Geotechnical properties of rock masses: their control on slope form and mechanisms of change along the Napier Range, Western Australia

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ABSTRACT

Slope form and the mechanisms of change which slope profiles exhibit are frequently subject to scrutiny by geomorphologists. However, the majority of studies do not consider fundamental material properties and rock mass geotechnical characteristics. The results presented here highlight the importance of synthesising standard geomorphological site investigation techniques with quantifiable rock geotechnical parameters, in order to understand slope form and development. Field research has been undertaken along the Napier Range of the Kimberley Region, Western Australia. The Napiers are an extensive, upraised, Devonian limestone reef, along which a number of characteristic slope profiles can be identified. Laboratory studies of yield strength, stress–strain characteristics, elastic properties and discontinuity parameters have been conducted on material sampled at sites representative of each slope profile type. The results suggest that highly concave slopes have formed in limestone which exhibits little deformation before yield, has a high modulus of elasticity and few irregular fractures. Convexo-concave slopes, on the other hand, are characteristic of material which displays a greater ability to strain below yield, a relatively low modulus of elasticity and a pronounced discontinuity pattern. It is the combination of field investigations and laboratory study which most successfully explains variations in slope form.

Introduction

Although natural slopes and cliffs which develop in jointed, brittle rock masses are often the subject of geomorphological research, data which identify associations between morphology and the geotechnical characteristics of the rock mass such as strength and material elasticity are comparatively rare. Studies which investigate cliff form and the nature and mechanisms of change are usually semi-quantitative (see May and Heeps, 1985 for example). The models used for describing hillslope profiles are frequently based on profile components (Parsons, 1988) such as the nine-unit model presented by Dalrymple et al. (1968). An approach which has increased in popularity recently is to use a rock mass classification (Bieniawski, 1973, 1980; Selby, 1980; Moon, 1984a; Abrahams and Parsons, 1987) as a semi-quantitative method of explaining variations in morphology (see Selby, 1982; Moon, 1984b; Allison and Goudie, 1990a for example).

In geotechnical engineering the importance of the mechanical properties of the rock mass in controlling slope stability is often recognised (Hoek and Bray, 1981; Johnson and De Graff, 1988). Inevitably, site investigations are usually aimed at identifying the critical slope angle and kinematic factor of safety which marks the boundary between stable and unstable conditions. One of the principal objectives of such studies is often the design of slope profiles, abutments and quarry free faces and, in this respect, the methodology can be linked

to the analysis of natural slopes. It is also important to recognise that by using photographic evidence, map and survey data, the form of a slope and any inference about future change is based solely on past events. Conclusions will therefore partly reflect the response time of natural landforms to external forces and may not reflect equilibrium between current process and form.

There is potentially much to be gained from considering the fundamental geotechnical properties of jointed rock masses when studying the form of natural slopes and their mechanisms of change. Adopting such an approach goes some way towards overcoming problems like changes in process environments which accompany climatic change for example. It is all but impossible to unravel the complexities associated with the superimposition of one set of processes upon another in geomorphological systems where there are likely to be long relaxation times towards equilibrium forms (Thornes and Brunsden, 1977). Rock mass parameters are more likely to remain constant or at least display only small temporal variations.

The results presented here examine variations in slope form using quantifiable rock mechanics parameters. The study uses the bounding cliffs of an ancient limestone reef complex, which displays marked variations in morphology from steep, vertical cliffs on the one hand, to smooth concavo-convex forms on the other.

The study area

The Napier Range, located at approximately 17°S and 125°E, trends northwest to southeast in direction and forms part of the west Kimberley region of Western Australia (Fig. 1) (Wright, 1964; Playford and Lowry, 1969; Derrick and Playford, 1973; Hancock and Rutland, 1984; Spath, 1987; Ollier et al., 1988). The Range is approximately 110 km long, 5 km across at its widest point, reaches altitudes of 190 m and fringes the northern
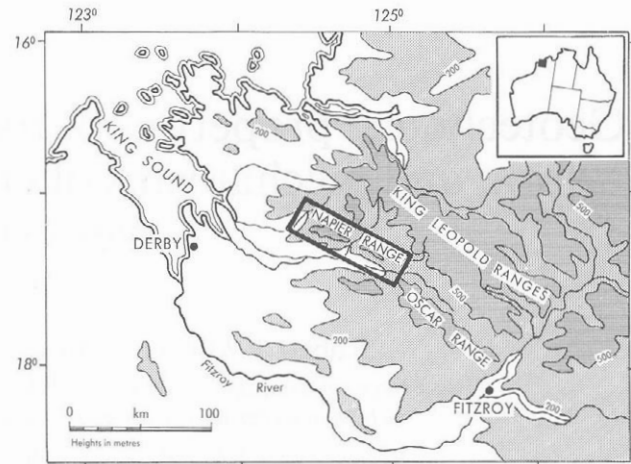

Fig. 1. Location of the Napier Range.

margin of the Canning Basin (Towner and Gibson, 1983). The Napiers are flanked by flat, low lying plains which have an altitude of 90 to 100 m above sea level. Parts of the Range are also fringed by a rock cut pediment which has mean slope angles of 1° to 3°. The Napiers are an exhumed and highly dissected Devonian fringing and barrier reef complex (Jennings and Sweeting, 1963; Playford and Lowry, 1969), which grew along the southern margins of the Kimberley Block (Ollier et al., 1988). The King Leopold Ranges to the north mark the southern limit of the ancient land surface. The flat plain between the King Leopolds and the Napier Range represents an area originally submerged beneath a fresh water lagoon, while the plain to the south of the Range identifies the location of the ocean floor.

The original reef deposition comprises three facies, all of which are clearly visible along the Range today (Derrick and Playford, 1973). The Pillara limestone represents back-reef, shallow shelf lagoon deposits. The Pillara is exposed in places along the north side of the Range, exhibits gentle dips but is highly eroded with only remnants of the original outcrop remaining today. The Windjana formation represents the main reef facies (Playford, 1980). The unit has widely spaced joints and reduced porosity due to precontemporaneous cementation. The Windjana is mostly exposed along

the southern bounding slopes of the Range although limited outcrops are found elsewhere, where the other reef units have been heavily eroded. The Napier formation, or fore-reef unit, is widely distributed, has a silty/sandy matrix and is characterised by dips of up to 35°.

The morphology of the bounding slopes of the Range and their classification has been discussed previously (Allison and Goudie, 1990b) and consequently detailed consideration is not necessary here. The main characteristics of each of the identified slope profile types are as follows.

Type A slopes: one distinct free face unit with mean angles of 60° to 70°, a low angle pediment fronting the rock outcrop and an immediate break of slope at the top of the cliff.

Type Ai: essentially a sub-set of type A, grouped separately due to large talus blocks at the base of the cliff.

Type B: steep slopes with mean angles between 25° and 40°. A rock step, usually 8 to 10 m high, fronts the Range and the mean angle of the main part of the slope is similar to the angle of dip of bedding.

Type C: compound slopes including two talus and free face units, one at the front and the second at the rear of the Range, separated by a flat inter-range area.

Type D: a simple two component talus and free face profile, which terminates abruptly at the top of the cliff section.

Type E: broken rock outcrops separated by flat benches rising gradually from a low-angle pediment to a reasonably level summit area. The bench components have mean angles of 2° to 10° and the free face sections average 25° to 35°.

Type F: concavo-convex profiles but with a succession of low relief rock steps and benches.

Type Fi: smooth concavo-convex slope profiles, rising from a low-angle rock cut pediment, through gradually increasing gradients to a mid-profile steep section. Low slope angles
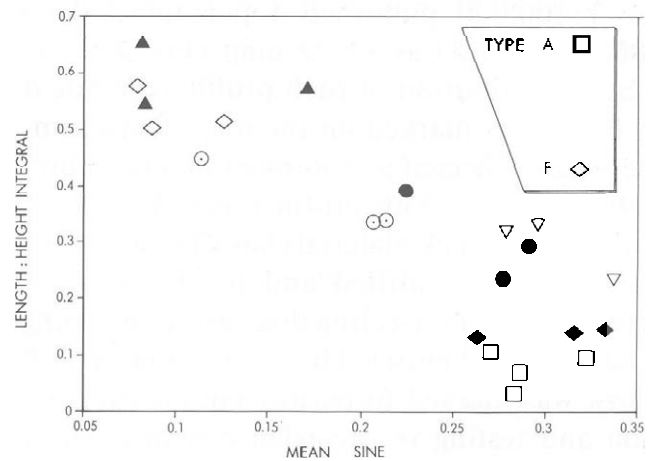

Fig. 2. Height–length integral results for slope profiles along the Napier Range.

characterise the crest of the profile, which flattens out to a summit area.

Characteristic profiles surveyed for each of the different forms are presented in Fig. 2. The lower limit of each profile was taken as that point at which the angle of the ground surface first exceeds 10° as the Range is approached. The crest of each slope profile was identified as the highest point across the Range.

The variations in morphology of the slope profiles can be quantified using a height–length integral (Kennedy, 1967, 1969; Chorley and Kennedy, 1971; Allison and Goudie, 1990a). The integral is the area under the slope profile divided by the product of the slope height and slope length. It varies between zero and one. A perfectly straight slope would have a value of 0.5, a predominantly convex one above 0.5 and a predominantly concave slope one of below 0.5. The results (Fig. 2) show that the profiles range from highly concave forms on the one hand (type A and type Ai), through a transitional group (types B, C, D and E) which, despite being concave, have a generally smoother form. At the other end of the spectrum are concavo-convex and slightly convex forms (type F and type Fi).

Methods

A geomorphological map was constructed for all accessible parts of the Napier Range using

the 1:100,000 published topographic sheet 2863 (Lennard) as a base map (Fig. 4). The spatial distribution of each profile type noted in Fig. 3 was marked on the map. Rock samples were collected at a number of sites representative of the slope profile types. At each location in situ rock material characteristic of the outcrop was identified and blocks were removed along intersecting discontinuities using a hammer and chisel. The orientation of each block was marked to permit sample preparation and testing in accordance with its field disposition.

Data were collected on material compressive strength, stress–strain characteristics, elastic properties and discontinuity orientations. Such rock properties have considerable engineering value (see Johnson and De Graff,

1988 for example) and are relevant to geomorphology. The compressive strength of a material can be a good pointer to its susceptibility to weathering, for example, while elasticity is an indicator of the response of intact material to the stresses within a rock mass. Fractures act as lines which promote preferential weathering and release surfaces for the generation of rock falls and they frequently control the precise nature of rock block detachment.

Six 38 mm diameter core samples were prepared from material collected at each location to determine the material compressive strength and stress–strain characteristics. The ends of each sample were ground to a tolerance of ±0.5 mm. Tests were conducted using a triaxial Hoek Cell following standard procedure (Brown, 1981). Specimens placed in the Cell
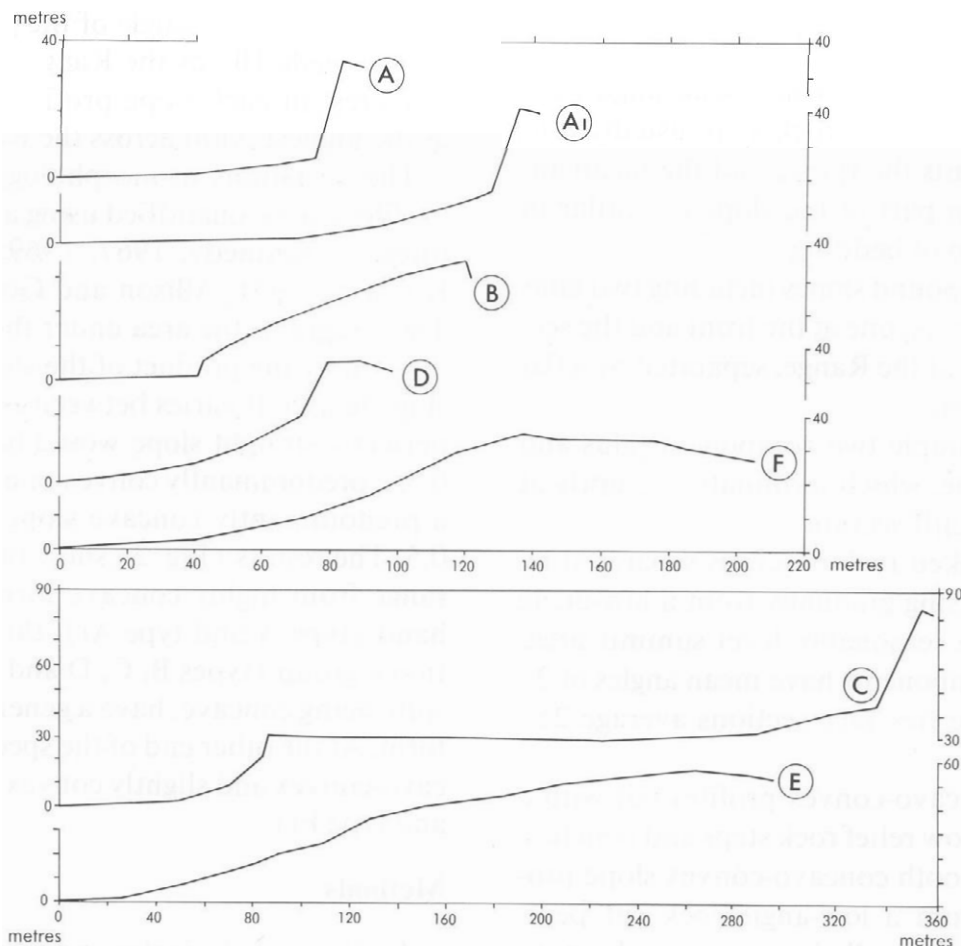

Fig. 3. Surveyed slope profiles along the Napier Range highlighting variations in morphology between the different forms.

were protected from the hydraulic fluid used to apply the confining pressure by a rubber membrane. Tests were conducted at confining pressures ($\sigma3$) of 15, 20, 30, 40, 50 and 60 MPa. Results were recorded at ten second intervals using an electronic laboratory data logger. Data are presented in two forms. Stress–strain curves are used to illustrate the deformational characteristics of the rock below yield, including the differences between elastic and non-elastic material. Values of stress at failure are drawn as Mohr's circles. Failure envelopes fitted to the Mohr's circles can be used to elucidate the yield characteristics of the material under different deviatoric stresses.

A second set of samples were prepared to examine the elastic properties of the materials using ultrasonic apparatus (Allison, 1988, 1990). It has been recognised for some time in geomechanical studies that rock performance is affected by both the strength and the elastic deformability of the rock mass (Pinnaduwa and Kulatilake, 1985). The test pieces were machined to bar shapes with a length:thickness ratio of greater than three to maximise the accuracy of results. Final preparation involved machine grinding to ensure that each sample had parallel sides and square edges. Before testing, each specimen was cleaned and dried to constant weight. For each ultrasonic test ten readings were taken using the apparatus and the mean value was used in the calculation of dynamic Young's Modulus.

Rock joint discontinuity data were collected using scan-line surveys. At each site 30 m tapes were placed parallel to and at 90° to bedding. All fractures cross-cutting the tape were logged. The survey concentrated on persistent discontinuities, since these have the most significant influence on rock mass resistance and strength (Einstein et al., 1983). A total of 150 discontinuities were logged at each site. Type A and type Ai locations were an exception to this rule. At these locations the absence of discontinuities made it impossible to collect a large data set. The lack of joints is, however, of signifi-

cance and will be considered later. At all other sites, care was taken to collect an adequately large number of readings to increase statistical precision, following previously proposed guidelines (Priest and Hudson, 1981; Hudson and Priest, 1983; Kulatilake and Wu, 1984; Matheson, 1988). The data are presented diagrammatically using hemispherical projections. The technique is explained in detail by Phillips (1979) and Priest (1985). Each set of results iscontoured on equal area, polar stereonets, marked at 2° intervals, with data representation on the lower hemisphere. Poles have been plotted using the guidelines reported by Hoek and Bray (1981) and contoured using the method outlined by Priest (1985).

Results

The distribution of the different slope types along the Napier Range is presented in Fig. 4. Specific cliff types are characteristic of particular lithological units, although the precise location and orientation of the outcrop relative to the direction of the bounding slopes of the Range are also important in determining slope type. Type A and type Ai cliffs are always found in the Windjana limestone. The rear profile free face unit of type C slopes is also a product of the Windjana. The geomorphological map shows that type C profiles occur where the Windjana limestone and one of the other two rock units are adjacent in outcrop. In other words, a complex situation exists. Associations between the rock mass geotechnical properties and slope form can only be effectively studied at type C locations if the profiles are sub-divided into two components due to the juxtaposed reef facies. Steep, high, free face dominated profiles are thus associated with the Windjana fore-reef unit of the Napier Range complex.

Type B, D and E slopes and the lower free face unit of type C slopes occur where the Napier formation is exposed along the edge of the
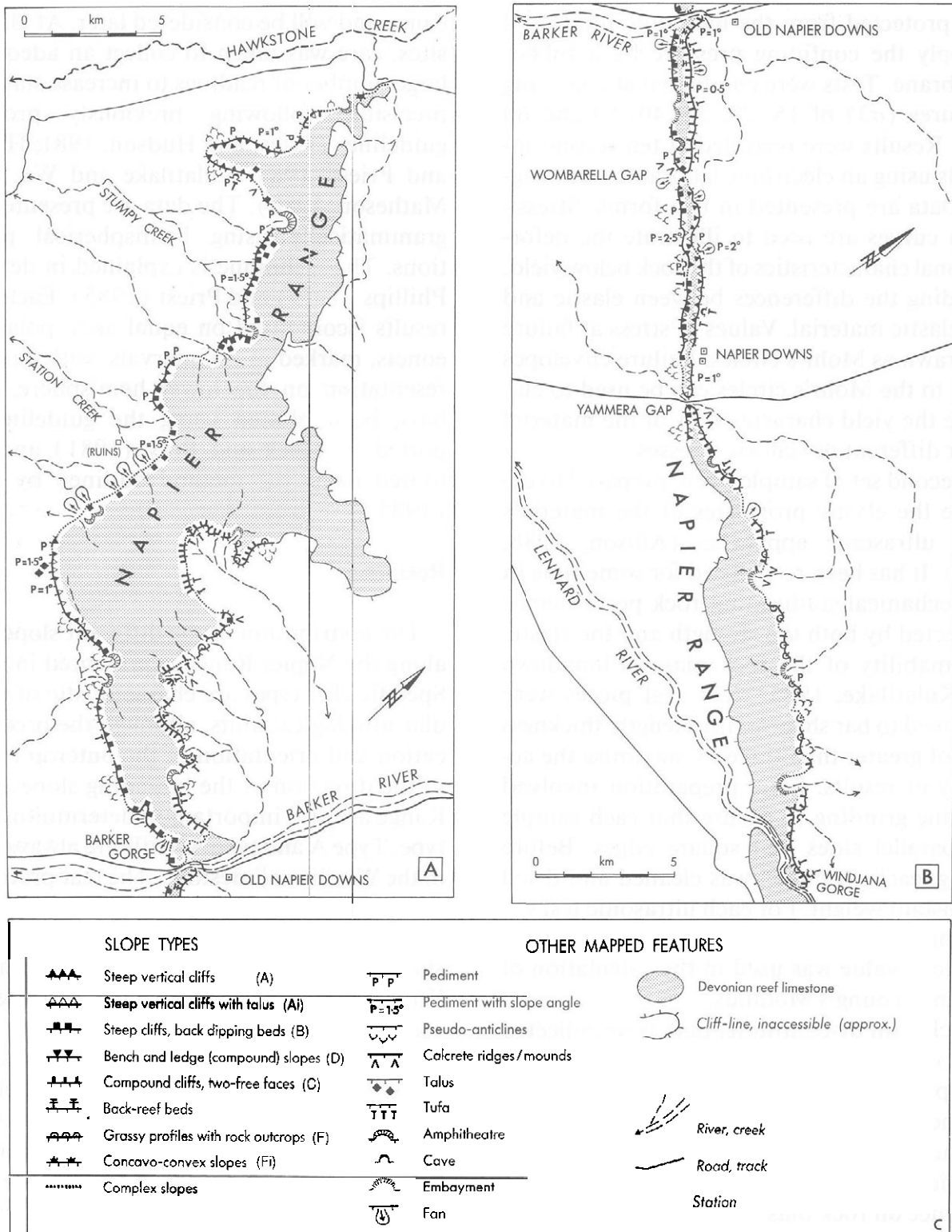
Fig. 4. Distribution of slope profile types along the Napier Range and the location of material sample points.

Range. There is a noticeable spatial pattern to the distribution of each profile. Type B slopes only occur along the south side of the Napier

Range. Type D slopes are found predominantly along the north flank but with two small areas in the far northwest corner of the Range

near Barnet Spring. Type E slopes are present only on north facing slopes and are all concentrated within a few kilometres between Barker Creek and Wombarella Gap. The smooth concavo-convex type F and type Fi profiles always appear on the geomorphological map where the back-reef Pillara limestone crops out. Consequently the distribution of F and Fi profiles is limited to the eastern end of the north-facing bounding slopes of the Range between Barralumna Spring and Windjana Gorge.

The associations between slope form and the different rock units provide the framework for examining the geotechnical data and their associations with slopeform, profile distributions and mechanisms of change. Three sets of results must be considered: yield strength and stress–strain characteristics, material elastic properties and the discontinuities present within the rock mass.

Mohr's circles of stress are presented in Fig. 5. The results are drawn up in three groups, based on the different limestone units composing the Range. For type A, Ai and the rear part of C profiles (Windjana limestone), yield strengths at 30 MPa confining pressure range from 335 to 262 MN m^{-2} (Fig. 5, top). The Windjana limestone at one of the type C locations displays the highest yield strength (Table 1), being the only location where failure exceeds 400 MN m^{-2} at 60 MPa confining pressure. At type B, D and E locations (Napier limestone) yield strengths are generally lower at 30 MPa confining pressure than they are for the type A, Ai and C test results (Fig. 5, middle). This is most noticeable at type D sites, where both the yield strengths are below 250 MN m^{-2}. The trend is not so clear at high confining pressures. Indeed at 60 MPa many of the yield strength values are similar and there are few distinctions between specific profile types (Table 1). For type F and Fi slopes (Pillara limestone), yield strengths are 235 and 206 MN m^{-2}, respectively at 30 MPa confining pressure, rising to 300 and 358 MN m^{-2} at 60 MPa (Fig. 5, bottom). The 30 MPa compres-

sive strength values are among the lowest in the data set.

Although broad variations can be identified from the yield strength data, particularly at low confining pressures, there is no definitive overall trend to the results. The stress–strain curves for the individual tests at 30 MPa confining pressure (Fig. 6) provide some further explanation. Stress–strain plots for material taken from type A, Ai and C slope profiles are indicative of a stiffer type of rock. For an applied axial stress ($\sigma 1$) below the yield point, the samples undergo relatively little strain before shear occurs in triaxial compression when compared with the other limestones. This is confirmed by the steep gradient of the A, Ai and C stress–strain curves in Fig. 6. The plots indicate that failure is followed by infinite strain for no further increase in applied stress. In other words, before the yield point is reached, there is relatively little deformation of the rock. Failure of the Windjana limestone is thus characterised by sudden fracture, identified on the stress–strain curves as a sudden change in gradient towards the top of the plotted line.

The stress–strain curves for samples taken from type F and type Fi locations exhibit a different type of failure. At stresses below the yield point, the material undergoes a more gradual deformation as a response to increasing stress. In other words, the material deforms and compacts with individual grains distorting and grains within the mineral matrix moving relative to each other prior to failure. At low stresses under a confining pressure of 30 MPa the rate of strain prior to yield gives an almost constant stress : strain ratio for much of the test. At high stresses, however, the strain rate of the sample increases significantly, illustrated by the convex nature of the upper part of the stress–strain curve. At the yield point there is a sudden reduction in the rate of axial stress rise due to sample deformation along the newly developed shear plane. Eventually a condition of infinite strain is reached for no further increase

TABLE 1

The limestone units of the Napier Range and a summary of their principal geotechnical properties

| Sample Site	Chedda Cliffs	Napier Downs	Wombarella Gap	Stumpy Creek	West Wombarella Gap	West Wombarella Gap	Barker Creek	Telecom Tower	East Napier Downs	Old Napier Downs Cave	Barralumna Spring	West Barralumna Spring
Slope Profile Type	A	Ai	B	B	C	C	D	D	E	E	F	F
Grid Reference	716957	915841	878866	715983	876871	877871	837906	839909	838906	851896	026788	026786
Yield Stress at Failure (MNm^{-2}) (30 MPa Confining Pressure)	261.5	280.4	252.9	235.6	335.2	273.9	179.3	243.8	266.4	288.4	206.3	234.7
Yield Stress at Failure (MNm^{-2}) (60 MPa Confining Pressure)	301.02	332.68	331.30	304.37	441.80	381.83	271.33	337.00	344.18	386.50	358.44	299.97
Modulus of Elasticity ($kNmm^{-2}$)	63.23	72.82	48.09	47.32	77.16	43.04	26.61	59.33	62.87	74.29	30.18	45.63
Lithological Unit	W	W	N	N	N & W	N & W	N	N	N	N	P	P
Angle of Dip of Bedding	NOT CLEAR	NOT CLEAR	29°	30°	21°	29°	24°	22°	14°	22°	06°	08°
Transect Division across Range	046°	214°	026°	110°	224°	211°	284°	281°	253°	228°	239°	231°
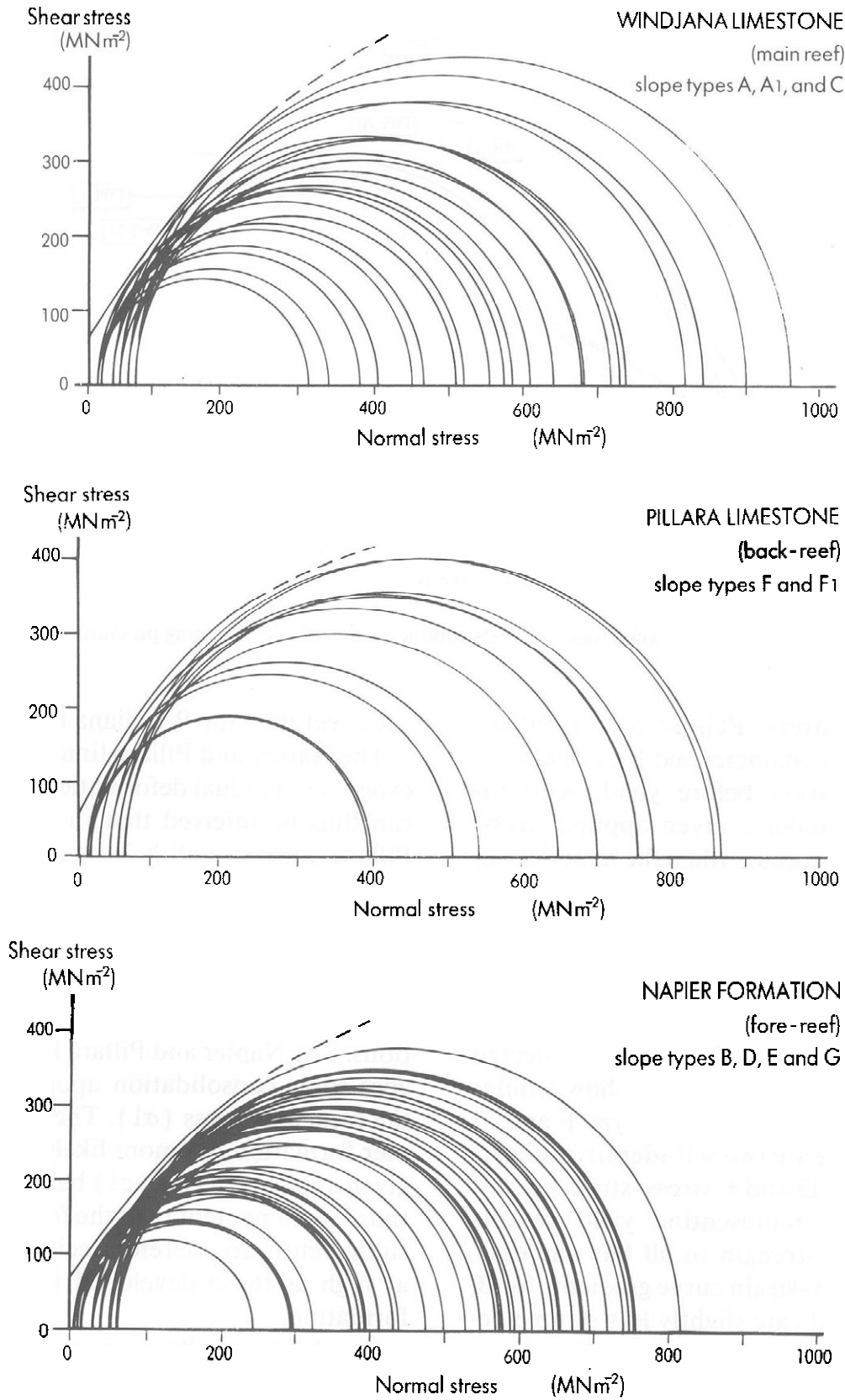
Fig. 5. Mohr's circles of stress for the slope profile types recorded along the Napier Range
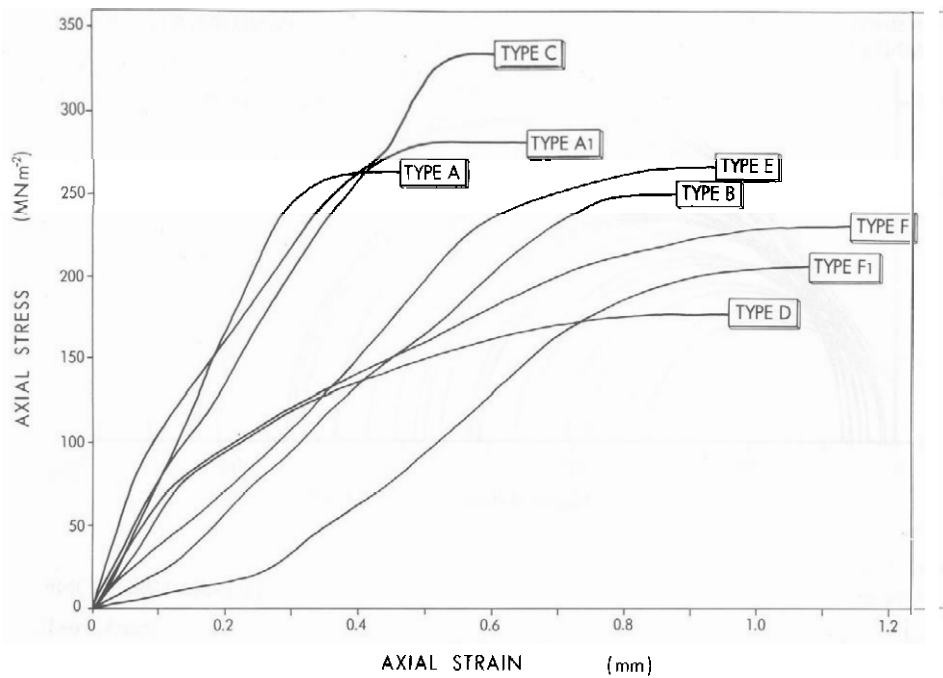
Fig. 6. Stress–strain curves for the triaxial Hoek Cell tests conducted at 30 MPa confining pressure.

in the applied stress. Failure of the Pillara limestone is thus characterised by a degree of gradual deformation before yield, with increasing strain under a given applied stress. Failure ultimately occurs when the material can no longer withstand stress levels by slow deformation within the sample. It is interesting that the behaviour noted here is found in the limestone unit which contains a high silt and sand content.

The stress–strain plots for material collected from type B, D and E locations show similar characteristics to the curves for type F and Fi samples but there are two self-identifying characteristics for B, D and E stress–strain curves. First, the peak representing yield reflects greater material strength in all but one case. Second, the stress–strain curve gradients for B, D and E sites indicate slightly less sample deformation before yield than for type F and type Fi materials. The differences were confirmed following tests by examining variations in sample axial shortening and the barrelling of test specimens. In other words, the Napier formation bears greater similarity to the Pillara back-reef than the Windjana fore-reef facies.

The Napier and Pillara limestone units both experience gradual deformation before yield. It can thus be inferred that in situ Napier and Pillara material will be more likely to distort without actually failing. Stiffer material, the Windjana limestone in this case, does not exhibit deformation before fracture to such a great degree and will therefore probably be more likely to form stable cliffs of high elevations. The Napier and Pillara limestone undergoes some consolidation upon application of the principal stress ($\sigma 1$). The Pillara and Napier formation are more likely to deform for given applied stresses ($\sigma 1$) below yield and are thus less competent than the fore-reef unit. Resulting cliffs are therefore neither as steep nor as high as those developed in the Windjana formation.

Results from ultrasonic tests to determine dynamic Young's Modulus (Table 1) can be used to confirm inferences about the elastic properties of the materials obtained from triaxial testing. Similar comparisons have been made in other studies (see Haberfield and

Johnston, 1988 for example). The brittle character of the Windjana limestone is reflected in high modulus values, between 63.23 and 77.16 kN mm^{-2} in three out of four cases. It is probable that the low value of 43.04 kN mm^{-2} for one of the type C slopes is due to undetected microscopic sample imperfections. The elastic properties of the Napier formation type B, D and E slopes are somewhat different when compared with the Windjana limestone. The dynamic Young's Modulus values are lower for B (48.09 and 47.32 kN mm^{-2}) and D (26.61 and 59.33 kN mm^{-2}) sites. The type E results do not fit this trend, however, reflecting the higher yield strengths reported previously. The most significant anomaly is recorded for type F sites, developed in the Pillara beds. The type Fi result, as might be expected from other data and the morphological characteristics of the slope profile, has the lowest recorded dynamic Young's Modulus value at 30.18 kN mm^{-2} but the type F result is the highest of the data set at 95.63 kN mm^{-2}.

At first the type E and type F results appear to be unusually high but a hypothesis can be proposed to explain the values. Both type E and type F slope profiles comprise bench and rock step units. Samples for testing in this study were removed from the step components of the profile which are likely to be the strongest and most resistant of the two types of unit. Similar problems were experienced by Gunsallus and Kulhawy (1984), who examined variations in strength as a function of lithological differences within one rock formation. Although their study concentrated on sandstone rather than limestone, the results indicated that it is important to select sample points carefully at the site under examination to eliminate local controls.

The geotechnical results for intact rock go some considerable way towards elucidating associations between form and material properties. However, some of the results make it clear that it is insufficient to consider intact material properties in isolation. The key to under-

standing some of the anomalies discussed above may well lie in the fracture pattern of the rock mass and, in particular, how joint orientation changes between the different limestone facies. The importance of collecting fracture data is confirmed by Beavis (1985), who regards such information as essential to the geomechanical study of rock masses. The data can be easily evaluated and, if necessary, incorporated or extended into more detailed stability analysis.

The trend of bedding is outlined in Table 1 and general details of the fracture pattern are recorded in Table 2. Key results for each of the cliff types are presented as stereographic projections (Fig. 7). At the majority of sites bedding dips to the south at angles of 18° to 34°. There are three exceptions here. First, for type F slopes bedding is much more gentle, dipping at mean angles between 6° and 8°. Second, for type A and type Ai sites, bedding surfaces are not easily identified. It is not possible to confirm any one specific fracture set as the bedding surfaces. Third, for the type D slope profiles, bedding appears to swing towards the west and although a southerly fracture set is present within the rock mass, its associated dip angles are very steep and uncharacteristic of bedding planes.

There are six other separately identifiable fracture sets which, for the purpose of clarity, will be termed sets I to VI (see Table 2). There is some evidence of overlap between the six groups but in general either the dip or the dip direction can be used to identify each specific set. Set I comprises joints which strike approximately north to south at steep angles of dip; all plunge to the east. Set II includes joints striking approximately east to west and dipping to the north, again at steep mean angles. Discontinuity sets I and II are found at all locations along the Range. Sets III, IV and V are more sporadic in their distribution. Set III dips to the northeast at angles between 57° and 77° but is not present at any of the A, Ai or C locations. Set IV dips southeast at angles be-

TABLE 2

Characteristics of the discontinuity pattern logged in the cliff sections

JOINTS

DISCONTINUITY	SETS	A_1	A_2	A_3	Ai_1	Ai_2	Ai_3	B_1	B_2	B_3	C_1	C_2	C_3	D_1	D_2	D_3	E_1	E_2	E_3	F_1	F_2	F_3
I	Dip ∠ E	78°	67°	81°		75°	84°	81°	66°	72°	78°	68°	62	71°	67°	77°	42°	76°	78°	79°	78°	79°
	Strike	177°	020°	016°		025°	029°	035°	028°	012°	018°	165°	016°	026°	017°	020°	010°	011°	029°	016°	011°	019°
II	Dip ∠ N	83°	61°	60°		73°	78°	61°	79°	59°	70°	60°	62°	71°	80°	72°	58°	56°	67°	73°	74°	70°
	Strike	127°	121°	110°		124°	124°	100°	096°	123°	110°	107°	115°	103°	069°	095°	111°	105°	119°	098°	110°	104°
III	Dip ∠ NE								66°	57°				68°	77°	68°	77°	64°		65°	76°	74°
	Strike								157°	136°				159°	145°	146°	148°	135°		128°	135°	137°
IV	Dip ∠ SE			77°					66°	72°		70°				79°	77°	77°		77°	77°	77°
	Strike			145°					047°	049°		038°				055°	053°	052°		038°	041°	037
V	Dip ∠ NW										71°					79°		68°	76°	76°	77°	77°
	Strike										049°					060°		058°	050°	044°	036°	041°
VI	Dip ∠ W	81°	82°	70°		76°	73°	80°	30°B	72°	76°	69°	72°	24°B	22°B	80°		73°		80°		
	Strike	026°	010°	016°		040°	029°	018°	031°	011°	021°	040°	028°	015°	019°	164°		024°		017°		
VII	Dip ∠ S	63°	27°	65°		23°	18°B	29°B	77°	34°B	21°B	29°B	26°B	79°	75°	19°B	14°B	22°B	20°B	06°B	08°B	08°B
	Strike	143°	150°	121°		120°	102°	111°	069°	117°	095°	107°	132°	080°	070°	134°	158°	110°	127°	090°	096°	093°

NO CLEAR DISCONTINUITIES (column Ai_1)
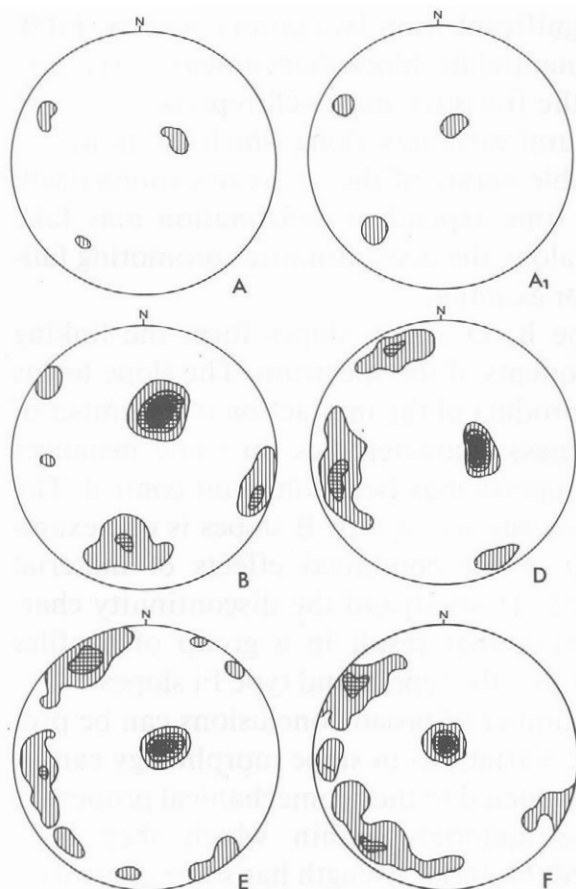
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Fig. 7. Contoured polar equal area stereonets of discontinuity patterns for each type of slope profile taken from representative sites along the Napier Range.

tween 66° and 77° and is generally absent from type A, Ai, C and D locations. The most infrequent joint set, group V, is only common at type E and type F locations, dipping to the northwest at angles between 68° and 79°. Finally, discontinuity set VI strikes north to south and dips to the west, usually at steep angles.

By plotting and contouring the results on stereonets a detailed consideration of the fracture pattern is possible. Type A and type Ai (Fig. 7) slopes lack any regular discontinuity pattern and those fractures which are found have nomarked frequency. Both points are confirmed by the low density contours. It is impossible to identify bedding using the stereonets and the low joint density results in massive blocks of rock. A regular or characteristic failure mechanism due to intersecting frac-

tures is absent at type A and type Ai sites. Bedding at type B sites (Fig. 7) dips to the south at angles around 30°. The high density, tightly packed contours on the stereonet indicate a uniform pattern to bedding. In addition there are noticeable north, northwest and southeast joint sets. All dip at steep angles. The southeast and northwest joint sets contour very close to the edge of the stereonet and as such they may well represent the same discontinuity set swinging across the vertical plane. It is significant that the angle of dip of bedding of type B slopes is the same as the mean slope angle for the main part of the profile and that B profiles are only found along the southern margin of the Range. The relative orientation of the dominant discontinuities precludes any key fracture control failure mechanism along two or more intersection joint sets at type B sites.

Due to the compound nature of type C slope profiles it is impossible to draw firm conclusions from the fracture pattern for the overall slope profile as can be done for other locations. Consequently a stereonet has not been drawn for the type C slope profile data. Some interesting trends can be identified for the type D, type E and type F (Fig. 7) slope profiles. The angle of dip of bedding becomes gradually flatter, changing from a mean of 23° (D) to 18° (E) and 7° (F). The angle of dip is to the north for type B slopes but swings to the west at type D sites and back towards the north at type E and type F locations. In the latter instance bedding is almost horizontal, confirmed by the proximity of the contours to the edge of the stereonet. All the joint sets are generally steeply dipping and as a consequence the representative contours on the stereonets plot close to the edge of each net, confirming the mean data recorded in Table 2. The flat lying bedding planes, in association with the steeply dipping fractures at D, E and F locations, raise the possibility of wedge failures occurring from exposures where free faces are oriented in the correct direction and there is sufficient outcrop for detachment to occur.

The potential for joint-controlled failure thus changes along the outcrop depending on the frequency, orientation, angle of dip, consistency of dip direction and dominance of each of the fracture sets. There are implications for the slope profile types, their distribution and the nature and mechanisms of cliff change along the Napier Range. Nevertheless, it seems likely that the best explanation is likely to come from a synthesis of all the geotechnical data presented as part of this study.

Conclusions

It is the combination of all the results presented in this study, rather than any individual data set, that provides the most comprehensive explanation of morphological variations in slope profiles. The slope forms can be considered in terms of a continuum of profile types from A on the one hand to Fi on the other.

Type A, highly concave slopes, with steep, almost vertical cliffs, have developed in limestone which is a stiffer type of material. The rock exhibits little deformation below yield and has a high modulus of elasticity. In parallel with this, type A slopes have few fractures and those which are present do not follow a regular pattern. In addition it is almost impossible to identify bedding. The type Ai and rear cliff face section of type C slopes have very similar characteristics to the type A sites but the presence of large talus blocks at the foot of some of the profiles is probably due to an increase in the predominance of joints within the free face slope components.

At the other end of the slope profile continuum are the type F and type Fi slopes, formed in the Pillara limestone. The compressive strength of the material is below that of the Windjana formation. The Pillara also displays a greater ability to strain below yield and has a relatively low modulus of elasticity. The discontinuity pattern is more pronounced in the Pillara limestone than in the Windjana and bedding is well developed. The discontinuities

are significant from two points of view. First, the potential for block detachment exists. Second, the fractures may well represent lines of structural weakness along which the more deformable nature of the rock can express itself. Slow, time-dependent deformation may take place along the discontinuities promoting failure, for example.

Type B, D and E slopes form the linking components of the spectrum. The slope forms are a product of the interaction of a number of rock mass characteristics. In some instances one property may be a dominant control. The bedding surface of type B slopes is one example. It is the combined effects of material strength, elasticityand the discontinuity characteristics that result in a group of profiles which link the type A and type Fi slopes.

A number of broad conclusions can be proposed. Variations in slope morphology can be clearly related to the geomechanical properties of the materials within which they have formed. Material strength has some control on profile steepness and form but not merely in terms of yield strength values. The behaviour of the rock below yield stress values and the elasticity of the rock are important. The presence and persistence of discontinuities have a direct effect on the nature of the slopes in terms of controlling failure mechanisms, the size of detached blocks and the potential for detachment.

Clearly the form and distribution of different slope profile types along the Napier Range is closely related to variations in key material properties but it is only when all the material properties are considered together that a clear understanding of the relationships between form, process and geotechnics emerges.

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