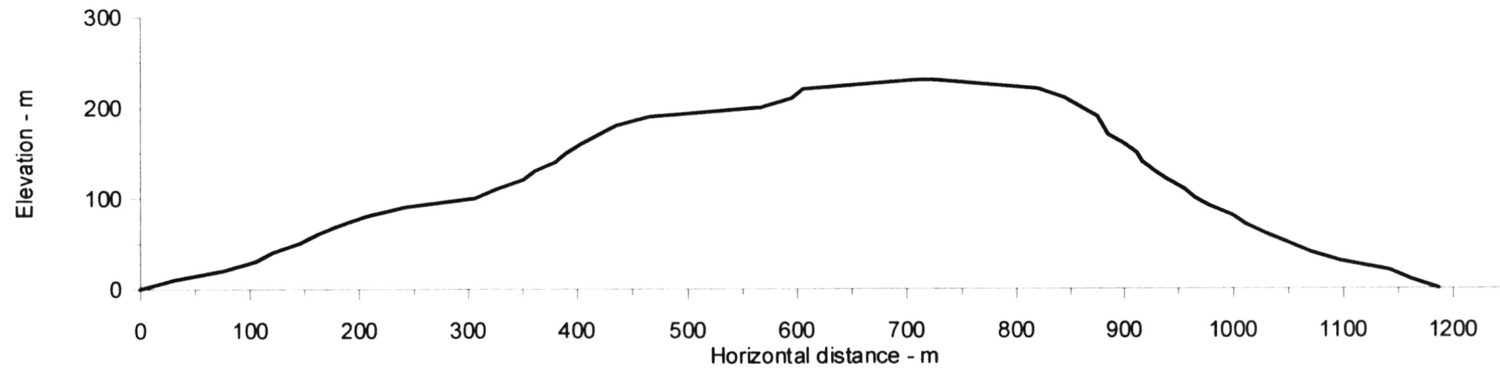
MAUAO STABILITY ASSESSMENT

Views from top of Oceanside Tower Block

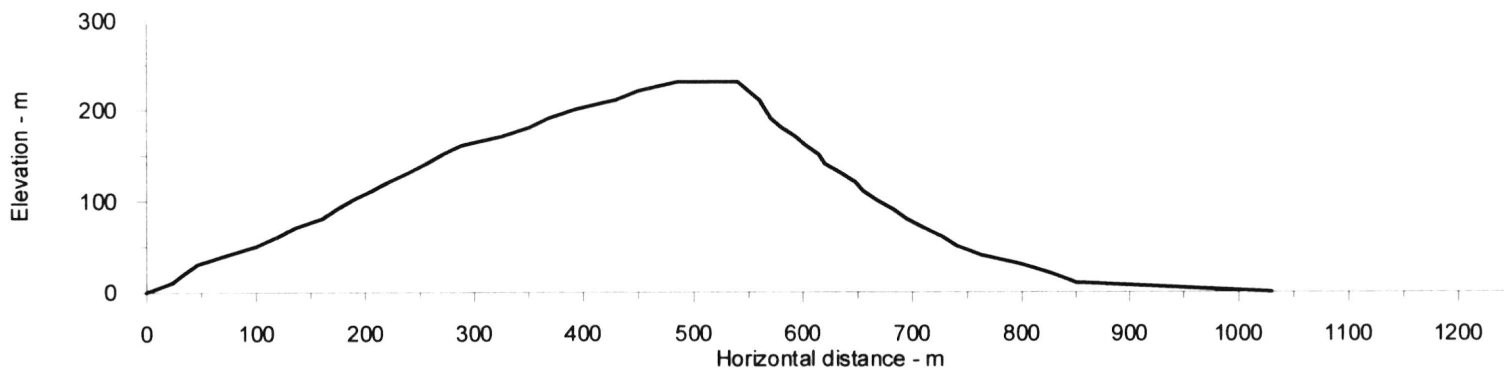


MAUAO STABILITY ASSESSMENT
Location of sections

Figure 5



SECTION A-A' : SOUTH - NORTH



SECTION B- B': WEST - EAST

MAUAO STABILITY ASSESSMENT

Sections through Mauao

Figure 6

Debris flow entered site behind caravans and below pohutukawa tree at northern end of camping ground

Debris flow was triggered by water piping from area of new timber retaining wall at top of photo.
Landscaping works had been carried out prior to debris flow

MAUAO STABILITY ASSESSMENT

Photos of 11 July 1998 debris flow area

Figure 7

New timber retaining wall erected after debris flow. Water pipe was located at vee of wall.

Surface drains installed after debris flow

MAUAO STABILITY ASSESSMENT

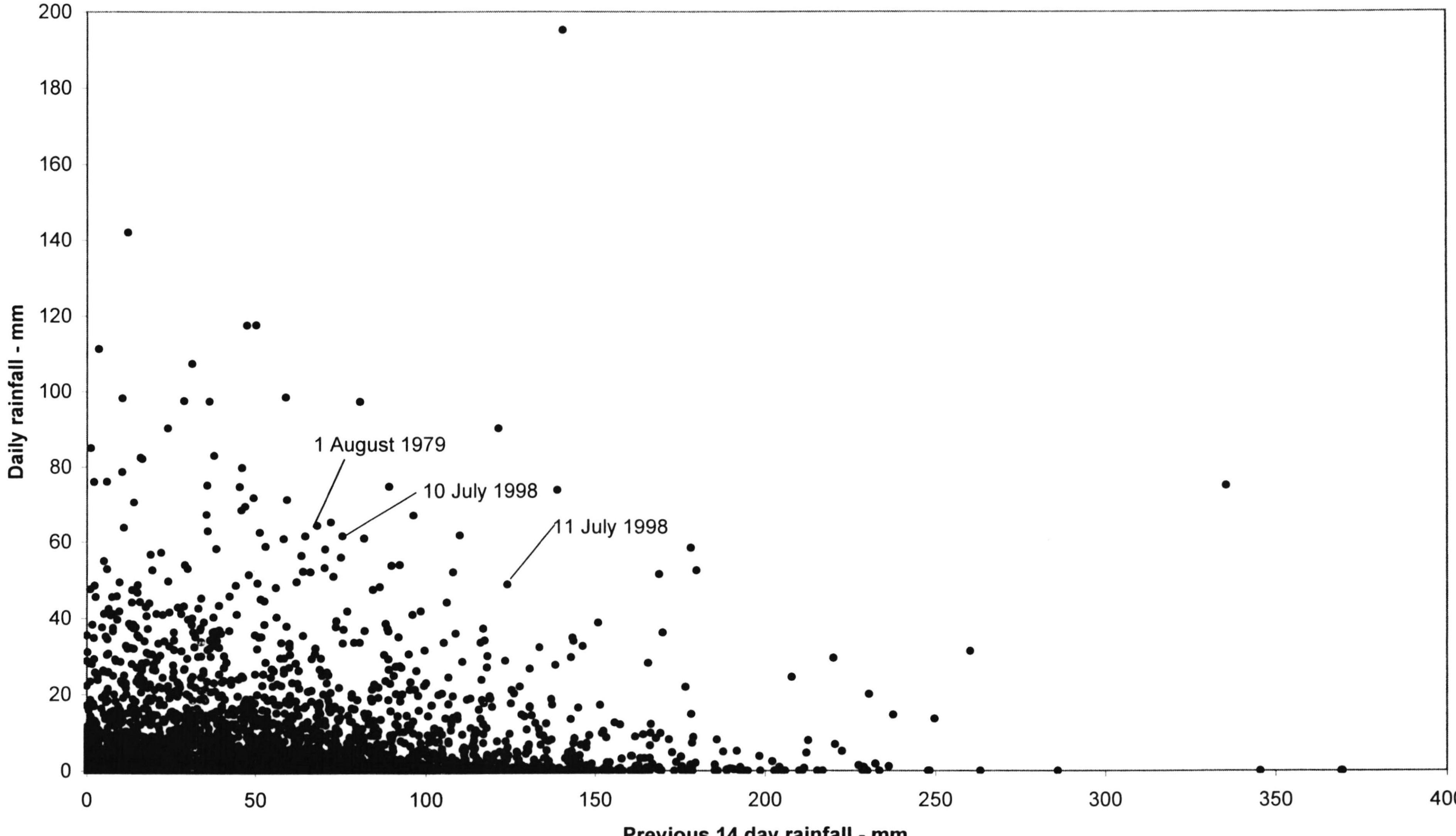
Photos of 11 July 1998 debris flow area

Figure 8

New drainage line from walking track

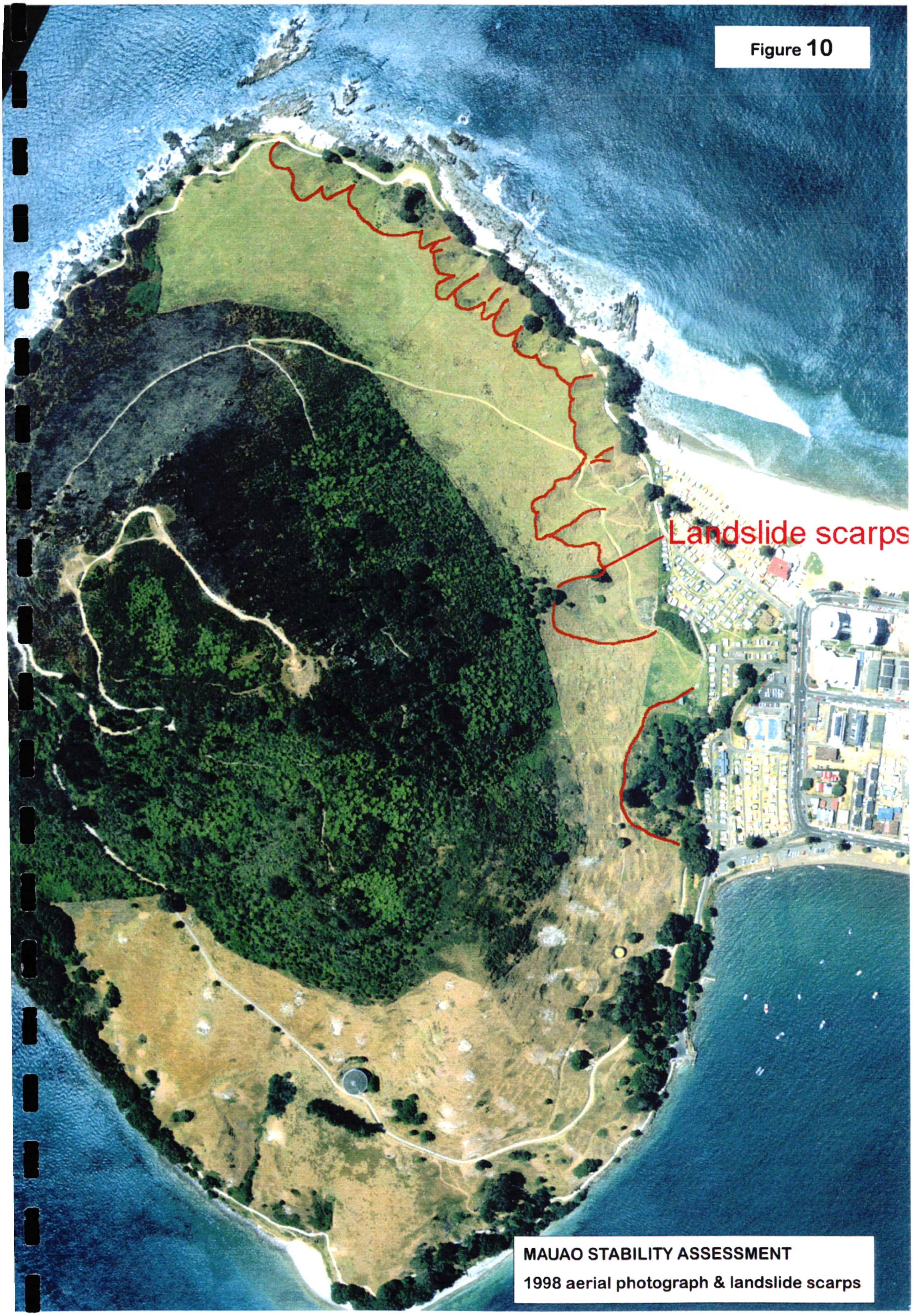
Gabion baskets at previous overflow point

MAUAO STABILITY ASSESSMENT
Photos of 11 July 1998 debris flow area



MAUAO STABILITY ASSESSMENT
Rainfall data from 1977 to 1998

Figure 10



MAUAO STABILITY ASSESSMENT

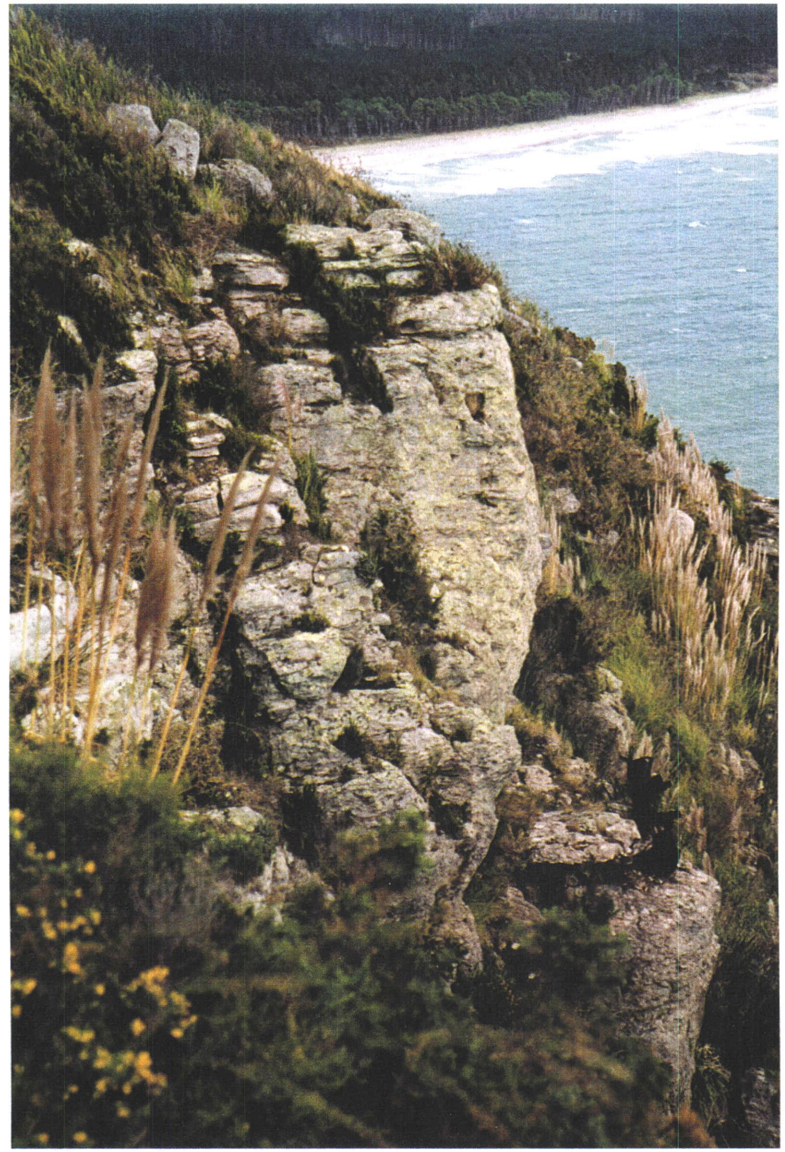
1998 aerial photograph & landslide scarps

Figure 11

MAUAO STABILITY ASSESSMENT

Views of summit cliffs from Adams Avenue

Figure 12



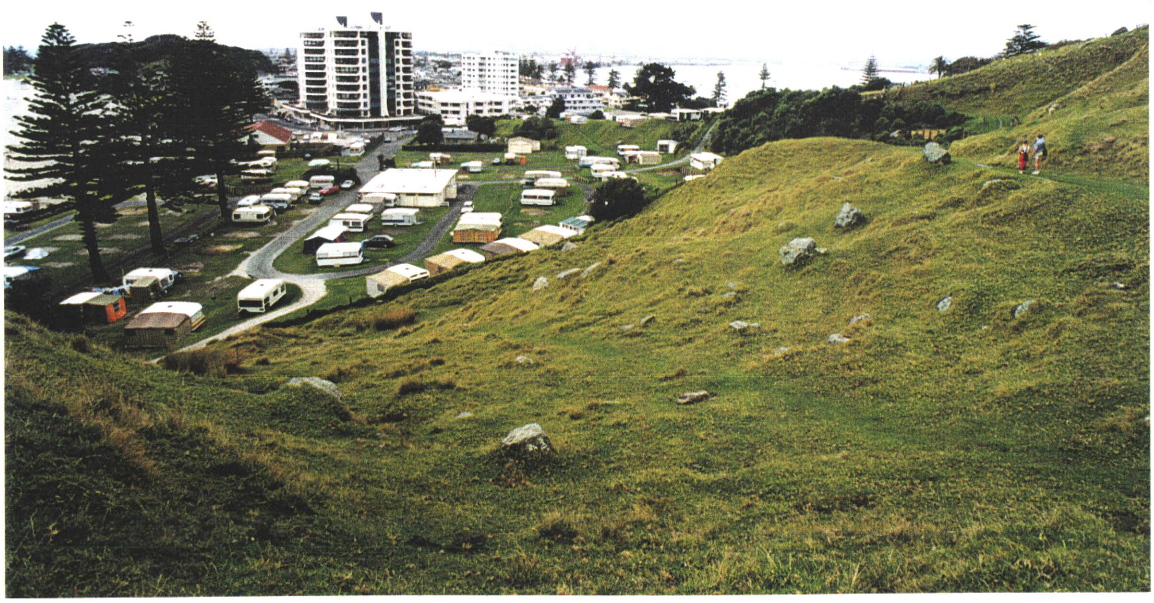
MAUAO STABILITY ASSESSMENT
Jointed rock mass on north end of summit cliffs

Figure 13

MAUAO STABILITY ASSESSMENT

Views of steep, open-jointed rock at summit

Figure 14



MAUAO STABILITY ASSESSMENT

Boulder fields above camp site

Figure 15

MAUAO STABILITY ASSESSMENT

Boulder falls above sites 93-98

Figure 16

MAUAO STABILITY ASSESSMENT

Boulder and tree above site 63

Figure 17

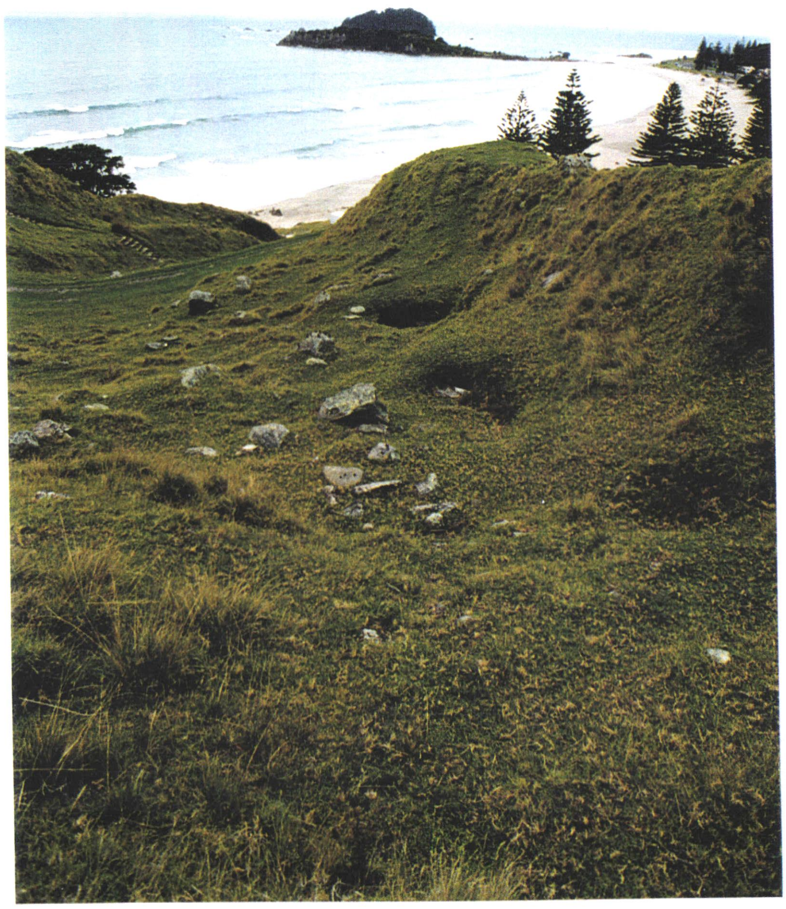
View from top of Oceanside Tower block

View from within camp area

MAUAO STABILITY ASSESSMENT

Landslide feature above Ocean Camp

Figure 18



MAUAO STABILITY ASSESSMENT

Sinkhole formation in Stone Steps gully

Figure 19

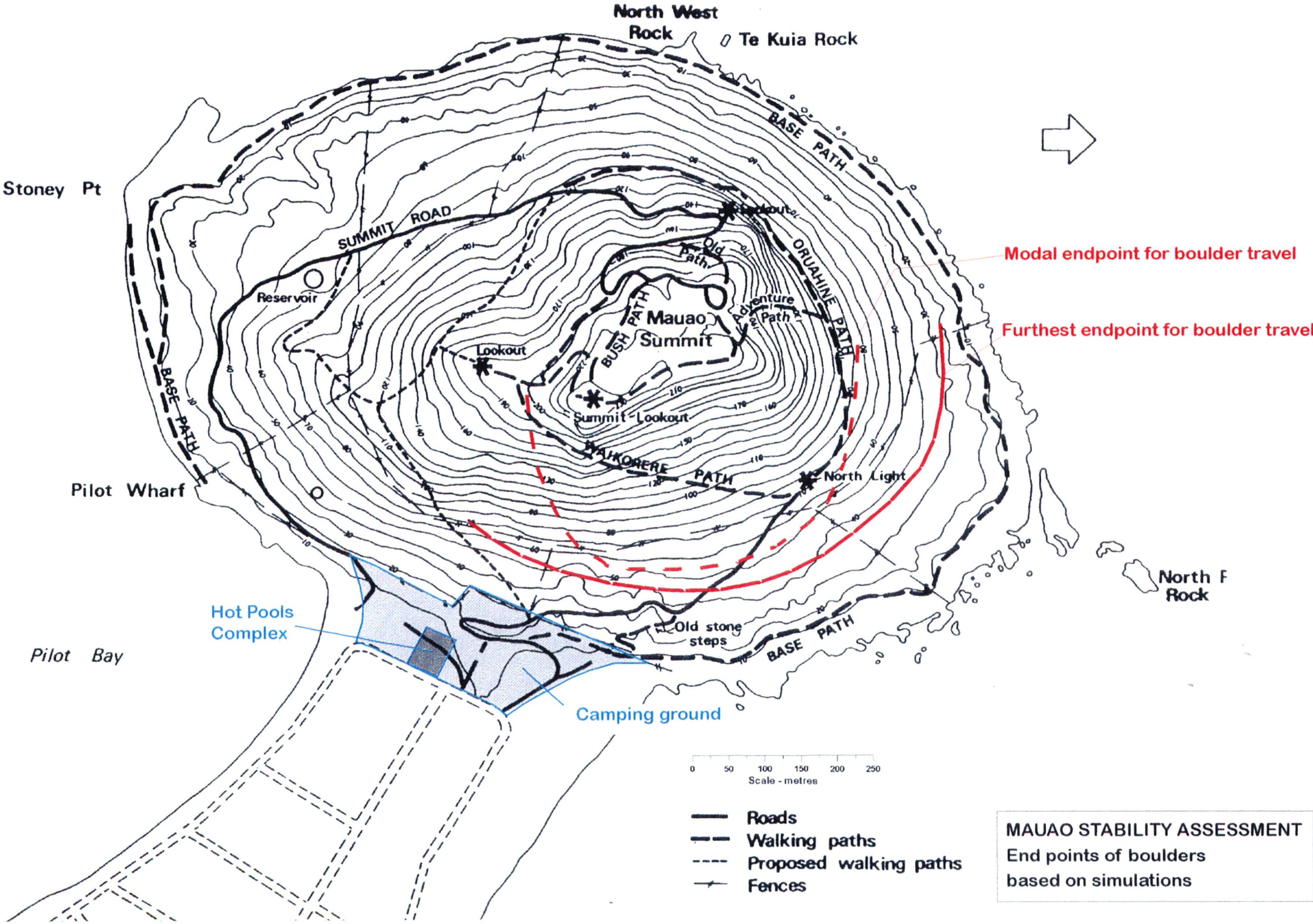
MAUAO STABILITY ASSESSMENT

Examples of active areas directly above the Base Track

Figure 20

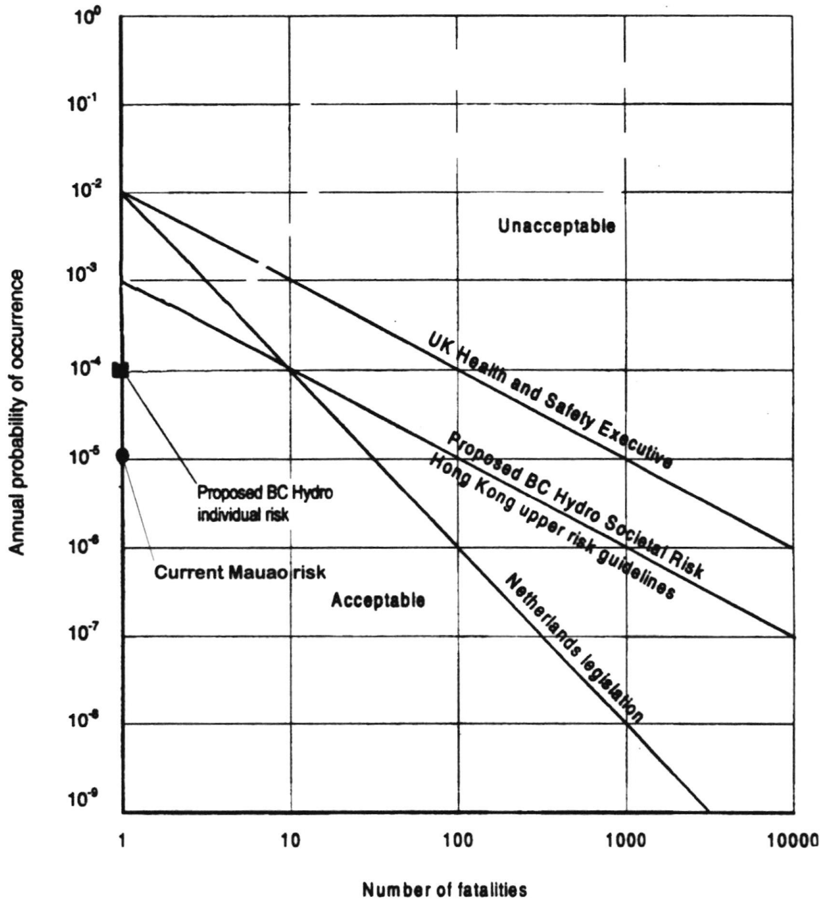
MAUAO STABILITY ASSESSMENT

Caravan sites directly adjacent to undercut toe of landslide



MAUAO STABILITY ASSESSMENT
End points of boulders based on simulations

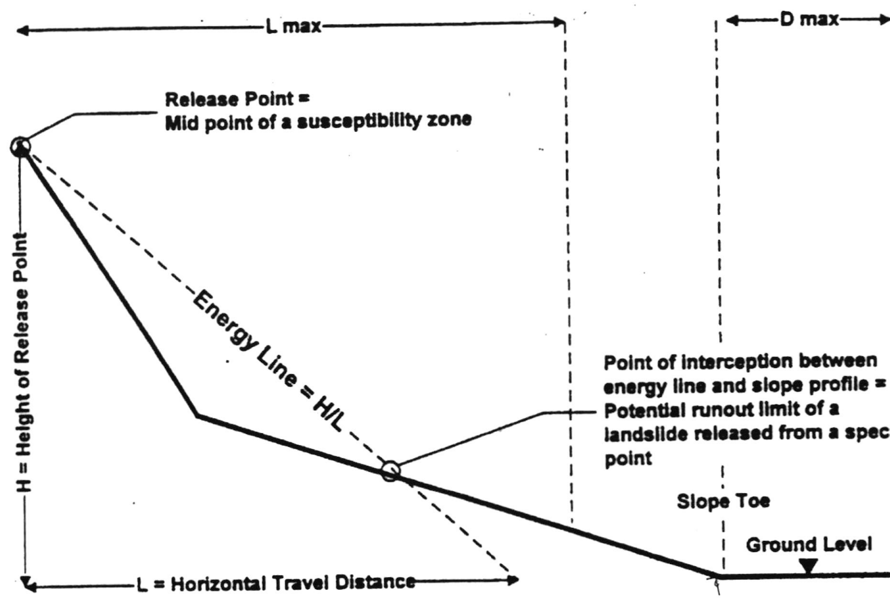
Figure 22



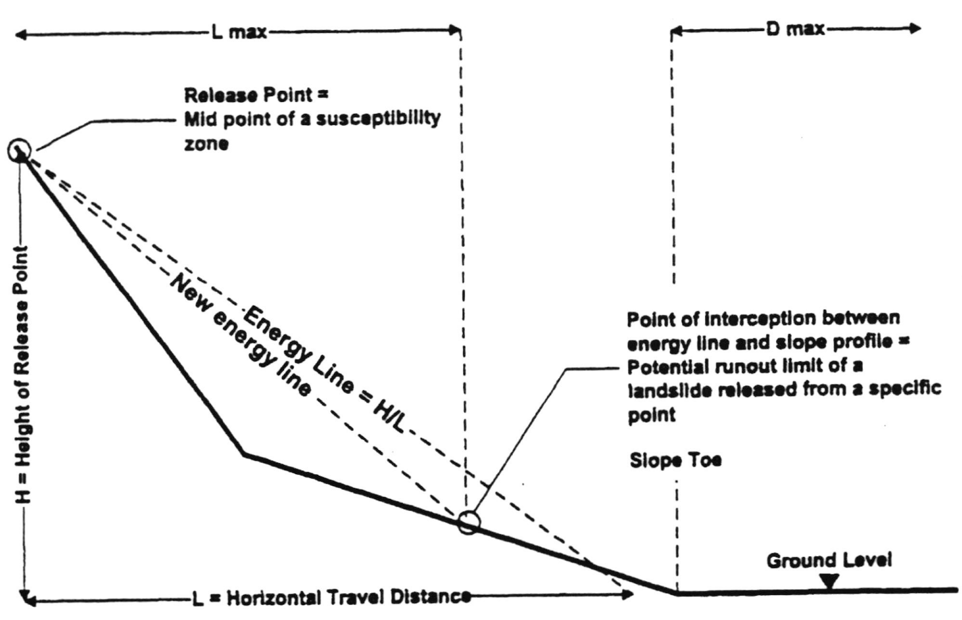
MAUAO STABILITY ASSESSMENT

Risk compared with other defined criteria

Figure 23



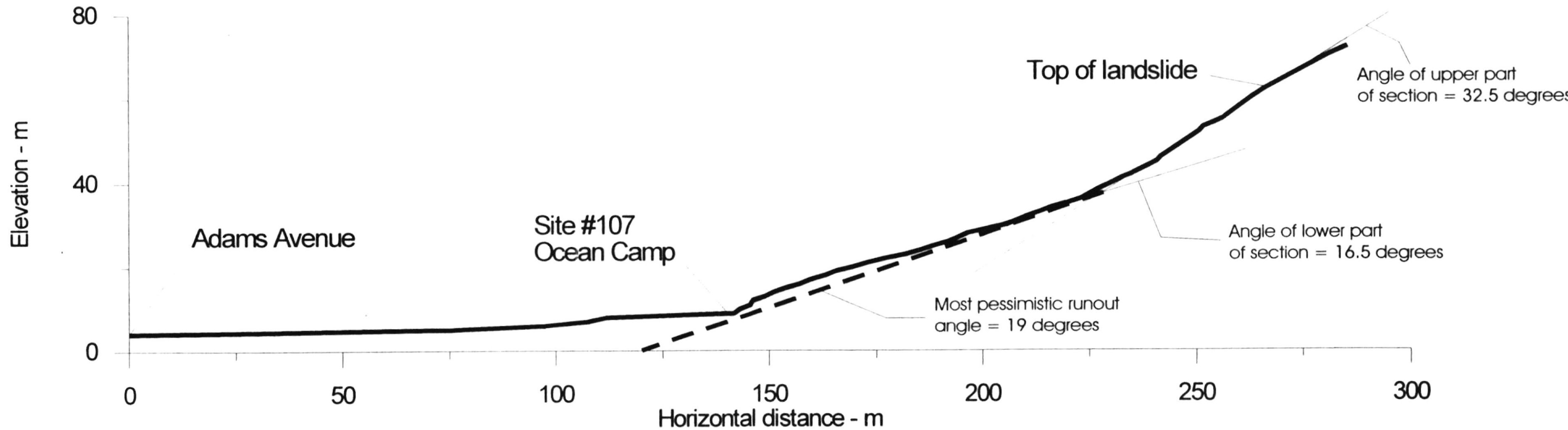
Case 1: L is less than L_{max}



Case 2: L is greater than L_{max}

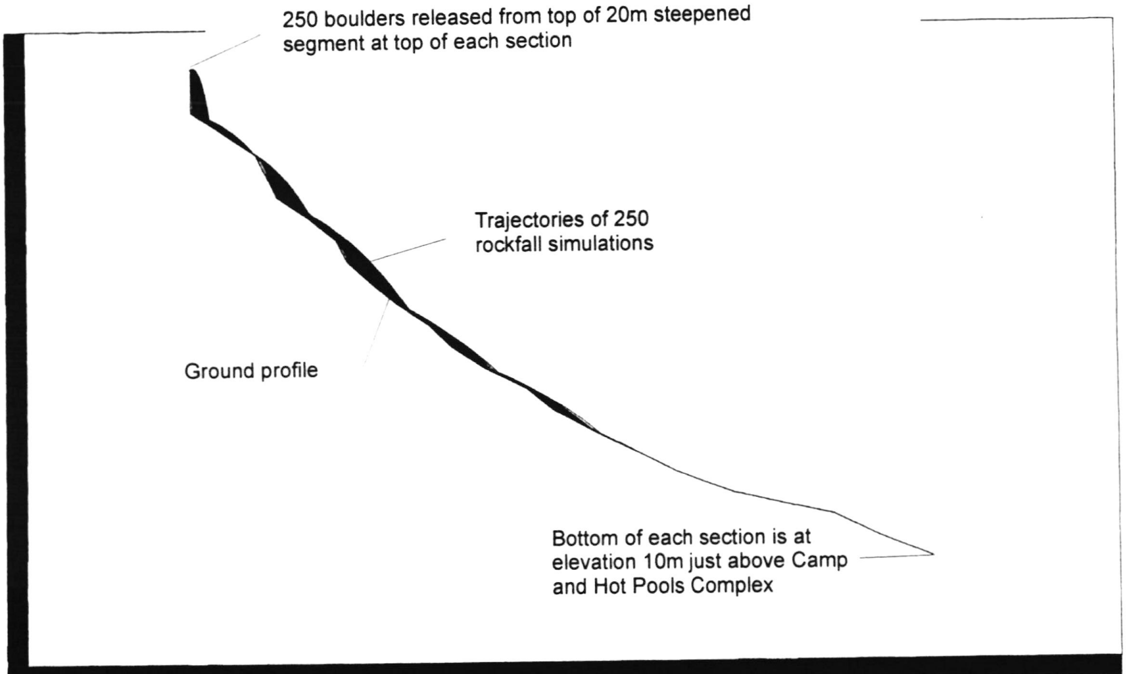
MAUAO STABILITY ASSESSMENT

Definition sketch for landslide runout criteria



MAUAO STABILITY ASSESSMENT
Section through landslide directly above Site 107 Ocean Camp

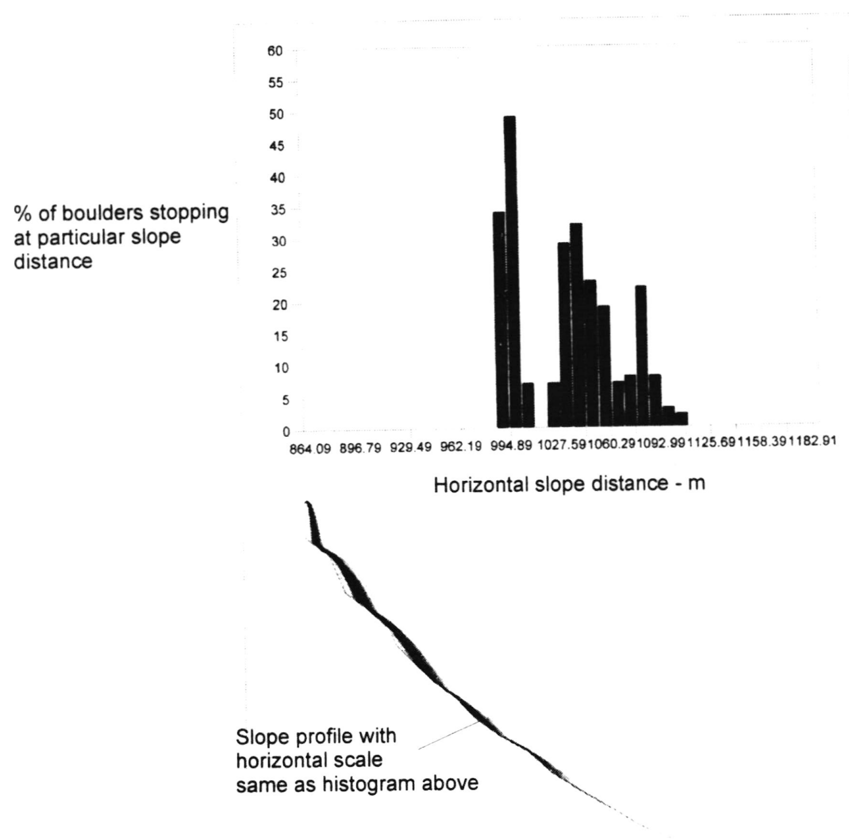
APPENDIX A: COMPUTER SIMULATIONS OF ROCKFALL BEHAVIOUR



Rockfall simulation parameters:

	Mean	Standard deviation
r_n	0.3	0.05
r_t	0.8	0.05

MAUAO STABILITY ASSESSMENT
Simulated boulderfall trajectories for North Slope Section A-A'

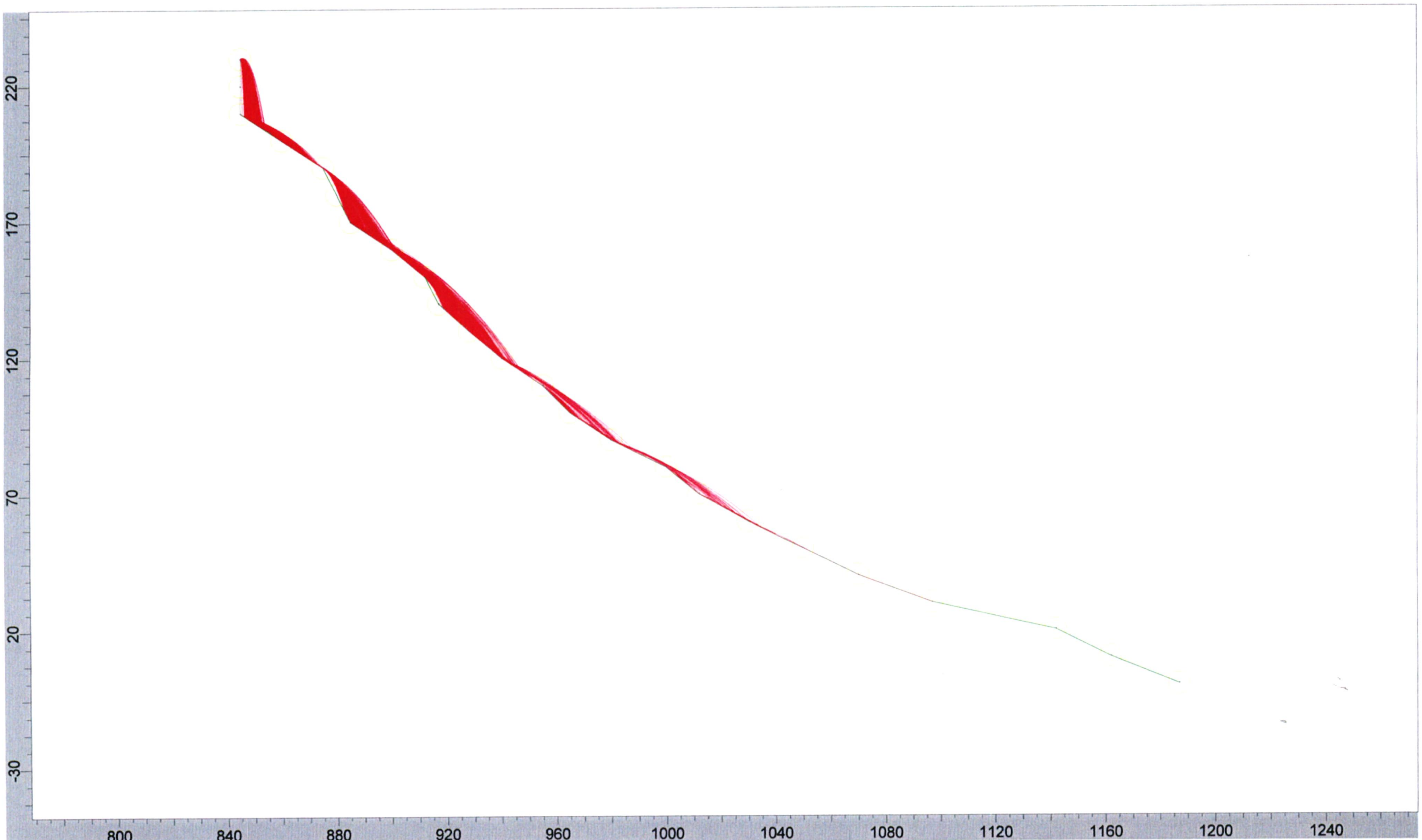


Rockfall simulation parameters

	Mean	Standard deviation
r_n	0.3	0.05
r_t	0.8	0.05

MAUAO STABILITY ASSESSMENT
Boulder endpoints for North Slope Section A-A'

MAUAO STABILITY ASSESSMENT
Definition sketch for rockfall analyses

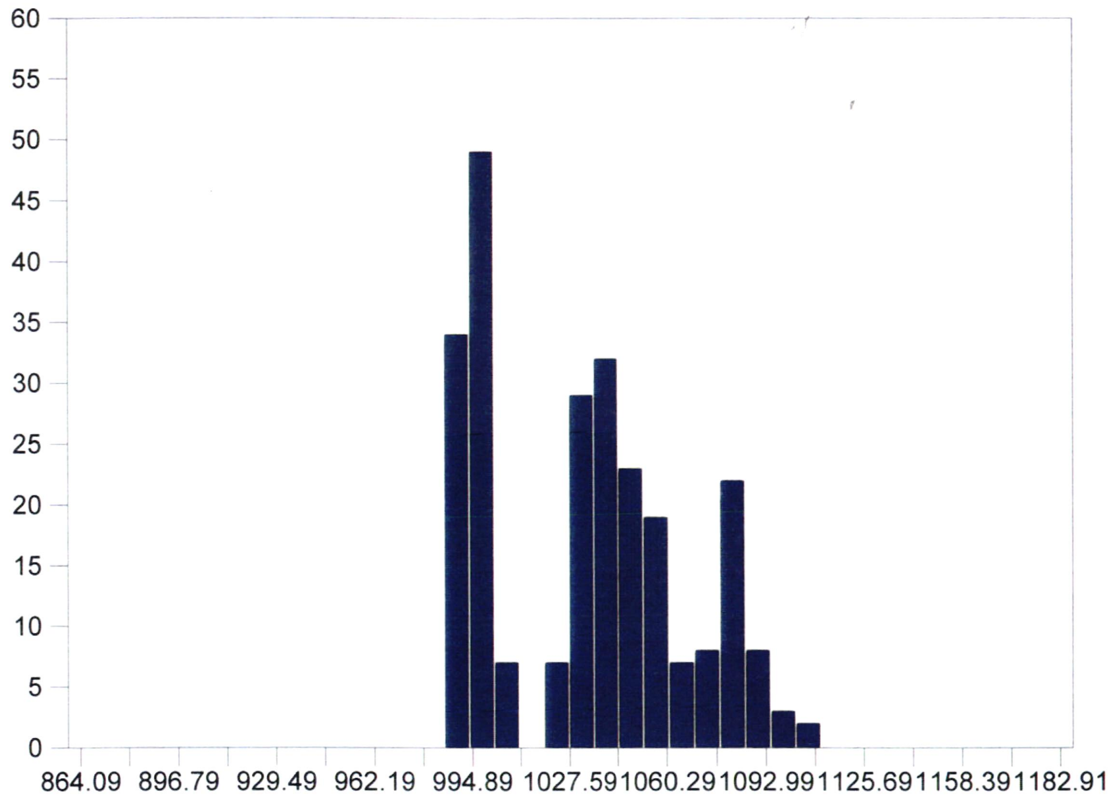


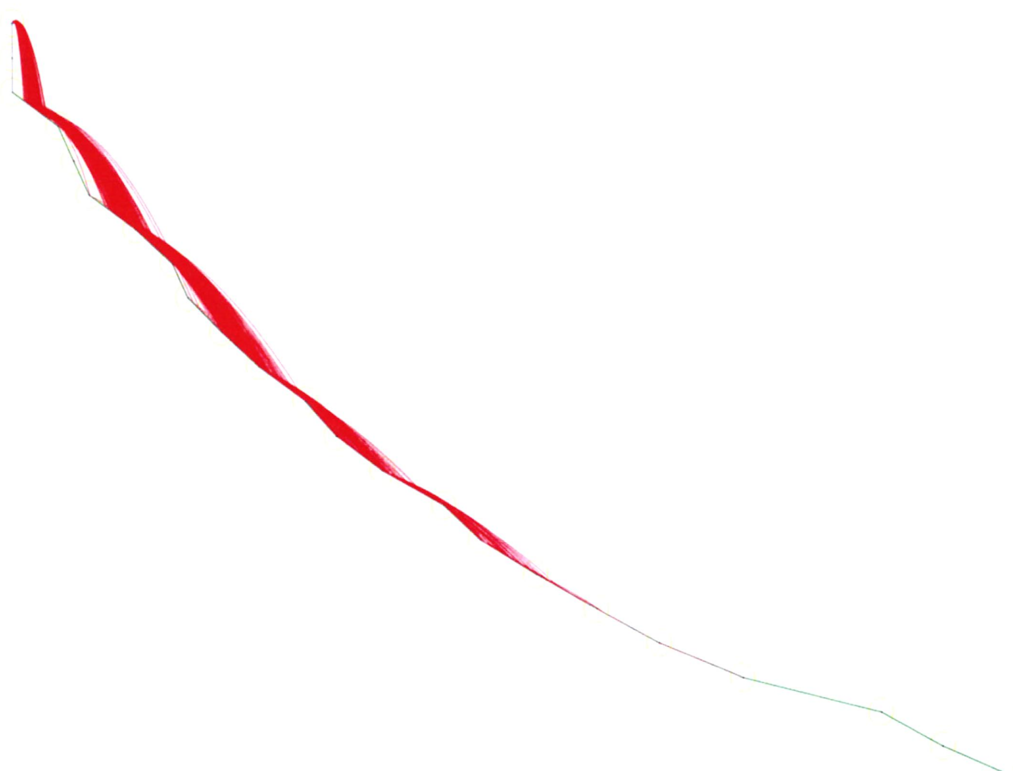
Rockfall simulation parameters:

	Mean	*Standard deviation*
r_n	*0.3*	*0.05*
r_t	*0.8*	*0.05*

MAUAO STABILITY ASSESSMENT
Simulated boulderfall trajectories for North Slope Section A-A’

Figure **A2**





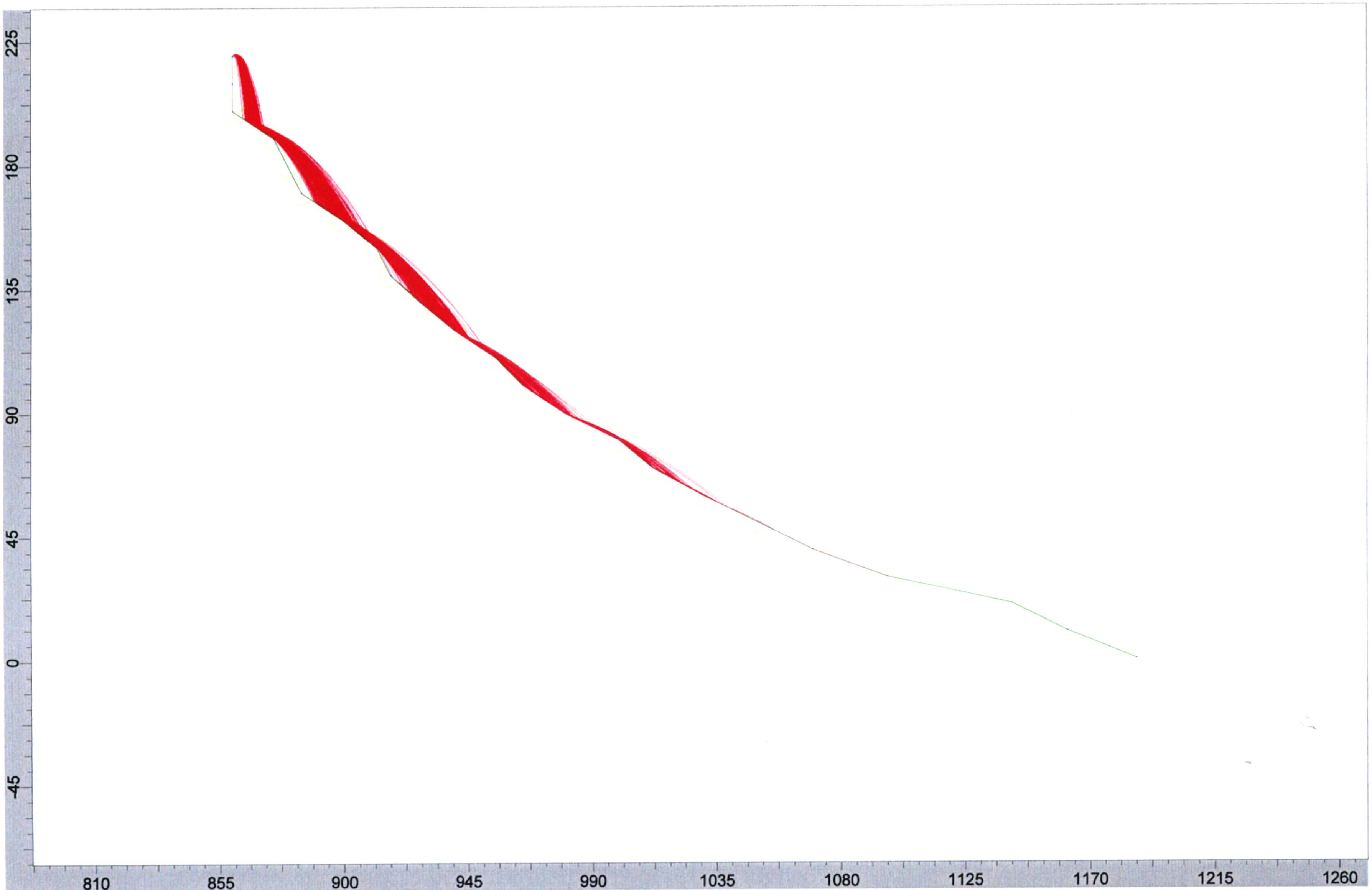
Rockfall simulation parameters

	Mean	*Standard deviation*
r_n	*0.3*	*0.05*
r_t	*0.8*	*0.05*

MAUAO STABILITY ASSESSMENT

Boulder endpoints for North Slope Section A-A'

Figure A3

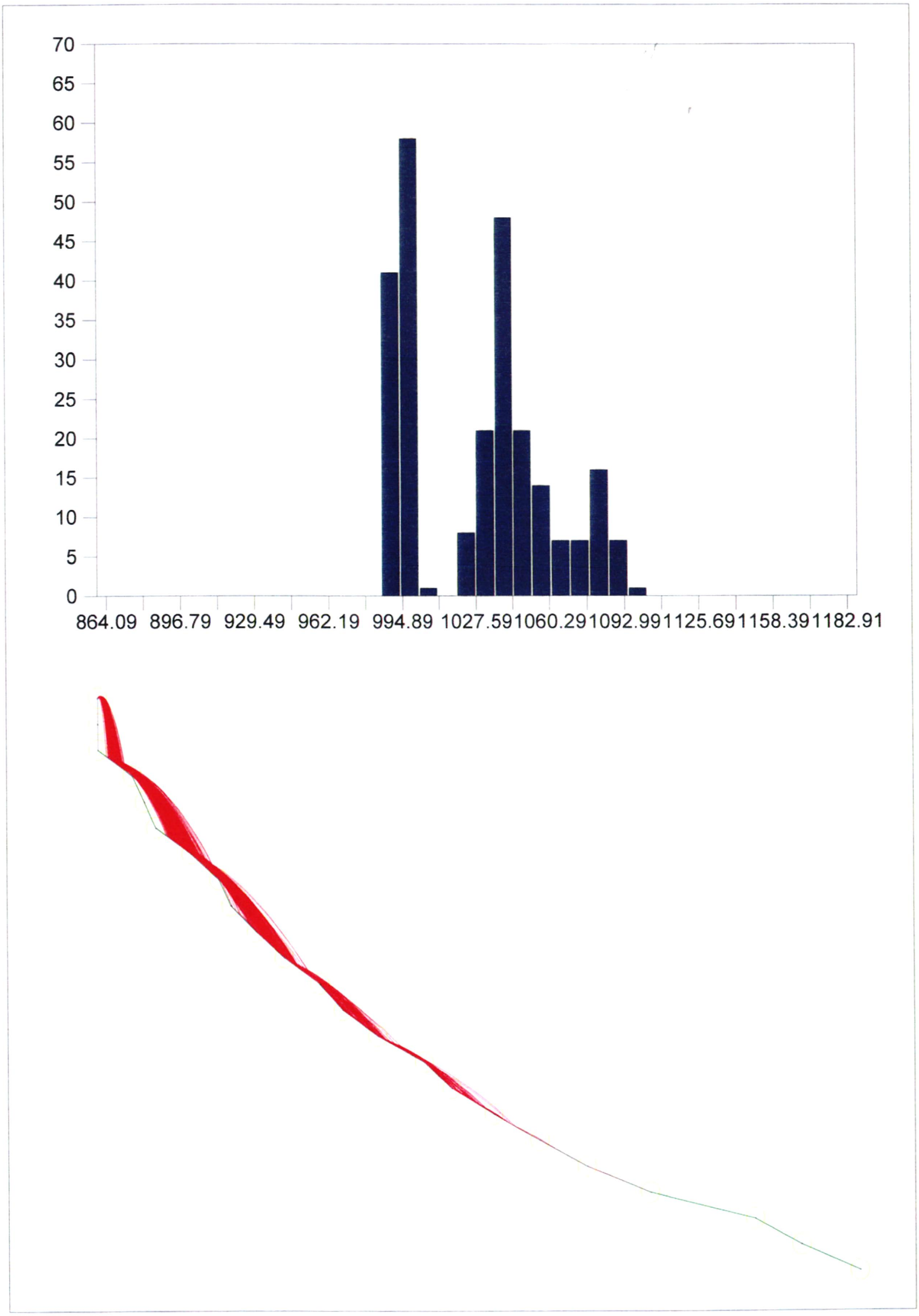


Rockfall simulation parameters:

	Mean	*Standard deviation*
r_n	*0.2*	*0.05*
r_t	*0.6*	*0.05*

MAUAO STABILITY ASSESSMENT
Simulated boulderfall trajectories for North Slope Section A-A'

Figure A4



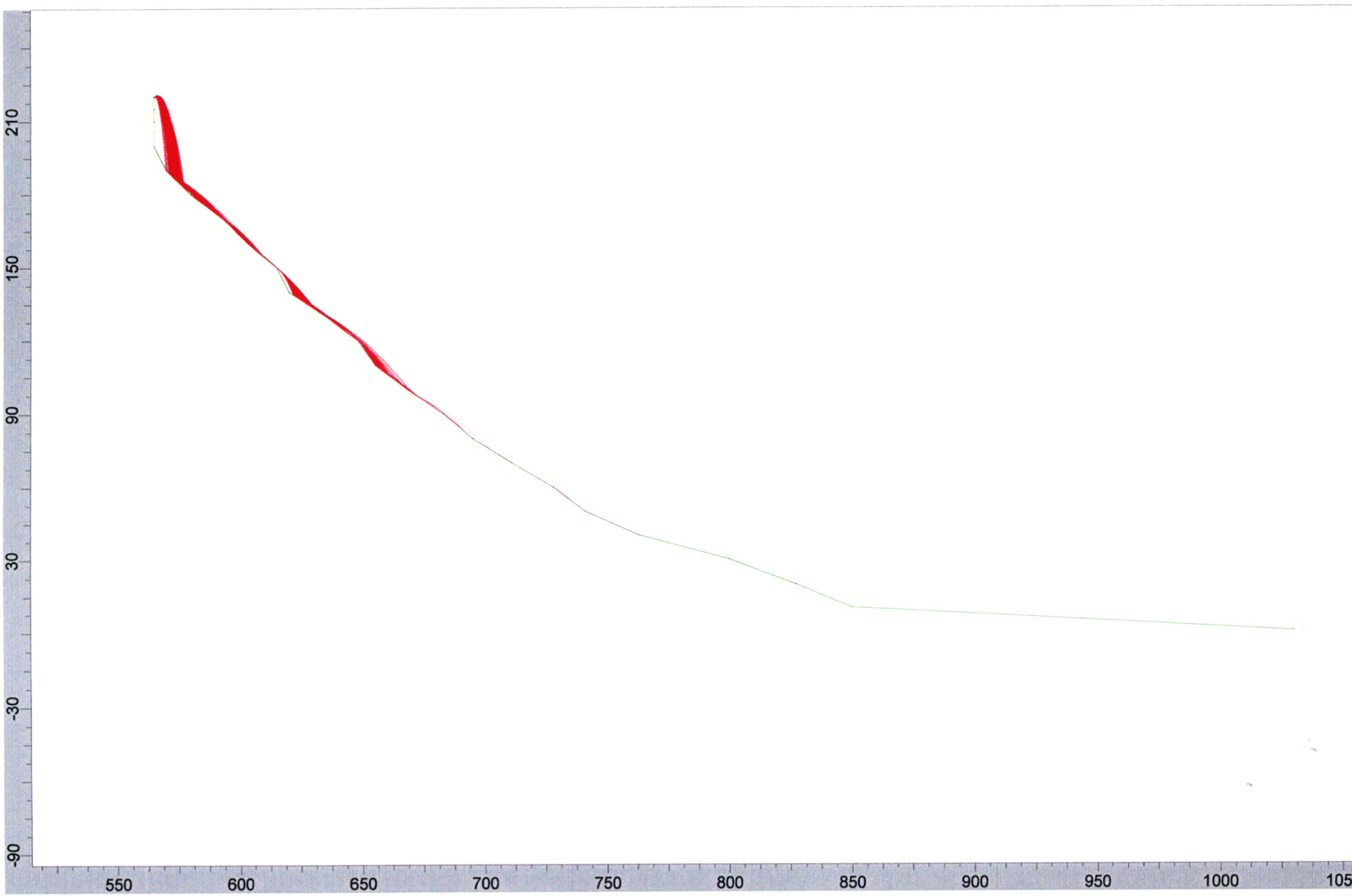
Rockfall simulation parameters

	Mean	*Standard deviation*
r_n	*0.2*	*0.05*
r_t	*0.6*	*0.05*

MAUAO STABILITY ASSESSMENT

Boulder endpoints for North Slope Section A-A'

[redacted]re [redacted]

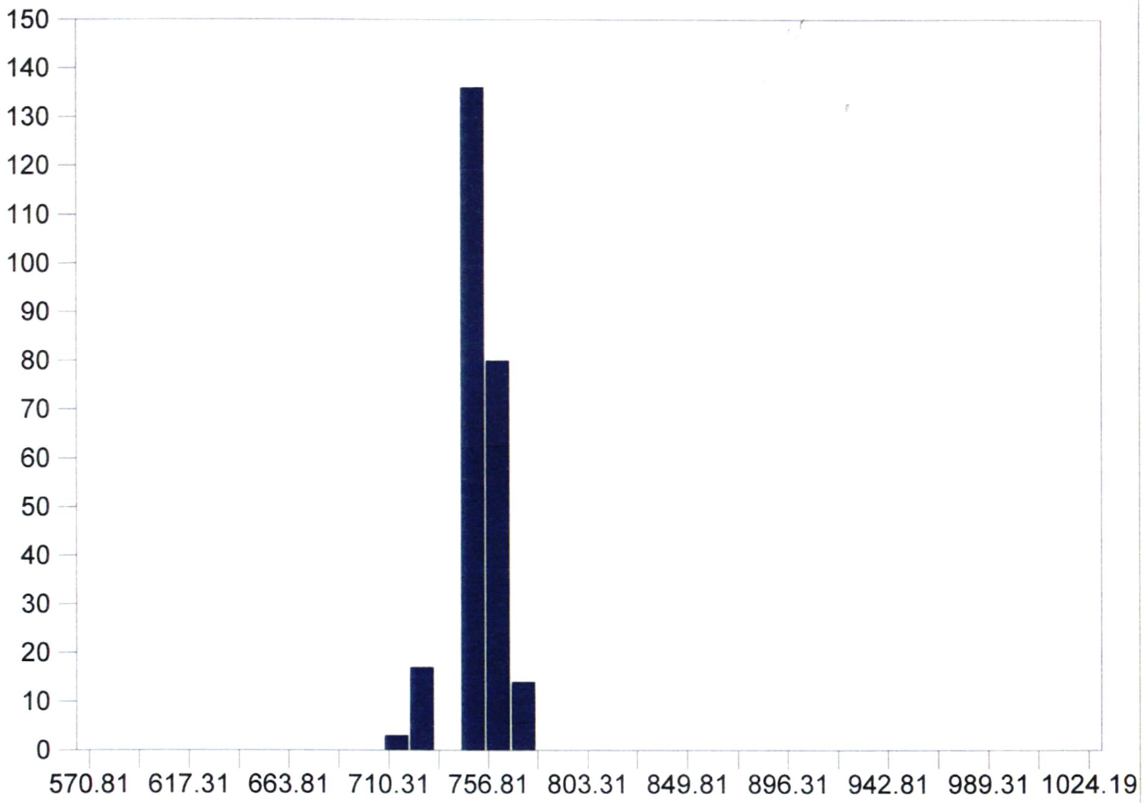


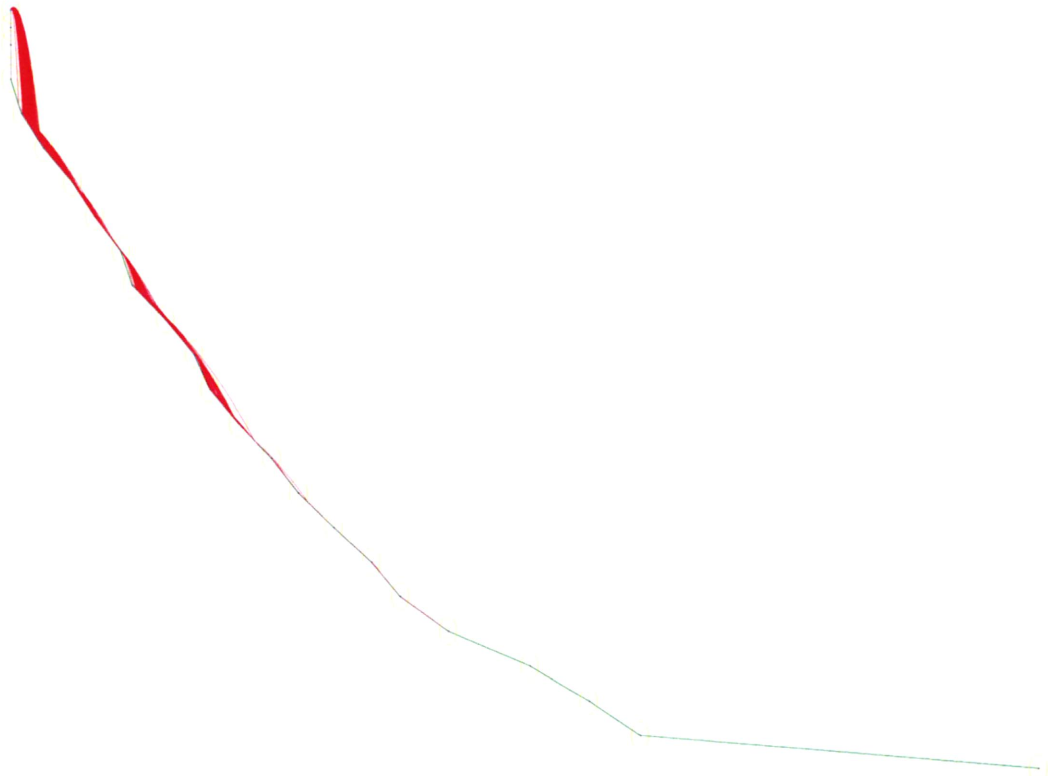
Rockfall simulation parameters:

	Mean	*Standard deviation*
r_n	*0.3*	*0.05*
r_t	*0.8*	*0.05*

MAUAO STABILITY ASSESSMENT
Simulated boulderfall trajectories for East Slope Section B-B'

Figure **A6**



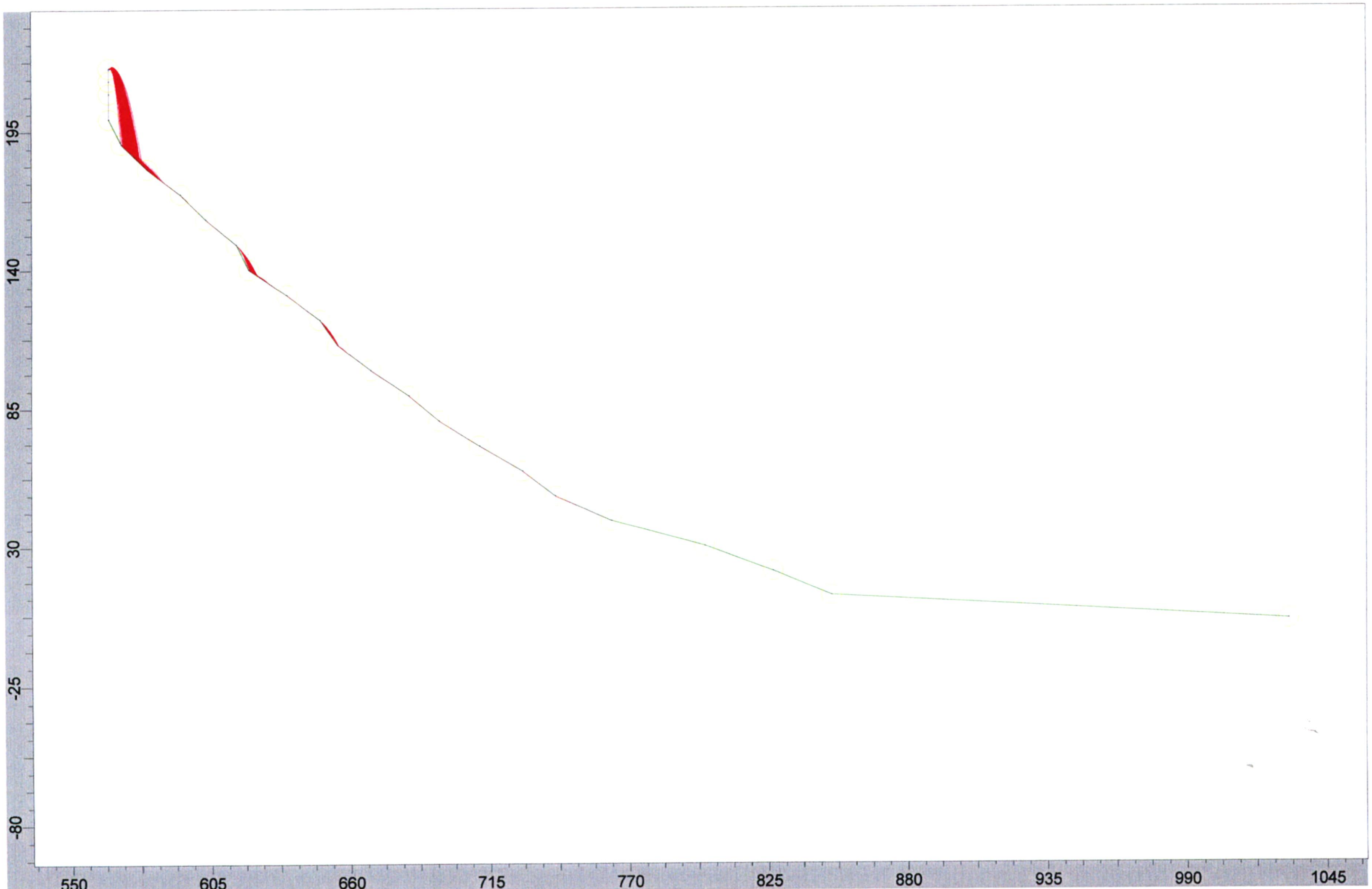


Rockfall simulation parameters

	Mean	*Standard deviation*
r_n	*0.3*	*0.05*
r_t	*0.8*	*0.05*

MAUAO STABILITY ASSESSMENT

Boulder endpoints for East Slope Section B-B'

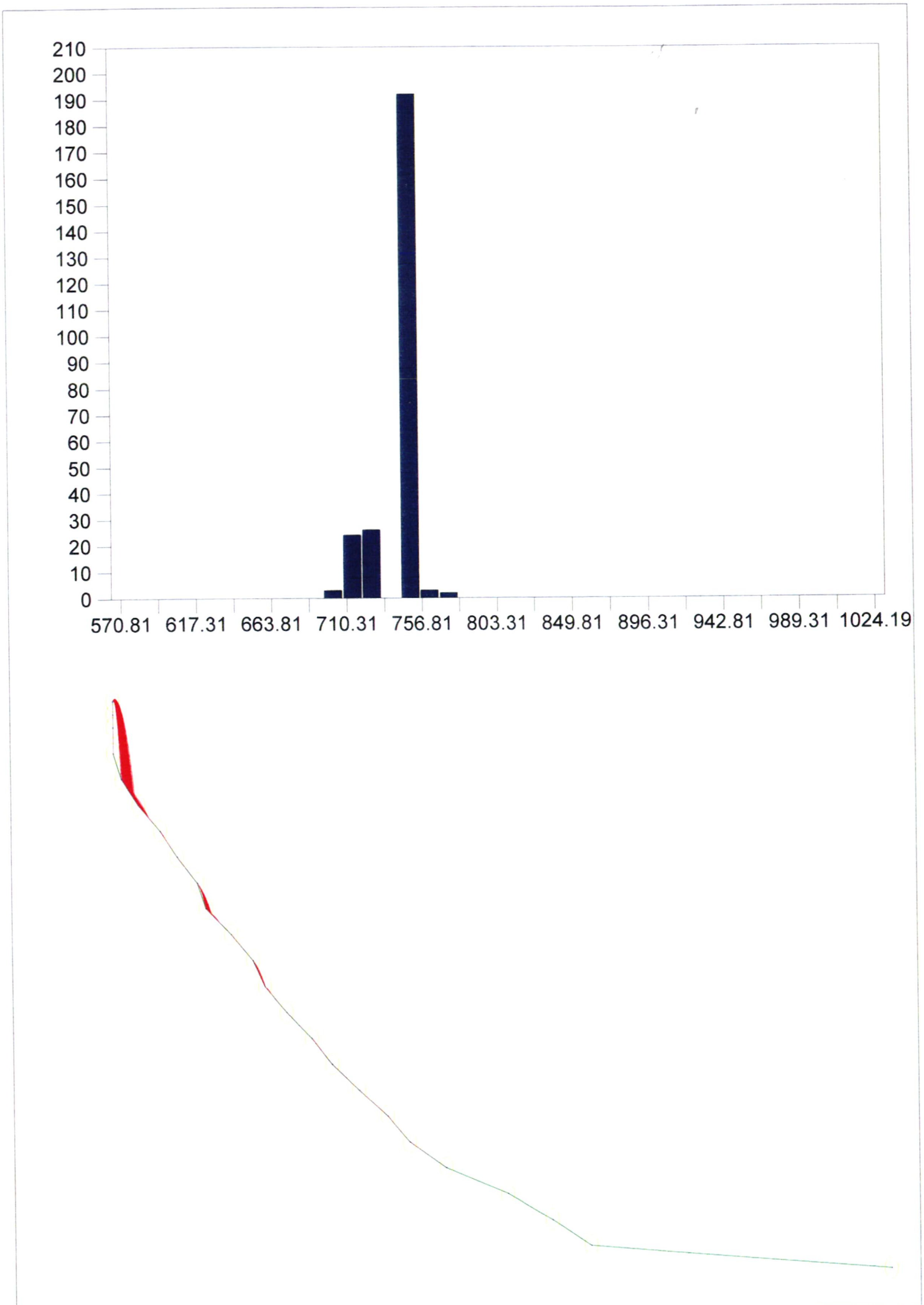


Rockfall simulation parameters:

	Mean	Standard deviation
r_n	0.2	0.05
r_t	0.6	0.05

MAUAO STABILITY ASSESSMENT
Simulated boulderfall trajectories for East Slope Section B-B'

Figure A8



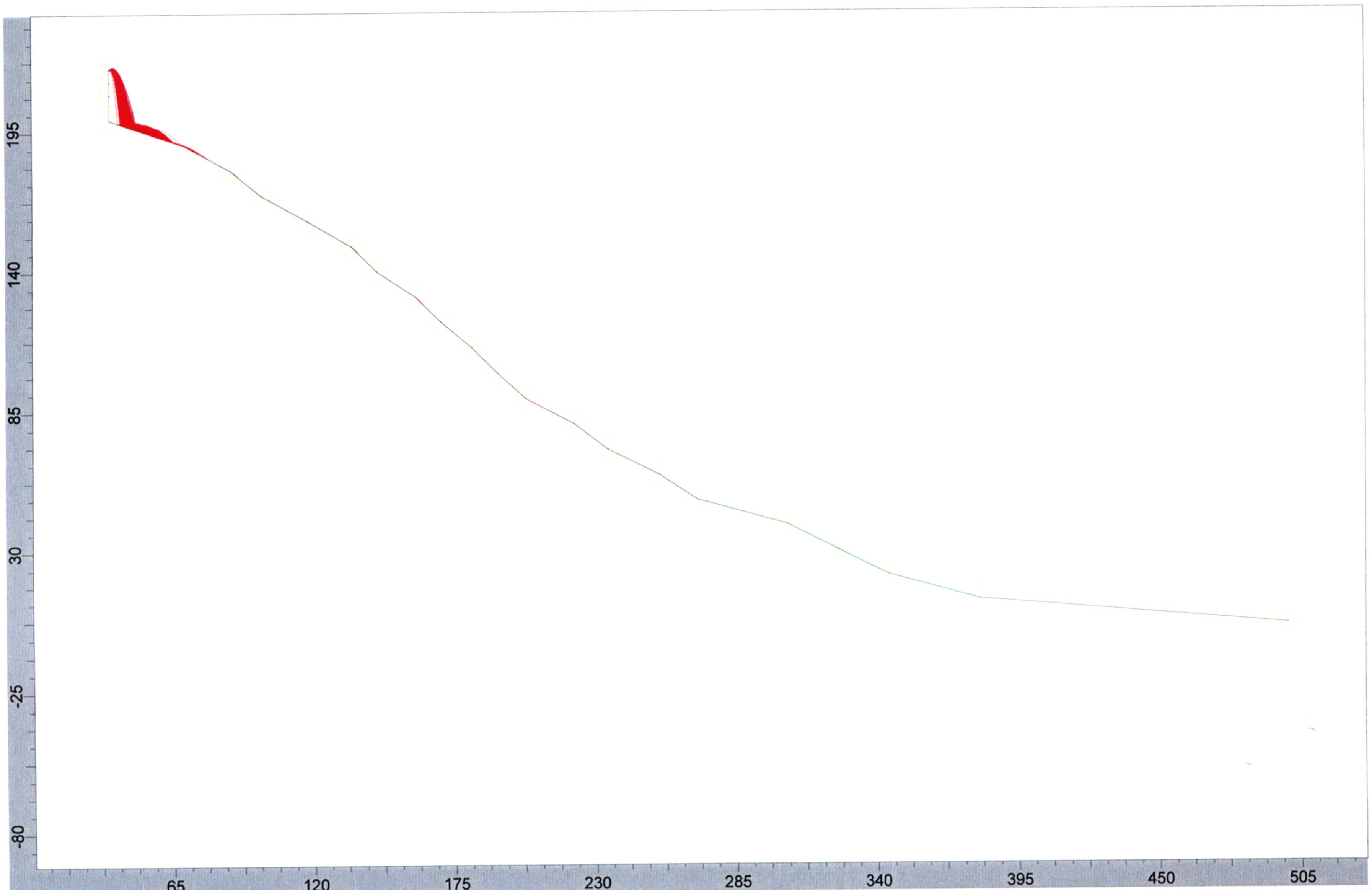
Rockfall simulation parameters

	Mean	*Standard deviation*
r_n	*0.2*	*0.05*
r_t	*0.6*	*0.05*

MAUAO STABILITY ASSESSMENT

Boulder endpoints for East Slope Section B-B'

Figure A9

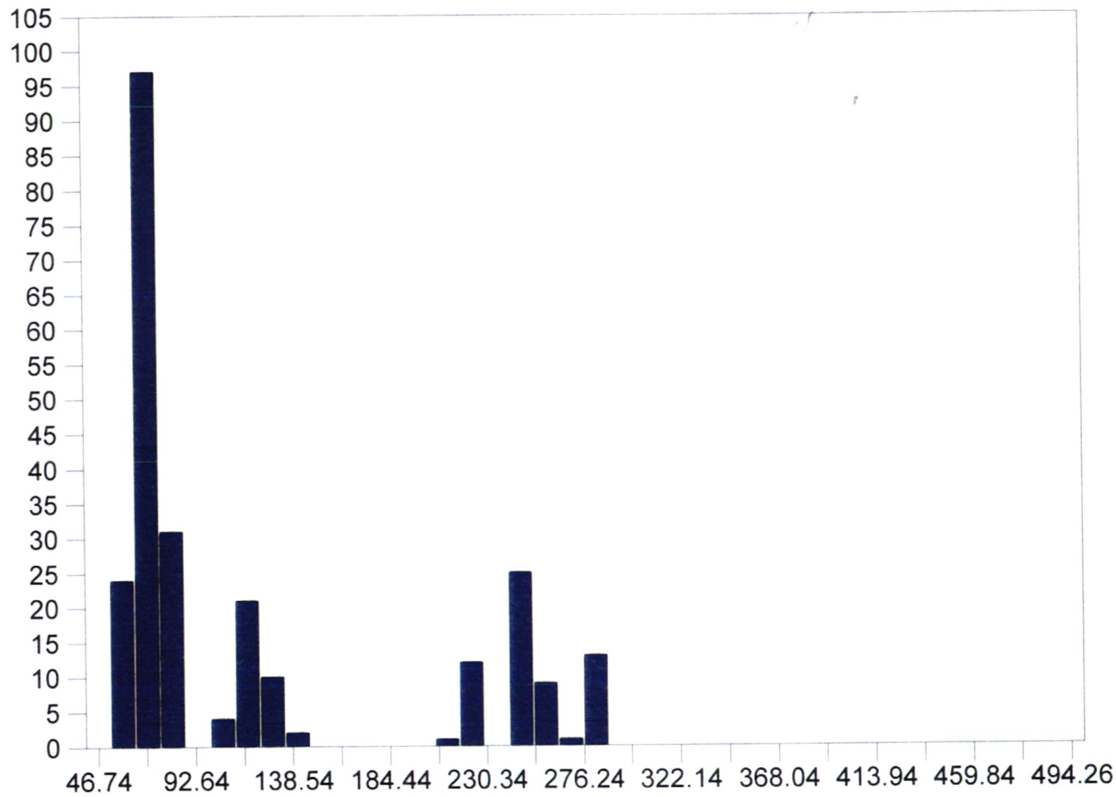


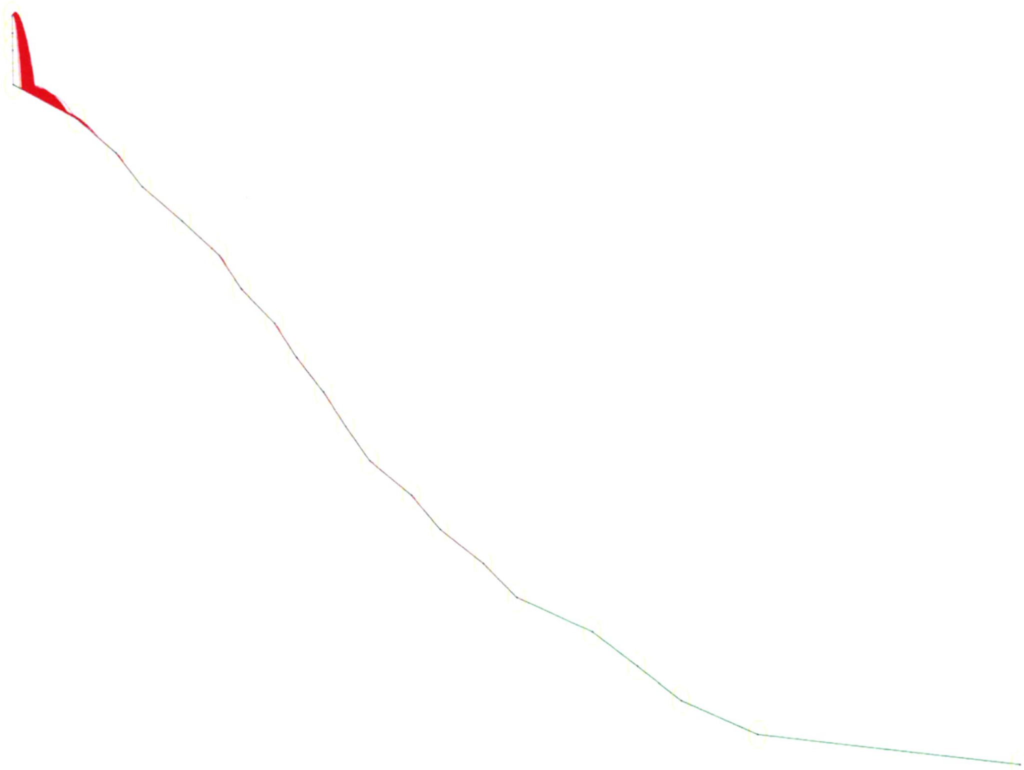
Rockfall simulation parameters:

	Mean	Standard deviation
r_n	0.3	0.05
r_t	0.8	0.05

MAUAO STABILITY ASSESSMENT
Simulated boulderfall trajectories for Hot Pools Section

Figure **A10**





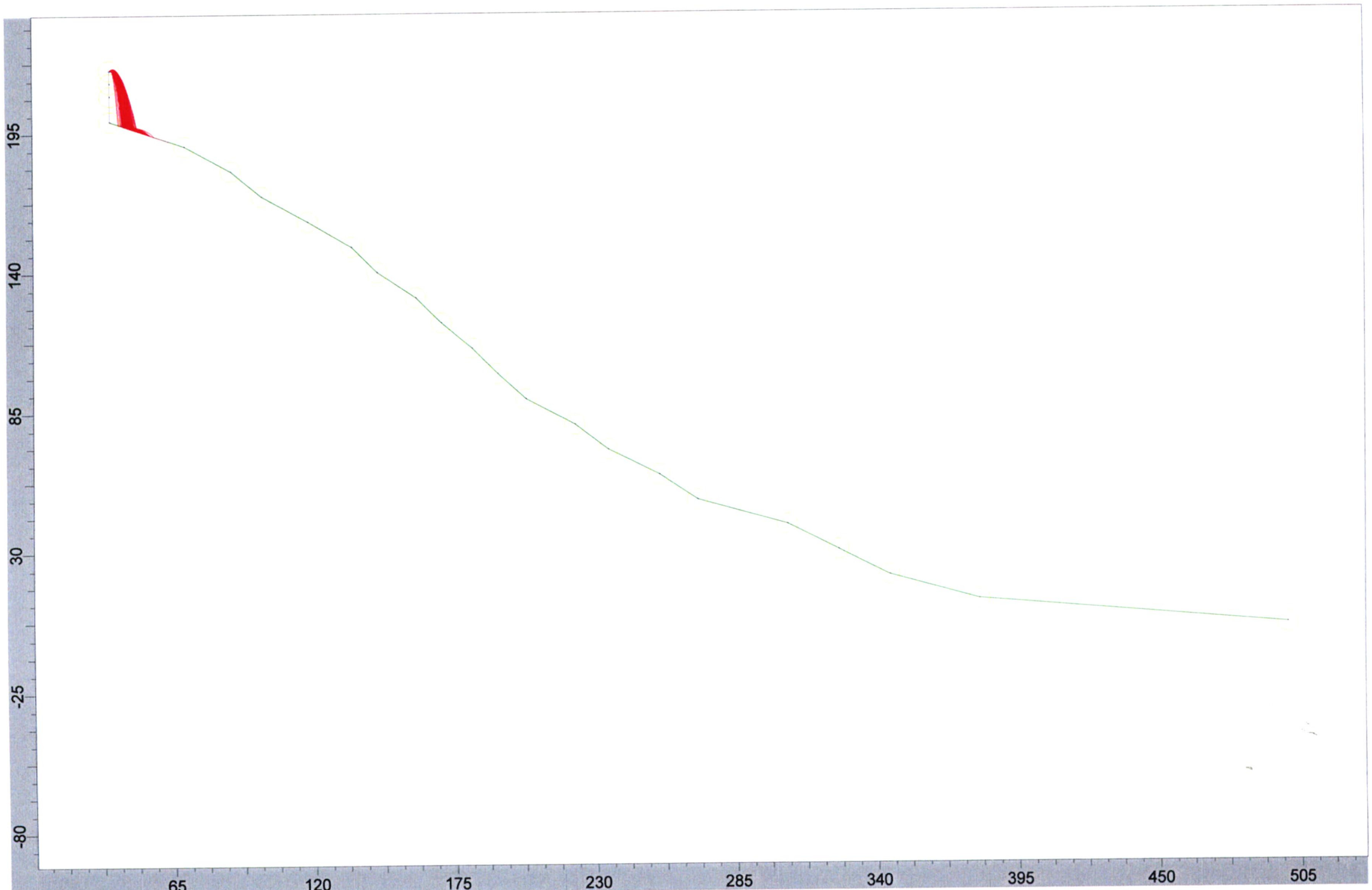
Rockfall simulation parameters

	Mean	*Standard deviation*
r_n	0.3	0.05
r_t	0.8	0.05

MAUAO STABILITY ASSESSMENT

Boulder endpoints for Hot Pools Section

Figure A11

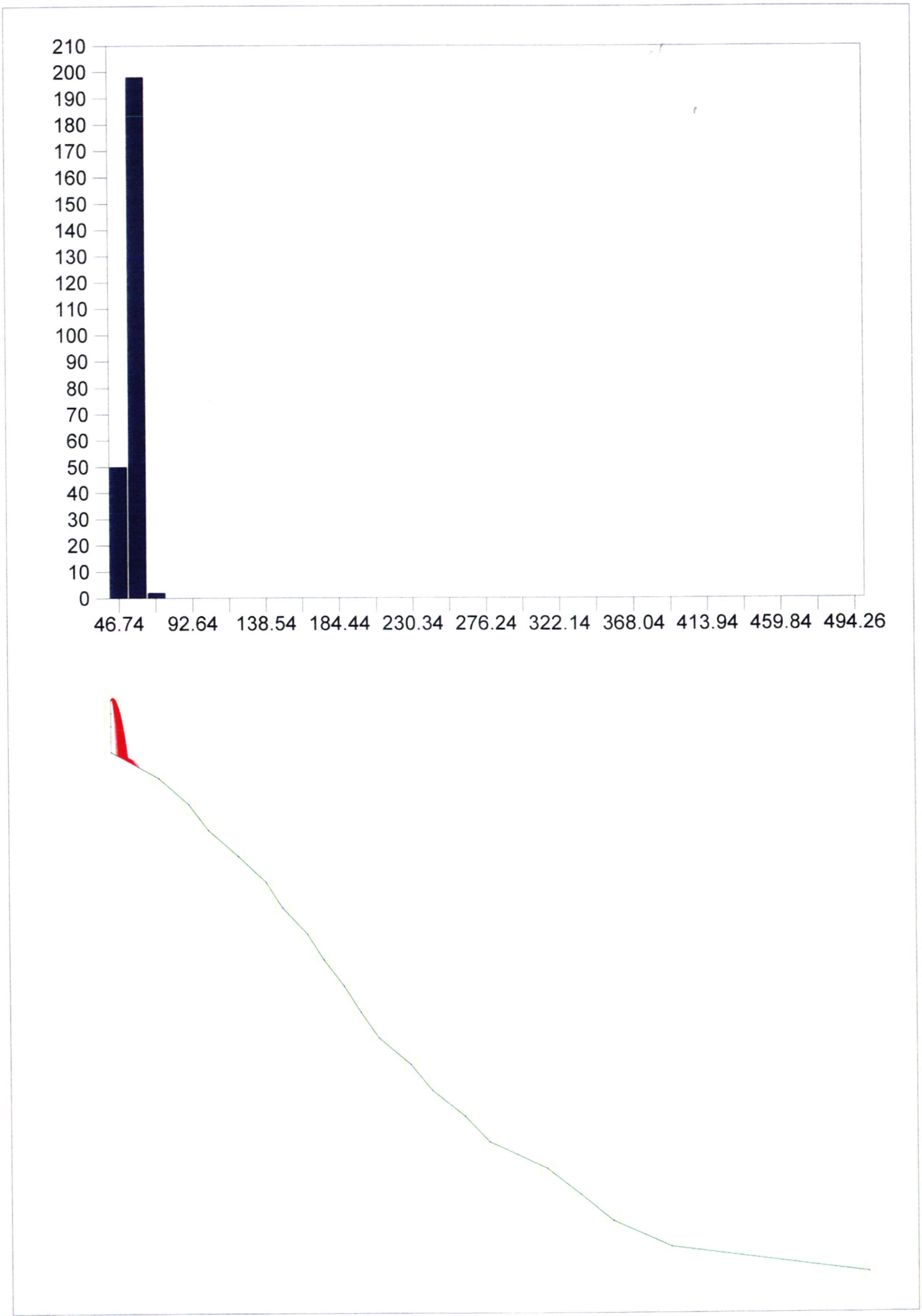


Rockfall simulation parameters:

	Mean	Standard deviation
r_n	0.2	0.05
r_t	0.6	0.05

MAUAO STABILITY ASSESSMENT
Simulated boulderfall trajectories for Hot Pools Section

Figure A12



Rockfall simulation parameters

	Mean	*Standard deviation*
r_n	*0.2*	*0.05*
r_t	*0.6*	*0.05*

MAUAO STABILITY ASSESSMENT

Boulder endpoints for Hot Pools Section

APPENDIX B: RISK CALCULATIONS

APPENDIX B: RISK CALCULATIONS

1. INTRODUCTION

This appendix considers the hazards associated with falling rocks for a moving or stationary visitor on Mauao. The risk assessment has been carried out using the methodology described by Bunce et al.[1]

The analysis has involved a number of simplifying assumptions:

- Visitor movement around Mauao is uniformly distributed in time and space and independent of rockfalls
- The annual number of visitors is 150,000
- 100,000 visitors walk around the Base Track only
- Each walking visitor has a vulnerable space of 1m diameter around them
- Walkers move at 2 km/hr on all tracks
- Visitors do not take evasive action when alerted to rockfalls
- Visitors remain stationary for significant periods only in the area of the Base Track where a person may remain for 30 minutes at a time
- The boulder falls are uniformly distributed in time and space and independent of the visitor movements
- 75% of the boulders from the summit cliffs reach the upper tracks (Oruahine, Waikorere and Bush path)
- 1% of the boulders from the summit cliffs reach the Base Track

Although more detailed analyses could be carried out, these are not warranted by the available data. For example, the analysis could consider separately day and night events. However, this would not alter the end result significantly since the lower probability of a rockfall accident at night would be offset by the increased probability during the daytime. The analysis may, in fact, overestimate the likely hazard since visitor numbers would be much reduced during times of heavy rainfall when the likelihood of rockfalls was higher.

Definition of symbols used in appendix

Symbol	*Definition*
P(A)	Probability of a rock hitting a person
PAI	Probability of a rock hitting a particular individual
$P(S, N_a)$	Probability of N_a people being hit when N_r rocks fall
P(S)	Probability of at least one person occupying the location of a rockfall
$N_a!$	Factorial of N_a
P(S:H)	Probability of spatial impact given the event or the probability that the person occupies the portion of the track affected by a rockfall
P(T:S)	Probability of temporal impact given spatial impact or the probability that a person occupies the rockfall path when the rock impacts the track
L_i	Distance occupied by a person
S_i	Interval between people on the track
L_t	Length of track
V_i	Average walking speed of an individual
t	Average time to walk track

The probability, $P(S,N_a)$ of N_a people being hit when N_r rocks fall is given as:

[1]
$$P(S,N_a)=\frac{P(S{:}H)^{N_a}(1-P(S{:}H))^{(N_r-N_a)}N_r!}{N_a!(N_r-N_a)!}$$

where $P(S{:}H)$ is the probability that a person occupies the portion of the track affected by a rockfall and $N_a!$ is the factorial of N_a.

When N_a is zero, the above equation reduces to

[2] $$P(S,0) = (1 - (1 - P(S:H))^{N_r}$$

the probability that no person is hit. So the probability that one or more persons is hit is:

[3] $$P(S) = 1 - (1 - P(S:H))^{N_r}$$

The following sections show the calculations for *P(A)*, the annual probability of an accident to one or more persons, and *PAI*, the annual probability of an accident to a particular person for two types of incident:

- Rockfall on to stationary persons
- Rockfall on to moving person

2. IMPACT OF A FALLING ROCK ON A STATIONARY PERSON

2.1 Annual probability of rock hitting person stopped on track

The annual probability, *P(A),* of a rock hitting a person stopped on the track is:

[4] $$P(T:S) \times P(S)$$

where *P(T:S)* is the probability that the person occupies the trajectory of the rock at the same time as it crosses the track.

[5] $$P(T:S) = \frac{t}{8760}$$

where *t* is in hours.

P(S:H) is the probability of impact given a fall and is calculated from:

[6] $$L_i / (L_i + S_i)$$

where L_i is the distance occupied by the person and S_i is the distance between people.

P(S) is as defined in equation [3] above and N_r is the annual number of rockfalls.

2.2 Probability of rock hitting an individual person

The fraction of the track occupied by an individual person is defined as follows.

[7] $$P(S:H) = \frac{L_i}{L_t}$$

where L_i is the distance occupied by the person and L_t is the length of the track.

P(S) is calculated from equation [3] and then the probability of a rock hitting an individual person is:

[8] $$PAI = P(S) \times P(T:S)$$

3. IMPACT OF A FALLING ROCK ON A MOVING PERSON

3.1 Annual probability of rock hitting a moving person

The proportion of the track that is instantaneously occupied by a walking person is:

[9] $$P(S:H)=\frac{\frac{N_i}{24}\times\frac{L_i}{1000}}{V_i}$$

where N_i is the number of people per day on the track, L_l is the distance occupied per individual (m) and V_l is the average walking speed (km/hr).

As the walking traffic in this case is uniformly distributed in time and space throughout the year:

[10] $$P(T:S) = 1.$$

The annual probability of a rock hitting an individual is:

[11] $$P(A)=P(T:S)\times P(S)$$

3.2 Probability of an accident on a single walk around the tracks

The probability of an accident on a single walk around the tracks, *PAI,* can be approximated by *P(A)*, the annual probability of at least one accident, divided by the total number of trips per year.

Alternatively, the probability of a rockfall hitting a single person is equal to the fraction of the track occupied by the person, *P(S:H)*, as defined in equation [7].

P(S) is calculated as in equation [2].

The probability that the person is on the track is equal to the fraction of a year occupied by a single walk along the track:

[12] $$P(T:S)=t/8760$$

where:

[13] $$t=L_t/V_i$$

Then

[14] $$PAV=P(S)\times P(T:S)$$

since the accident requires a coincidence in space and time with the rockfall.

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[1] Bunce CM, Cruden DM, Morgenstern NR. *Assessment of the hazard from rock fall on a highway.* Can. Geotech. J. 34: 344-356, 1997

APPENDIX C:
REVIEW COMMENTS FROM MR BELL

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24 May 1999

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Dear Laurie

re: **MAUAO STABILITY ASSESSMENT FOR TAURANGA DISTRICT COUNCIL**

1. Introduction

Further to your request I have carefully read your draft report and examined the aerial photographs provided. I have also considered the specific comments in the letter of 22 April 1999 from Mr Paul Baunton of Tauranga District Council. This brief review endorses the conclusions reached in your excellent report, and also provides specific comment on the issues raised by Mr Baunton.

2. Aerial Photographs

Careful examination of the 1953, 1979 and 1998 aerial photographs provided has confirmed the following:

- there is no evidence to suggest any visible changes in boulder positions over time, nor to indicate that localised rockfall events have occurred in the 35-year period for which records are available.
- the gully positions on the north-east face of Mauao have not changed in the same period, except for the very localised area of disturbance from the 1998 debris flow event.
- other features, such as middens on the south face of Mauao, similarly show no changes within the period of record to indicate either ongoing slope instability or cultural modification.
- there has clearly been an increase in both height and density of vegetation on the upper slopes, which will be generally beneficial in limiting future rockfall events either by stopping boulders or absorbing kinetic energy.

I endorse your observations and conclusions in Section 3.1, and can confirm that changes due to slope instability (rockfall and/or landsliding) within the 35-year period of records have been negligible. I would note, however, that stereo pairs would have facilitated a much better geomorphological interpretation had they been available, but I am still of the opinion that the general tenor of conclusions would not have been changed by more detailed study of aerial photographs.

3. Draft Report

I carefully read and considered the draft report, and my comments are as follows:

- the report is thorough, logically organised, appropriately presented, and extremely well illustrated with figures and tables.
- your comments concerning the geology and geomorphology of Mauao accord with my understanding of the feature as a rhyolite dome, and the rock mass description reflects its complex evolution over time.
- I am not aware of any references which would add significantly to your data as presented in Section 2.1 regarding the geology and geomorphic evolution of the dome feature.
- I would agree that the present topography, with the boulder-littered colluvial apron below the bedrock summit, achieved its present configuration some 3-4,000 years ago, with little subsequent modification.
- The gullies on the north-east face of Mauao may relate to erosion occurring at slightly higher sea levels ($\leq$ 1m above present) during this period, although they may also simply reflect increased wave heights from NE storms.
- Despite the presence of numerous boulders littering the slopes of Mauao, the great majority appear to be embedded into the colluvium and their presumably episodic accumulation undoubtedly occurred over many thousands of years.
- While your trajectory analyses do not suggest any rockfall hazard concerns, I do consider that you have been somewhat pessimistic in your assumptions (eg of spherical rhyolite blocks when their shape is clearly joint-controlled).
- There may be merit in recommending retirement of the upper slopes from grazing and the planting of trees, as well as short-term buttressing or anchoring of some boulders, to further protect against rockfall hazards.
- I agree that there is no evidence for large landslides on Mauao, and your analyses provide convincing confirmation that long runout distances are unlikely in these colluvial soils.
- Given your observations of piping in the colluvial soils it is possible that the gullies referred to above are partly the result of tunnel-gully collapse and long-term erosion (as in the loess soils of the Port Hills, Christchurch).
- It is correct to identify possible future debris flows from the gully areas, particularly those behind the camping ground, and remedial measures such as tree and shrub planting should be considered to control soil moisture levels.
- Your conclusions and recommendations are consistent with the level of risk identified by your analyses, and these are endorsed along with the suggestion of retirement from grazing and tree/shrub planting on the mid-slopes.

Some minor editing is required, for example in Conclusion No 7 (page 9), but the report is thorough, reasonable and logically consistent. I could find no technical errors or omissions, and I consider that you have more than adequately dealt with the issues raised in your brief.

4. Baunton Comments

Some of the comments made in the Baunton letter of 22 April 1999 are simply editorial, and the following observations therefore relate only to those points on which I can offer useful comment:

A. *Scott – Sea Level Rise: As noted above I agree with your geomorphic interpretation that the eastern barrier spit was formed probably 4,000 ± 1,000 years ago. It is my personal view that the gullies on the NE face of Mauao may well date from around that time, especially given the literature evidence to suggest that sea level may then have been up to 1m higher than at present. This would imply wave undercutting, possibly associated with a greater incidence of NE storms as well, but I do note also that some at least may result from piping-type failures and subsequent gullying. The plotting of spring locations would be very useful in that regard, as these could be sources for gullying and/or increased soil moisture levels causing creep and/or slope failure.*

B. *AEP Storm: I endorse the concept of using the Lumb approach for storms in the Tauranga area, although I would have to agree with John Scott that Peter's boxes will not necessarily translate from Hong Kong without modification. It is in my view significant that the storm in question (1998) did not trigger extensive slope failures on Mauao, nor apparently did the 1979 storm that caused extensive damage at Omokoroa. Certainly there could be merit in developing the "Lumb model" further for Tauranga conditions as an emergency management tool, as is done in Hong Kong.*

C. *Debris Flow Generation: I agree that this is an issue, particularly in relation to the camping ground site and its future occupation. Some remediation of the frontal lobe areas is probably warranted, depending on the outcome of additional work, but my suggestion about retirement of the slopes from grazing and extensive vegetation planting may prove to be sufficient in the longer term.*

I can well understand Council's concerns with the situation at Mauao, and some further work adjacent to the camping ground is warranted. I would imagine that this would entail detailed topographic surveys, limited site investigation, and the development of a set of minor works based on the hazard analysis and zonation that results from the study. With regard to the rockfall hazard this does not appear to be as serious as first sight might suggest, and the key issue there is whether or not grazing is stopped and a planting programme is initiated.

I trust that these comments deal with all of the issues raised, but do not hesitate to contact me if you require further information on this matter or clarification of any of the points made in this review.

Yours sincerely

DAVID H BELL
Senior Lecturer in Engineering Geology