[論文]
オークランド南部の第三紀堆積岩がつくる地形と岩石物性

沖縄地理　第5号
147-170頁（2000）

Bull. Okinawa Geogr. Soc.
No. 5, p. 147-170 (2000)

Rock Controls on Hillslopes Made of the Oligocene Te Kuiti Group in South Auckland, New Zealand

Akira MAEKADO*

Introduction

Angles of hillslopes are strongly controlled by properties of slope-forming materials and agencies acting on the hillslopes. This suggests that investigation on properties of slope-forming materials and agencies acting on the hillslopes are requaired for studying angles of hillslope. From this view point, some workers have studied angles of hillslopes (*e.g.*, Lohnes and Handy, 1968; Carson, 1969, 1971, 1975; Carson and Petley, 1970; Rouse, 1975; Selby, 1980, 1982a; Pearce *et al.*, 1981; Matsukura *et al.*, 1984; Mizuno, 1984; Maekado, 1986). These studies pointed out a close relationship between slope angles and properties of slope materials.

Sometimes, joints develop within rocks. These joints controll rock slope stability, therefore, the joints controll erosional processes on rock slopes and slope angle (Selby, 1982b; Selby *et al.*, 1988; Maekado and Nelson, 1997). Slope angles have to be investigated from joints, properties of slope-forming materials and agencies acting on the slopes. Few studies on this point have been performed.

This study examines angles of valley-side slope and attempt to explain from rock properties and erosional processes.

Study Area

The study area is located at the south of Auckland, New Zealand (Fig. 1). Calcareous sandstones, limestones and siltstones of the Tertiary Te Kuiti Group are widely exposed in the study area. The rocks are almost horizontal in the bedding and form hills which have been dissected by many deep valleys. Deep valleys with a relative height of 100 m deep have been developed in the area. The siltstones are named Whaingaroa Siltstone and Te Akatea Siltstone, limestones named Waimai Limestone, Orahiri Limestone and Otorohanga Limestone, sandstone named Glen Massey Sandstone, Aotea Sandstone and Waitomo Sandstone in the order from the lower to the upper (Fig. 2).

Annual normal rainfall (1921-1950) near Port Waikato is 1400 mm, and mean annual temperature in the Waikato basin is 13-14 ℃ (Lisle, 1967). Lowest temperature during 1947 to 1960 at Maramarua near Port Waikato is -5℃ at August.

Angles of valley-side slope

Methods

In order to clarify the relationship be-

*Department of Geography, University of the Ryukyus, Nishihara, Okinawa 903-0213, Japan.

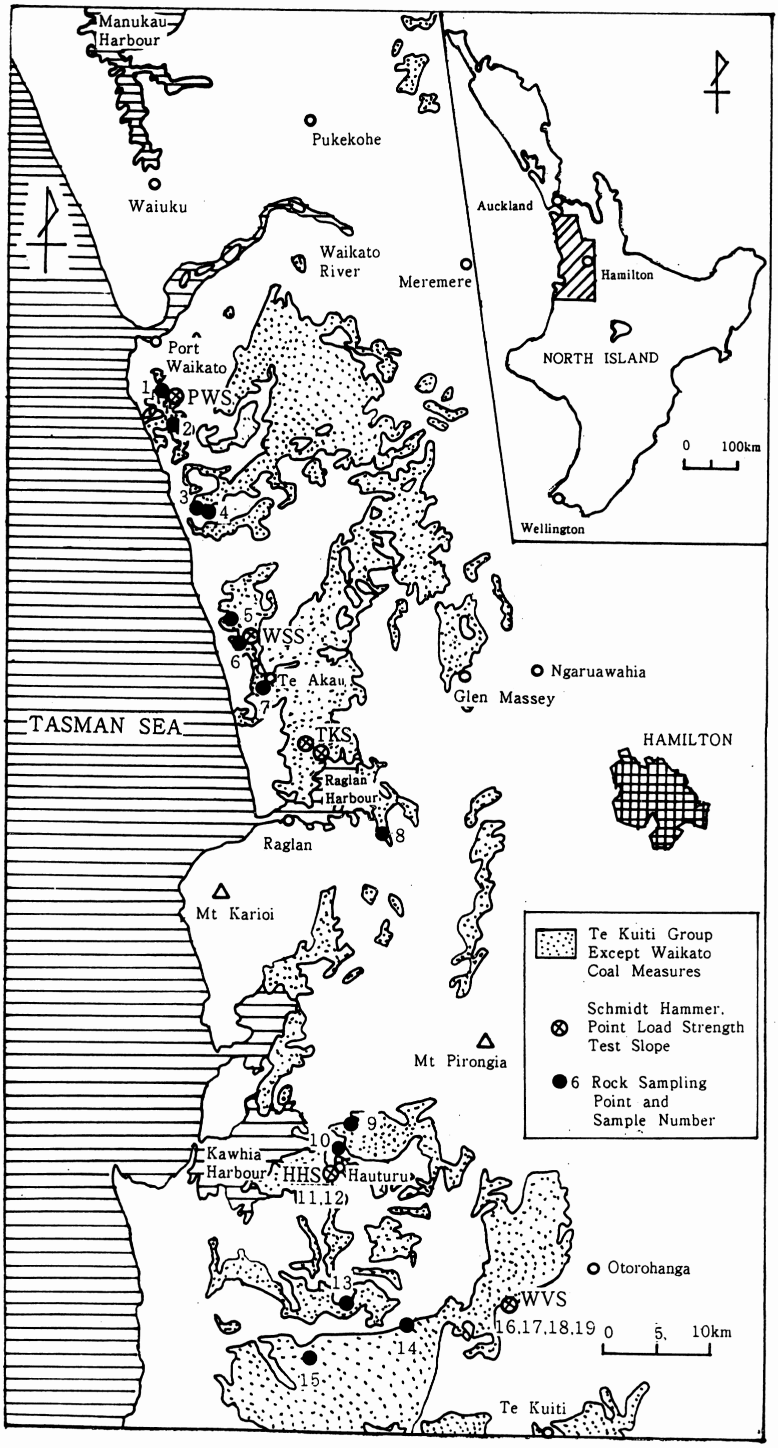

Fig. 1. Location of the study slopes and the distribution of Oligocene Te Kuiti Group.

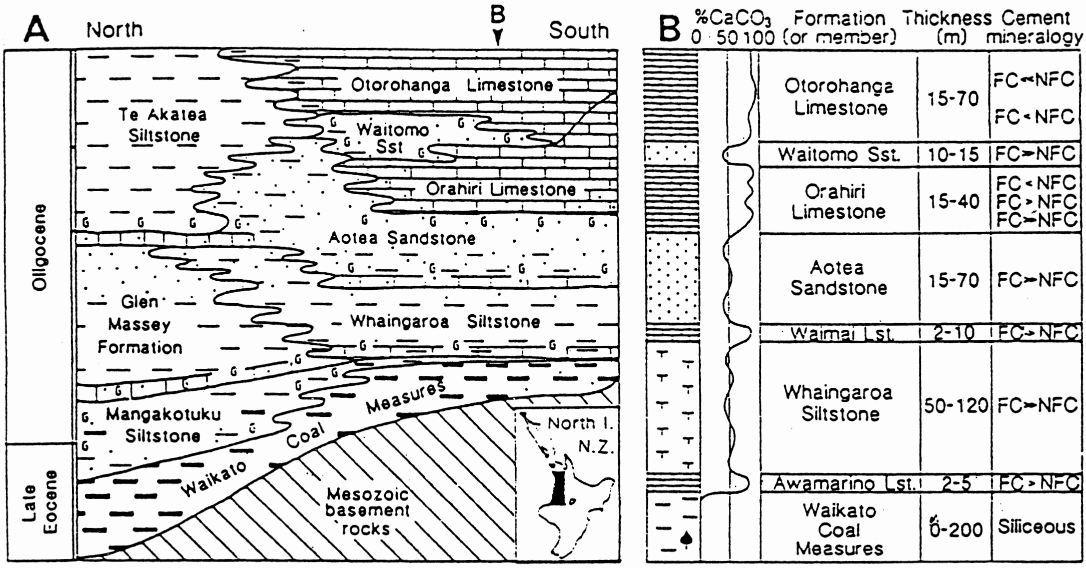

Fig. 2. Schematic north-south section through the Te Kuiti Group in the South Auckland region of North Island, New Zealand. Stratigraphic details are recorded by Kear and Schofield (1959) (after Nelson *et al.*, 1988).

tween the slope angles and the kind of slope-forming rocks, slope profiles were measured in five valley-side slopes located at Port Waikato, Waimai Valley, Raglan Harbour, Hauturu and Waitomo Valley (Fig. 1). The measurements were carried out using a transit or a clinometer and a measuring tape. In Waimai Valley and Kotuku, measuring lines of upper part of slopes are shifted to the lines where relationship between slope angle and slope-forming rock is clear.

Slope angles and slope-forming rocks

Fig. 3a-3e shows the results. The slope profiles indicate an approximately straight slope. The angles of valley-side slope range from 7° to 90°. Slopes less than 50° are covered by grass or trees, however, steep slopes over than 60° are unvegetated.

The study slopes are composed of several Oligocene horizontal rocks. At Port Waikato (Fig. 3a, Photo 1), the upper part of the slope is composed of the siltstone with a thickness of about 30 m, which is Te Akatea Siltstone. The siltstone forms slope with an angle of 39° and 48°. Waimai Limestone with a thickness of 4 m is intercalated between Te Akatea Siltstone and Glen Massey Sandstone. The limestone forms bluff with an angle of 76°. The lower part of the slope is occupied by Glen Massey Sandstone with a thickness of about 40 m. The sandstone forms gentle slope with an angle of 20° to 28° and bluff with an angle of 82°. Notch develops at the limestone and sandstone bluff base. Limestone and sandstone blocks are found at the foot of the limestone and sandstone bluff.

In Waimai Valley (Fig. 3b), upper part of the slope is composed of Te Akatea Siltstone with a thickness of 30 m, which is covered with volcanic ash. The siltstone forms gentle slope with an angle of 10° to 20°. Raglan Limestone with a thickness of 6 m is intercalated between Te Akatea Siltstone and Aotea Sandstone. The limestone forms bluff with an angle of 76°.

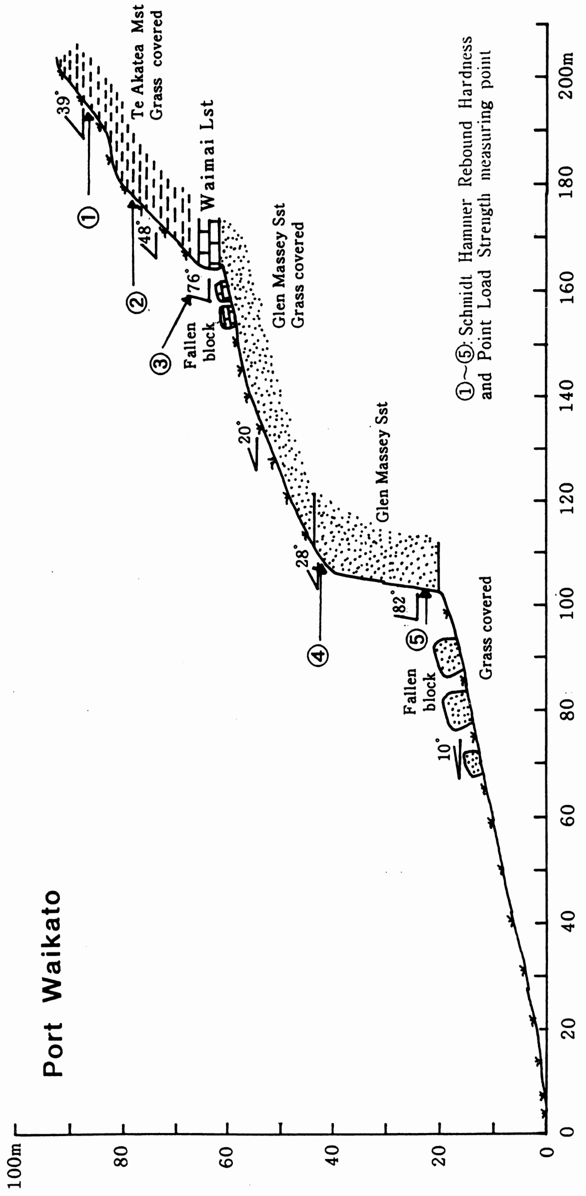

Fig. 3a. Topographic and geologic section of Port Waikato Slope.

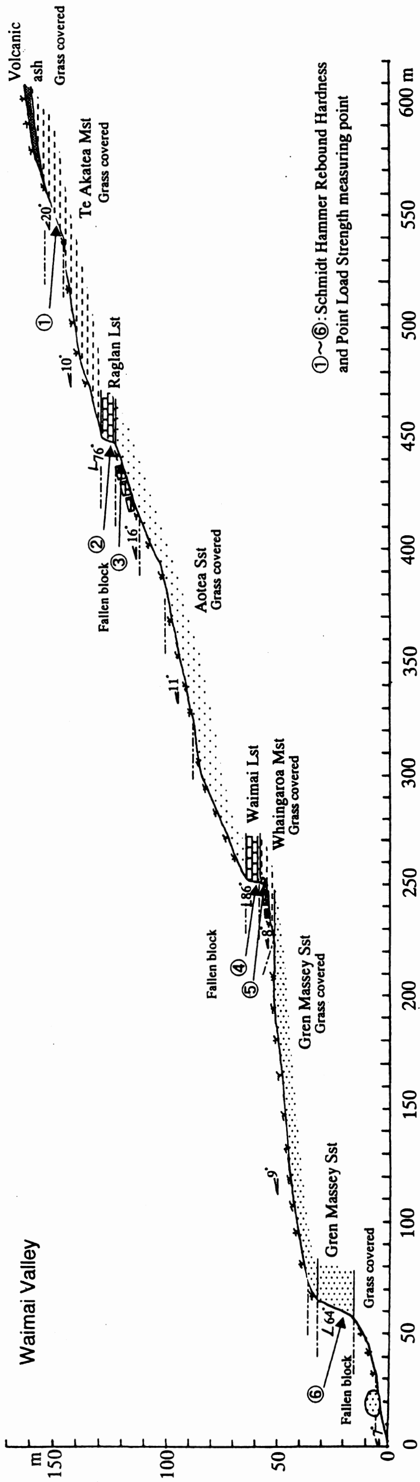

Fig. 3b. Topographic and geologic section of Waimai Stream Valley Slope.

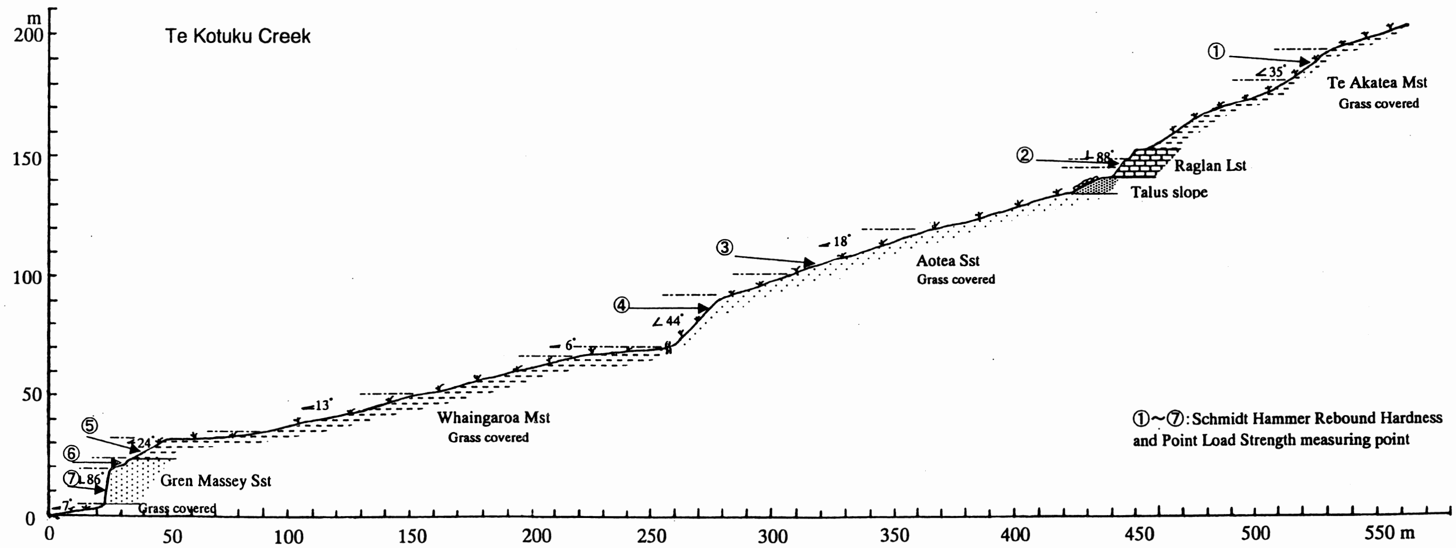

Fig. 3c. Topographic and geologic section of Te Kotuku Creek Slope.

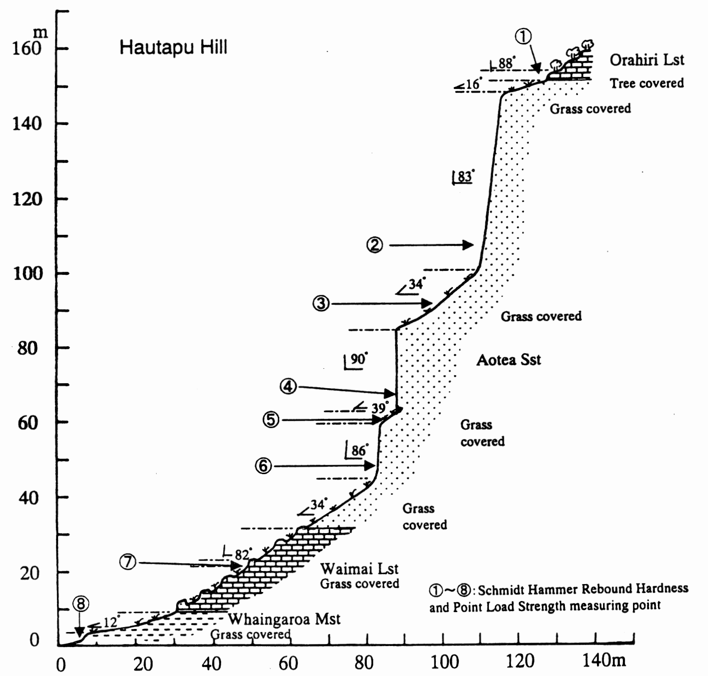

Fig. 3d. Topographic and geologic section of Hautapu Hill Slope.

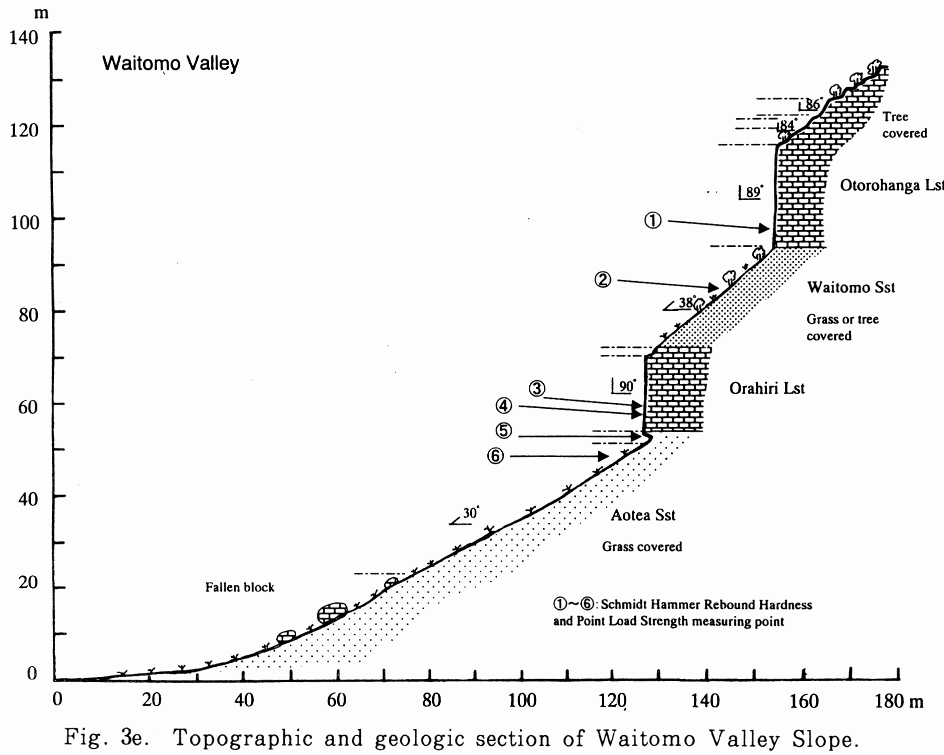

Fig. 3e. Topographic and geologic section of Waitomo Valley Slope.

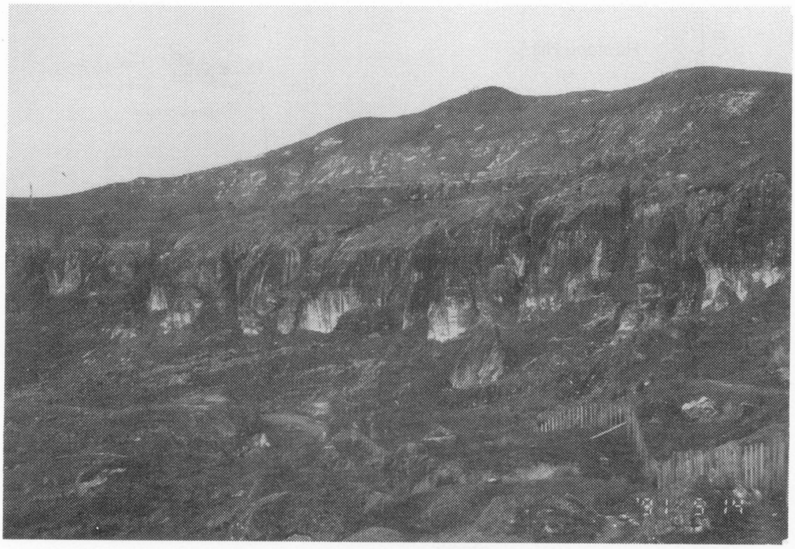

Photo 1. Port Waikato Slope. Valley-side slope is composed of Oligocene Te Kuiti Group. Relationship between slope angle and slope-forming rock is clear.

Aotea Sandstone with a thickness of about 60 m occupies large portion of the middle slope, and forms gentle slope with an angle of 11° to 16°. Waimai Limestone with a thickness of 7 m is intercalated between Aotea Sandstone and Whaingaroa Siltstone, and forms bluff with an angle of 86°. Whaingaroa Siltstone with a thickness of about 6 m occurs in the middle part of the slope and forms gentle slope with an angle of 8°. The lower part of the slope is occupied by Glen Massey Sandstone with a thickness of about 40 m, which forms gentle slope with an angle of 9° and bluff with an angle of 64°. Notch develops at the limestone and sandstone bluff base. Limestone and sandstone blocks are found at the foot of the limestone and sandstone bluffs.

In Kotuku (Fig. 3c), upper part of the slopes is occupied by Te Akatea Siltstone with a thickness of about 50 m, which forms gentle slope with an angle of 35°. Raglan Limestone with a thickness of 12 m is intercalated between Te Akatea Siltstone and Aotea Sandstone. The limestone forms step-like slope with an angle of 88°. Aotea Sandstone with a thickness of 65 m occupies large portion of the middle slope, and forms gentle slope with an angle of 18° and steep slope with an angle of 44°. The lower middle part of the slope is composed of Whaingaroa Siltstone with a thickness of about 50 m. The siltstone forms gentle slope with an angle of 6° to 24°. Lowest part of the slope is occupied by Glen Massey Sandstone with a thickness of 20 m. The sandstone forms bluff with an angle of 86°. Limestone and sandstone blocks are found at the foot of the limestone and sandstone bluffs.

The topmost part of the slope is occupied by Orahiri Limestone with a thickness of 8 m (Fig. 3d). The limestone forms step-like slope with an angle of 88°. Aotea Sandstone with a thickness of 120 m occupies large portion of the slope and forms bluff with an angle of 83° to 90° and gentle slope with an angle of 34° to 39°. Lower part of the slope is composed of Waimai Limestone with a thickness of about 20 m. The limestone forms step-like slope with an angle of 82°. Whaingaroa Siltstone with a thickness of about 10 m occupies lowest part of the slope and forms gentle slope with an angle of 12°.

In Waitomo Valley (Fig. 3e), the slope is composed of alternation of limestone and sandstone. Topmost part of the slope is occupied by Orahiri Limestone with a thickness of 40 m. The limestone forms step-like slope with an angle of 84° to 86° and bluff with an angle of 89°. Waitomo Sandstone with a thickness of 20 m occupies upper middle part of the slope and forms gentle slope with an angle of 38°. The lower middle part of the slope is composed of Orahiri Limestone with a thickness of about 20 m. The limestone forms bluff with an angle of 90°. Notch develops at the bluff base. Aotea Sandstone with a thickness of about 50 m occupies lowest part of the slope and forms gentle slope with an angle of 30°. Limestone blocks are found at the foot of the limestone bluff.

Recession of slopes

Weathering processes

Exfoliation is frequently observed on vegetationless Te Akatea Siltstone and Whaingaroa Siltstone slope. The Te Akatea Siltstone and Whaingaroa Siltstone on the surface of unvegetated slope are disintegrated into fine fragments by slaking.

Waimai Limestone, Raglan Limestone, Otorohanga Limestone and Orahiri Limestone are flaggy crystalline limestone, and large joints develop parallel to the bluff surface within the limestones (Photo 2). Joint spacings from bluff surface to the joints range from 1.0 to 2.5 m in Waimai Limestone bluff, 0.3 to 1.8 m in Orahiri Limestone bluff and 0.5 to 1.7 m in Otorohanga Limestone bluff (Table 1).

Honycomb weathering is observed on the surface of Glen Massey Sandstone and Aotea Sandstone bluff. Joints are parallel to the sandstone bluff (Photo 3). Joint spacings from bluff surface to the joints range from 0.7 to 13.6 m in Glen Massey Sandstone bluff and from 0.5 to 1.1 m in Aotea Sandstone slope (Table 1).

Erosional processes

Rockfalls were observed on the vegetationless Te Akatea Siltstone and Whaingaroa Siltstone slope. Many fragments of the siltstone fallen from the slope were found at the foot of the siltstone slope. The siltstone slopes are slightly eroded by rockfalls (Fig. 4). Shallow landslide scars and landslide blocks were found on the siltstone slope, therefore, siltstone slopes are largely retreated by shallow slides. Small terracettes occur on the siltstone gentle slopes, therefore, siltstone slopes are slightly eroded by soil creep.

Photo 2. Waimai Limestone bluff at Port Waikato Slope. The limestone is flaggy crystalline limestone and large joints develop parallel to the bluff surface within the limestone.

Table 1. Joint spacing (m) of Te Kuiti Group.

	Port Waikato	Te Kotuku CK	Waitomo Valley
Glen Massey Sandstone	5.7, 7.0, 13.6, 0.7, 1.4, 1.1, 1.7, 2.7, 4.0, 5.2	1.5, 1.5	
Aotea Sandstone		0.8, 0.9, 0.9, 1.1, 0.5, 0.7	
Waitomo Sandstone			0.04, 0.06
Waimai Limestone	2.5, 1.9, 1.2, 1.7, 2.1, 1.6, 1.9, 1.9, 1.0, 1.1, 1.0		
Orahiri Limestone			1.8, 0.8, 0.3, 0.4, 0.7
Otorohanga Limestone			1.7, 1.0, 0.7, 1.1, 0.5

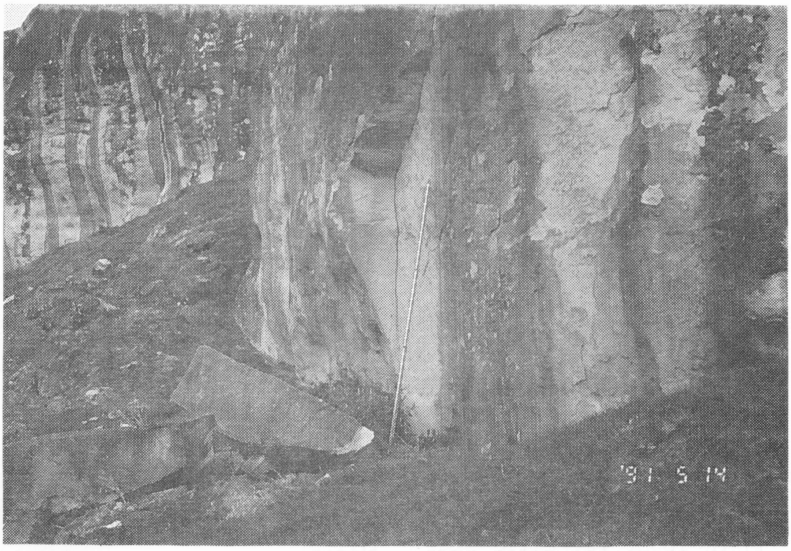

Photo 3. Glen Massey Sandstone bluff at Port Waikato Slope. Joints are parallel to the sandstone bluff. Sandstone blocks are found at the bluff foot.

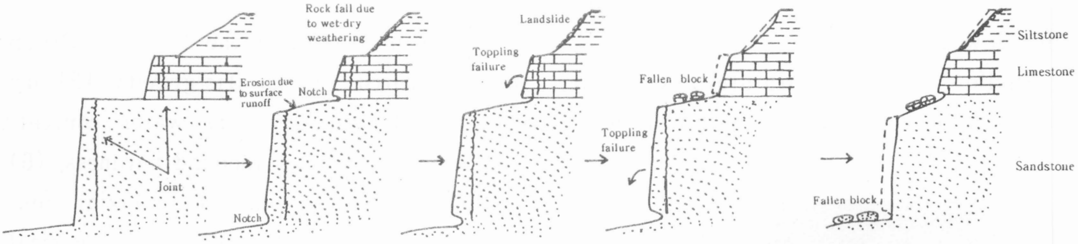

Fig. 4. Schematic diagrams illustrating slope recession made of Te Kuiti Group.

Many limestone blocks with a thickness of 1.3 to 5.0 m are found at the limestone bluff foot and bedding planes of the limestone blocks are tilted to downslope in many blocks (Table 2, Photo 3). Notches with various depths develop at the bluff base (Photo 3). Joints develop parallel to the bluff surface in the limestone. Sliding scars are not found on the bluff face, therefore, the bluff would not fail by sliding. From these field observations, it can be assumed that collapses of the bluff above the notch were caused by beam failure in tension processes. The bluff becomes unstable as notches develop and notch growth finally causes collapse of the bluff (Fig. 4).

At the sandstone bluff foot, many sandstone blocks with a thickness of 2.0 to 13.6 m are found (Table 2). Notches with various depths develop at the bluff base. Joints develop parallel to the bluff surface in the sandstone (Photo 4). Sliding scars

Table 2. Fallen block size(m).

	Port Waikato	Te Kotuku CK
Glen Massey Sandstone	5.7, 13.6, 2.0, 4.0, 7.0, 5.3, 9.0, 5.3, 2.7, 7.8	
Aotea Sandstone		0.9, 0.9, 0.5, 0.4, 0.7
Waimai Limestone	3.4, 2.8, 2.7, 5.0, 2.3, 1.9, 1.3	

are not found on the bluff face. From these field observations, it is considered that collapses of the bluff above the notch were coused by beam failure in tension processes (Fig. 4). Rills are found at the topmost part of the bluff. Therefore, topmost part of the bluff is eroded by rill erosion and becomes low angle.

Shallow landslide scars are observed at the sandstone gentle slopes. It is considered that shallow landslides are dominant erosional process in the sandstone gentle slopes.

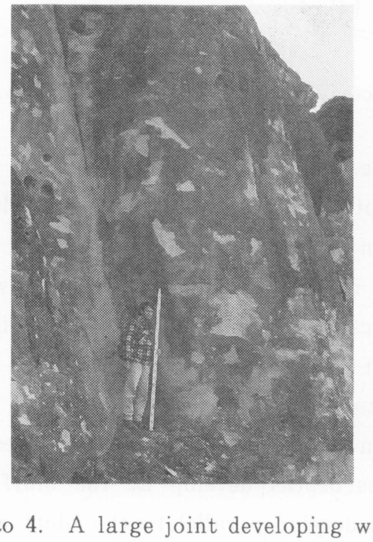

Photo 4. A large joint developing within Glen Massey Sandstone bluff.

Geotechnical properties of the Te Kuiti Group

Methods

Some properties of the Te Kuiti Group were measured: (1) specific gravity, (2) dry density, (3) porosity, (4) water content, (5) Schmidt Hammer rebound hardness, (6) point-load strength, and (7) uniaxial compressive strength. Samples for physical properties and uniaxial compressive strength tests were taken from roadside fresh outcrops, quarry and fallen blocks (Fig. 1, Table 3). Schmidt Hammer rebound hardness and point-load strength were determined at the study slope outcrops (indicated by numbers in Fig. 3a-3e).

Specific gravity was tested using powder specimens. Dry density was determined by dividing the weight by the volume of core specimens with a diameter of 54 mm. Porosity was calculated from the data of specific gravity and dry density.

Table 3. Sample numbers.

Sample No.	Rocks	Sampling points	Sheet numbers
1	Elgood Limestone	Maurice Cornille Road North	N51/264902
2	Elgood Limestone	North of Limestone Downs	N51/275867
3	Te Akatea Siltstone	Roadside opposite Waikaretu Quarry	N55/317755
4	Waimai Limestone	Waikaretu Quarry	N55/317755
5	Te Akatea Siltstone	North of Waimai Stream	N55/338657
6	Glen Massey Sandstone	Waimai Stream	N55/345645
7	Raglan Limestone	West of Te Akau	N55/370600
8	Whaingaroa Siltstone	Te Uku Landing	4/249543
9	Aotea Sandstone	Oparua South	R15/808466
10	Waimai Limestone	Hautupu North	R15/797448
11	Aotea Sandstone	Hautapu Hill	R15/788424
12	Waimai Limestone	Hautapu Hill	R15/788424
13	Aotea Sandstone	Te Koraha South East	S4/247494
14	Orahiri Limestone	Waitomo Caves West	264-4/686328
15	Whaingaroa Siltstone	Piripiri East	262-4/676324
16	Otorohanga Limestone	Waitomo Valley Quarry	S16/963294
17	Orahiri Limestone	Waitomo Valley Quarry	S16/963294
18	Orahiri Limestone	Waitomo Valley Quarry	S16/963294
19	Waitomo Sandstone	Waitomo Valley Quarry	S16/963294
20	Whaingaroa Siltstone	Torehina, Coromandel	S10/298005

The rebound hardness of the Schmidt Hammer test was obtained in the field by means of 10 measurements of Schmidt Test Hammer. The Type N hammer was used for the tests. The test was conducted horizontally to the bedding plane in the limestone and vertically to the slope in the sandstone and the siltstone. Point-load strength was determined using block specimens with a thickness of about 30 to 80 mm sampled from outcrops of the study slopes. The specimen shape is irregular and specimens were loaded perpendicular with respect to bedding planes. Average point-load strength was obtained for 10 specimens and water content was measured.

Uniaxial compressive strength was obtained for 5 core specimens having a diameter of 54 mm and a height of 135 mm. Soiltest CT-710M was used for the test and orientation of axis of loading is perpendicular with respect to bedding planes. Because the strength varies with water contents (Terzagi and Peck, 1948, p. 31; Chorley, 1959, 1964), the test was performed under natural-dry and saturated conditions.

Physical properties

Test results are listed in Table 4. Specific gravity of material forming each rock is nearly equal, i.e., about 2.6. Dry density of the Te Akatea Siltstone and Whaingaroa Siltstone is about 2100 kg/m^3 and smaller than taht of the limestones and the sandstones. The limestones have a dry density of 2320 to 2600 kg/m^3 and the sandstones have a dry density of 2100 to 2400 kg/m^3. Porosity of the siltstones

Table 4. Physical properties of Te Kuiti Group.

Rocks	Sample No.	Specific gravity	Dry density (kg/m³)	Porosity (%)
Te Akatea Siltstone	3	2.66	2084	21.7
Te Akatea Siltstone	5	2.57	2070	19.4
Whaingaroa Siltstone	8	2.61	2192	16.0
Whaingaroa Siltstone	15	2.55	2133	16.4
Waimai Limestone	4	2.62	2416	7.6
Waimai Limestone	10	2.62	2577	1.4
Waimai Limestone	12	2.68	2539	5.1
Raglan Limestone	7	2.57	2320	9.6
Elgood Limestone	1	2.68	2386	10.7
Elgood Limestone	2	2.61	2573	1.4
Otorohanga Limestone	16	2.66	2497	5.9
Orahiri Limestone	14	2.62	2352	10.2
Orahiri Limestone	17	2.61	2597	0.3
Orahiri Limestone	18	2.66	2495	5.9
Glen Massey Sandstone	6	2.58	2103	18.5
Aotea Sandstone	9	2.68	2209	17.5
Aotea Sandstone	11	2.58	2402	6.9
Aotea Sandstone	13	2.68	2260	15.6
Waitomo Sandstone	19	2.73	2249	17.5

ranges from 16 to 22% and larger than that of the limestones. The limestones have small porosity and porosity ranges from 0 to 10%. Porosity of the sandstones ranges from 7 to 18.5% and this value is nearly equal to the value of the siltstones. A mud content of the Aotea Sandstone and Waitomo Sandstone is about 20 to 40%, and clasified into muddy sandstone.

Schmidt Hammer rebound hardness

Test results of the Schmidt Hammer rebound hardness are shown in Table 5a-5e. The hardness of the Te Akatea Siltstone and Whaingaroa Siltstone is smaller than that of the limestones and sandstones under natural water content. The hardness of the Te Akatea Siltstone and Whaingaroa Siltstone is about 20 to 15, respectively. Waimai Limestone, Raglan Limestone, Orahiri Limestone and Otorohanga Limestone have a hardness of about 40 and this value is about 2 times greater than that of the siltstones. The hardness of the Glen Massey Sandstone, Aotea Sandstone and Waitomo Sandstone is about 30, 10 to 30 and 10, respectively. The hardness of the sandstones is larger than that of the siltstones and smaller than that of the limestones.

Point-load strength

Test results are listed in Table 5a-5e. The point-load atrength of the Te Akatea Siltstone and Whaingaroa Siltstone is smaller than that of the limestones and sandstones under natural water content. Point-load strength of the Te Akatea Siltstone and Whaingaroa Siltstone is 0.9 to 3.6 MPa when water content is 5.8 to 12.2%. Waimai Limestone, Raglan Limestone, Orahiri Limestone and Otorohanga Limestone have a point-load strength of 6.7 to 15.7 MPa when water content is 0.5 to 3.5% and this value is about 5 times greater than that of the siltstones. The point-load strength of the Glen Massey Sandstone, Aotea Sandstone and Waitomo

Table 5a. Strength of material forming Port Waikato Slope.

Measuring point	Schmidt Hammer rebound hardness		Point-load strength (MPa)		Water content (%)
	Measured	Mean	Measured	Mean	
① Te Akatea Siltstone	10-40	21	1.9- 8.1	3.6	5.8
② Te Akatea Siltstone	11-32	22	1.5- 3.8	2.7	8.2
③ Waimai Limestone	34-46	40	9.3-17.3	13.9	0.6
④ Glen Massey Sandstone	26-32	30	2.0- 3.1	2.5	3.8
⑤ Glen Massey Sandstone	30-33	32	2.0- 3.1	2.5	3.6

Table 5b. Strength of material forming Waimai Stream Valley Slope.

Measuring point	Schmidt Hammer rebound hardness		Point-load strength (MPa)		Water content (%)
	Measured	Mean	Measured	Mean	
① Te Akatea Siltstone	11-33	20			
② Raglan Limestone	30-44	35			
③ Aotea Sandstone	10-39	27			
④ Waimai Limestone	29-48	41			
⑤ Whaingaroa Siltstone	10-24	13			
⑥ Glen Massey Sandstone	23-40	31			

Table 5c. Strength of material forming Te Kotuku CK Slope.

Measuring point	Schmidt Hammer rebound hardness		Point-load strength (MPa)		Water content (%)
	Measured	Mean	Measured	Mean	
① Te Akatea Siltstone	28-33	31	1.3- 2.5	1.9	6.9
② Raglan Limestone	37-47	41	8.3-20.3	12.7	3.5
③ Aotea Sandstone	11-15	12			
④ Aotea Sandstone	21-28	24	1.6- 9.6	5.0	4.7
⑤ Whaingaroa Siltstone	17-26	20	0.9- 2.4	1.3	12.2
⑥ Glen Massey Sandstone	28-39	32			
⑦ Glen Massey Sandstone	35-59	49	3.7- 6.7	5.0	6.9

Table 5d. Strength of material forming Hautapu Hill Slope.

Measuring point	Schmidt Hammer rebound hardness		Point-load strength (MPa)		Water content (%)
	Measured	Mean	Measured	Mean	
① Orahiri Limestone	36-47	42	7.8- 12.3	9.7	1.0
② Aotea Sandstone	25-34	29	0.9- 2.2	1.6	1.8
③ Aotea Sandstone	17-28	23	0.5- 2.2	0.8	2.0
④ Aotea Sandstone	26-39	31	2.3- 6.5	3.5	1.4
⑤ Aotea Sandstone	13-20	17			
⑥ Aotea Sandstone	17-28	23	1.9- 4.0	2.8	1.0
⑦ Waimai Limestone	41-51	47	13.4-18.6	15.7	0.5
⑧ Whaingaroa Siltstone	10-24	15	0.4- 1.3	0.9	9.3

Table 5e. Strength of material forming Waitomo Valley Slope.

Measuring point	Schmidt Hammer rebound hardness		Point-load strength (MPa)		Water content (%)
	Measured	Mean	Measured	Mean	
① Otorohanga Limestone	36-50	44	8.5-16.2	12.9	1.4
② Waitomo Sandstone	10-14	11	0.5- 1.2	0.9	8.8
③ Orahiri Limestone	24-43	35	4.9- 9.1	6.7	2.4
④ Orahiri Limestone	24-41	34			
⑤ Aotea Sandstone	18-34	24			
⑥ Aotea Sandstone	10-20	12	1.2- 2.3	1.7	7.8

Sandstone is 2.5 to 5.0, 0.8 to 5.0 and 0.9 MPa, respectively, when water content is 1.0 to 8.8%. The point-load strength of the sandstones is larger than that of the siltstones and smaller than that of the limestones.

Uniaxial compressive strength

Test results are shown in Table 6a-6b. The strength of each slope-forming rocks, except Otorohanga Limestone, decreases with an increase in water content. However, the strength of the limestones is larger than that of the siltstones and sandstones. The strength of the Te Akatea Siltstone and Whaingaroa Siltstone is about 22 and 28 to 37 MPa, respectively, under fully saturated conditions, i.e., 7 to 10% water content. The Waimai Limestone, Raglan Limestone and Otorohanga Limestone have a strength of about 60 to 80 MPa under saturated conditions with a water content of about 1 to 5%. The strength of the Orahiri Limestone is about 30 to 40 MPa under saturated conditions, namely, 1 to 4% water content. The strength of the Orahiri Limestone is smaller than that of the Waimai Limestone, Raglan Limestone and Otorohanga

Table 6a. Uniaxial compressive strength of Te Kuiti Group under natural-dry condition.

Rocks	Sample No.	Measured value (MPa)	Mean value (MPa)	Water content (%)	Mean water content (%)
Te Akatea Siltstone	5	32.0-57.0	47.2	2.9-3.1	3.0
Whaingaroa Siltstone	8	40.0-43.3	41.5	4.1-4.8	4.4
Whaingaroa Siltstone	15	49.9-64.0	56.9	4.3-5.0	4.6
Waimai Limestone	4	72.2-96.0	84.0	0.8-1.0	0.9
Raglan Limestone	7	78.6-96.8	89.1	0.9-1.5	1.2
Elgood Limestone	1	32.7-57.8	44.1	1.3-1.7	1.5
Otorohanga Limestone	16	65.5-90.0	80.7	0.6-0.7	0.6
Orahiri Limestone	14	37.0-52.8	46.2	1.7-2.2	2.0
Orahiri Limestone	17	43.3-75.8	58.8	0.4-0.5	0.5
Glen Massey Sandstone	6	22.5-35.9	30.0	1.9-2.1	2.0
Aotea Sandstone	9	16.1-29.8	22.9	2.6-2.9	2.7
Aotea Sandstone	11	34.1-49.0	42.6	1.8-2.2	2.0
Aotea Sandstone	13	25.1-41.9	37.6	3.5-3.8	3.7
Waitomo Sandstone	19	27.9-32.2	30.0	3.6-3.8	3.7

Table 6b. Uniaxial compressive strength of Te Kuiti Group under saturated condition.

Rocks	Sample No.	Measured value (MPa)	Mean value (MPa)	Water content (%)	Mean water content (%)	*Scs/ Scd*	*Ws/ Wd*
Te Akatea Siltstone	5	17.4-28.1	22.0	9.5-10.0	9.6	0.47	3.2
Whaingaroa Siltstone	8	14.9-21.1	18.0	7.5- 7.8	7.7	0.43	1.8
Whaingaroa Siltstone	15	20.0-43.2	36.7	6.7- 8.8	7.2	0.65	1.6
Waimai Limestone	4	70.5-86.1	79.8	1.4-1.9	1.7	0.95	1.9
Raglan Limestone	7	57.4-64.1	61.4	5.1-5.5	5.3	0.69	4.4
Elgood Limestone	1	21.2-50.5	37.5	2.7-4.8	3.7	0.85	2.5
Otorohanga Limestone	16	77.0-98.9	85.1	1.3-1.6	1.4	1.05	2.3
Orahiri Limestone	14	29.7-39.1	32.6	3.3-5.0	3.8	0.71	1.9
Orahiri Limestone	17	29.7-49.8	40.4	0.7-1.1	1.0	0.69	2.0
Glen Massey Sandstone	6	16.5-29.6	25.1	5.4-6.0	5.8	0.84	2.9
Aotea Sandstone	9	12.4-22.0	16.7	6.5-6.9	6.7	0.73	2.5
Aotea Sandstone	11	23.1-35.9	27.3	3.8-4.9	4.3	0.64	2.2
Aotea Sandstone	13	16.2-24.8	21.3	6.1-6.7	6.4	0.57	1.7
Waitomo Sandstone	19	7.6-20.1	12.5	7.2-7.8	7.5	0.42	2.0

Scs : Uniaxial compressive strength under saturated condition, *Scd* : Uniaxial compressive strength under natural-dry condition, *Ws*:Saturated water content, *Wd*:Natural-dry water content.

Limestone under natural-dry and saturated conditions. The Glen Massey Sandstone, Aotea Sandstone and Waitomo Sandstone have a strength of about 25, 17 to 27 and 13 MPa, respectively, under fully saturated conditions with a water content of about 4 to 8%. Under saturated conditions, the strength of the sandstones is approximately similar to the strength of the siltstones.

Relationship between slope angles and rock properties

Slope angle and Schmidt Hammer rebound hardness

The relationship between slope angles of valley-side slope and Schmidt Hammer rebound hardness of slope-froming rocks is shown in Fig. 5. Siltstones and muddy sandstones, such as Te Akatea Siltstone, Whaingaroa Siltstone, Aotea Sandstone and Waitomo Sandstone, have low Schmidt Hammer rebound hardness, whereas limestones and sandstones, such as Waimai Limestone, Raglan Limestone, Orahiri Limestone, Otorohanga Limestone, and Glen Massey Sandstone have high Schmidt Hammer rebound hardness. Slope angles of siltstones and muddy sandstones valley-side slopes with low Schmidt Hammer rebound hardness indicate lower slope angles less than 60°. On the other hand, slope angles of limestones and sandstones valley-side slopes with high Schmidt Hammer rebound hardness show higher slope angles than 60°.

Valley-side slopes made of siltstones and muddy sandstones have low slope angles and low Schmidt Hammer rebound hardness, and slope angles of these rocks valley-side slopes tend to increase with the

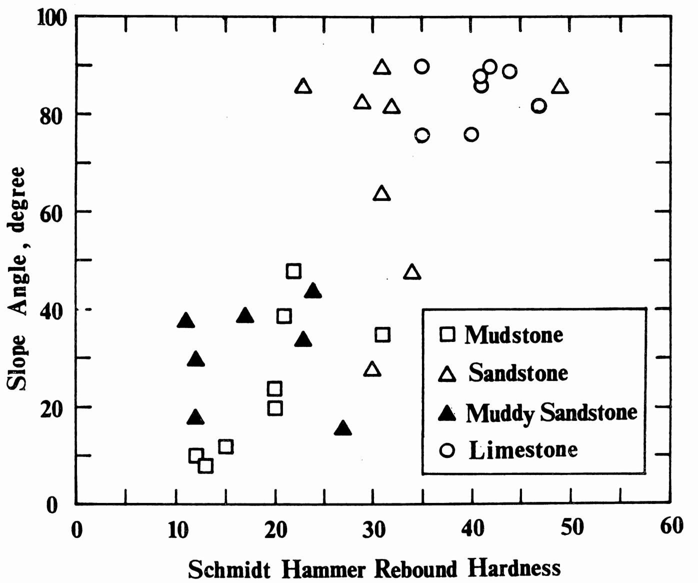

Fig. 5. Relationship between Schmidt Hammer rebound hardness of slope-forming rocks and slope angle.

increase of Schmidt Hammer rebound hardness of these slope-forming rocks. While slope angles of limestones and sandstones valley-side slopes are not correlated to Schmidt Hammer rebound hardness of these slope-forming rocks.

Slope angle and Point-load strength

Fig. 6 shows the relationship between slope angle of valley-side slopes and point-load strength of slope-forming rocks. Slope angles of siltstones and muddy sandstones valley-side slopes, such as Te Akatea Siltstone, Whaingaroa Siltstone, Aotea Sandstone and Waitomo Sandstone, increase with the increase of point-load strength of these slope-forming rocks. While slope angles of limestone and sandstone valley-side slopes, such as Waimai Limestone, Raglan Limestone, Orahiri Limestone, Otorohanga Limestone, and Glen Massey Sandstone show no correlations to point-load strength of these slope-forming rocks.

Slope angle and Uniaxial compressive strength

The relationship between slope angles of siltstones and muddy sandstones valley-side slopes, such as Te Akatea Siltstone, Whaingaroa Siltstone, Aotea Sandstone and Waitomo Sandstone, and uniaxial compressive strength under natural-dry condition of these slope-forming rocks are somewhat scattered (Fig. 7). While slope angles of limestones and sandstones valley-side slopes, such as Waimai Limestone, Raglan Lime-

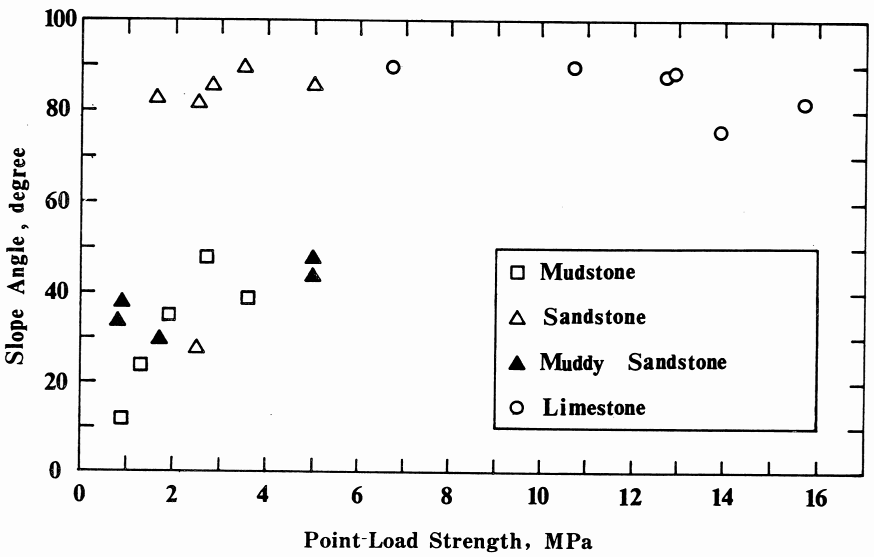

Fig. 6. Relationship between Point-load strength of slope-forming rocks and slope angle.

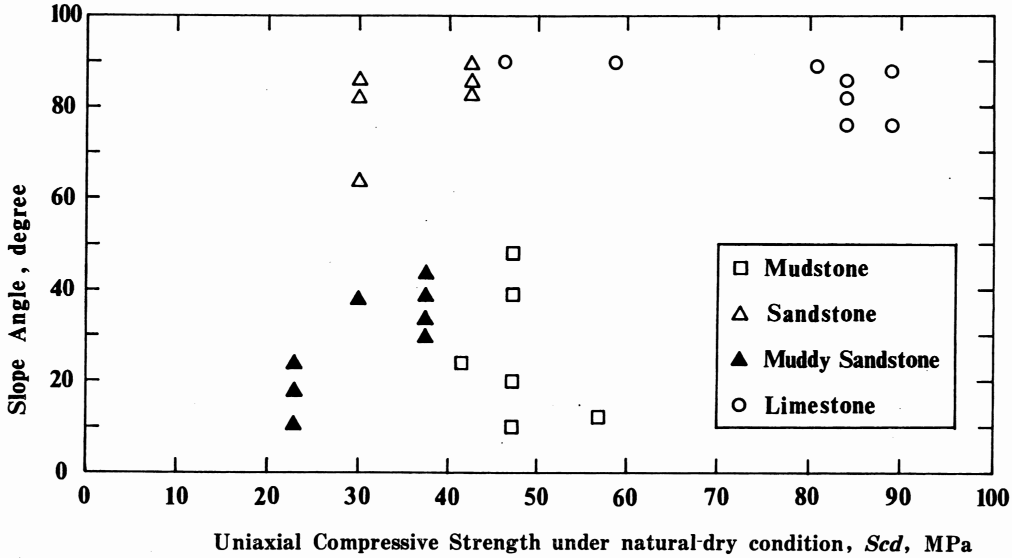

Fig. 7. Relationship between uniaxial compressive strength under natural-dry condition of slope-forming rocks and slope angle.

stone, Orahiri Limestone, Otorohanga Limestone, and Glen Massey Sandstone are not correlated to uniaxial compressive strength under natural-dry condition of these slope-forming rocks.

Fig. 8 illustrates the relationship between the slope angle of valley-side slope and uniaxial compressive strength under saturated condition of slope-forming rocks. Siltstones and muddy sandstones, such as Te Akatea Siltstone, Whaingaroa Siltstone, Aotea Sandstone and Waitomo Sandstone, have approximately equivalent uniaxial compressive strength under saturated condition, however, slope angles of these rocks valley-side slope are scattered. On the other hand, slope angles of limestone and sandstone valley-side slopes higher than 60°, such as Waimai Limestone, Raglan Limestone, Orahiri Limestone, Otorohanga Limestone, and Glen Massey Sandstone show no correlations to uniaxial compressive strength of slope-forming rocks.

Slope angle and Strength ratio

The relationship between slope angle and uniaxial compressive strength ratio (*Scs/Scd*) is shown in Fig. 9. Slope angles of siltstones and muddy sandstones valley-side slopes lower than 60°, such as Te Akatea Siltstone, Whaingaroa Siltstone, Aotea Sandstone and Waitomo Sandstone, are scattered. While slope angles of limestones and sandstones valley-side slopes, such as Waimai Limestone, Laglan Limestone, Orahiri Limestone, Otorohanga Limestone, and Glen Massey Sandstone are not correlated to uniaxial compressive strength ratio of these slope-forming rocks.

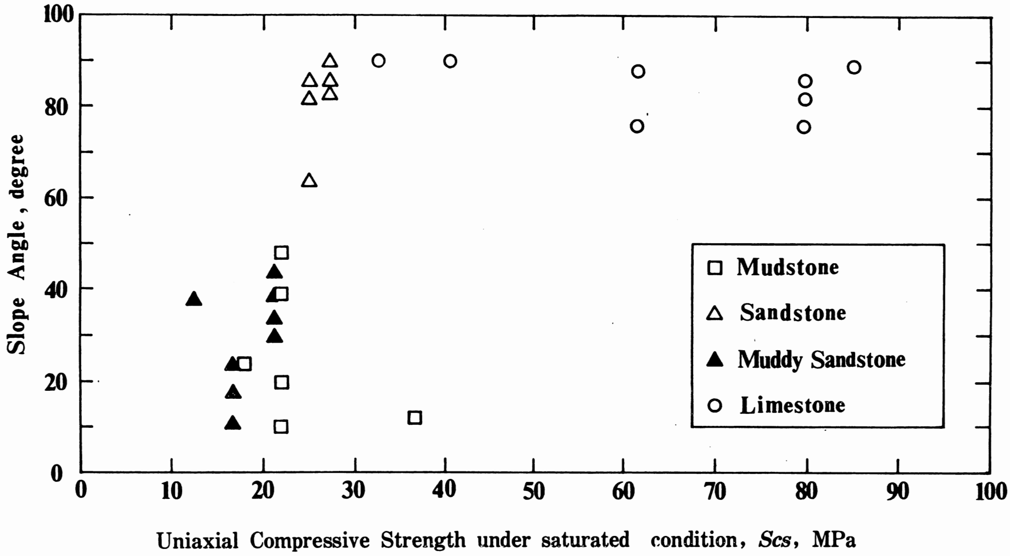

Fig. 8. Relationship between uniaxial compressive strength under saturated condition of slope-forming rocks and slope angle.

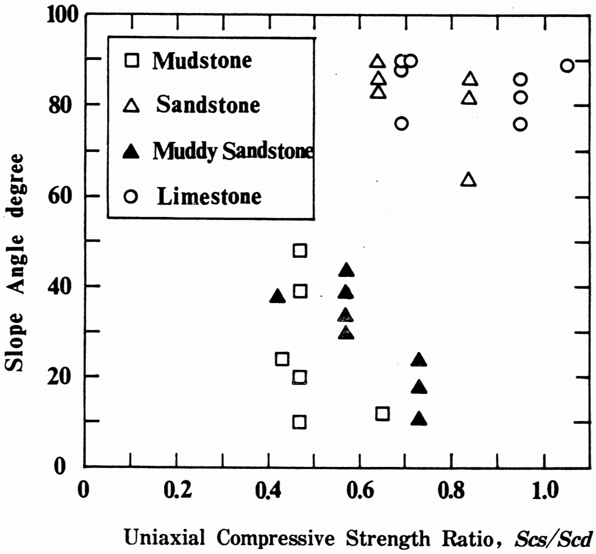

Fig. 9. Relationship between uniaxial compressive strength ratio of slope-forming rocks and slope angle.

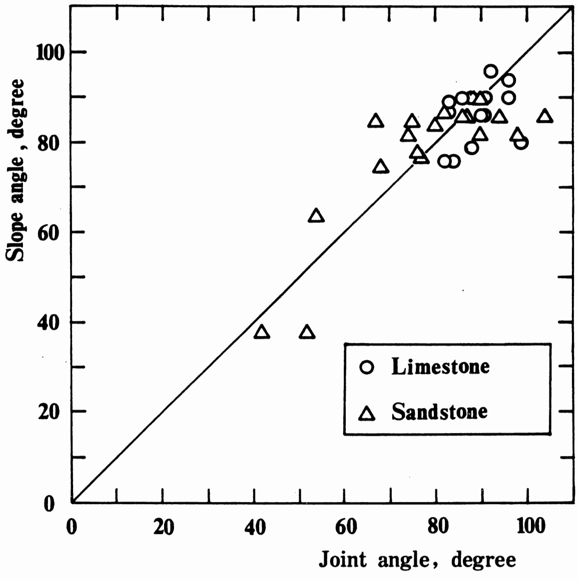

Fig. 10. Relationship between joint angle within slope-forming rocks and slope angle.

Slope angle and Joint angle

Fig.10 shows relationship between slope angle and joint angle developing within slope-forming rocks. Slope angles of limestones and sandstones valley-side slopes higher than 60° approximately agree with joint angles.

Summary

Tertiary Sedimentary rocks are widely distributed in South Auckland, New Zealand and these rocks form hills. Relationship between slope angle of valley slope and lithology is clear.

Valley-side slope profiles, erosional processes on valley-side slope, joint angles developing within slope-forming rocks, point-load strength of slope-forming rocks, the rebound hardness of the Schmidt Hammer Test of slope-forming rocks, uniaxial compressive strength of slope-forming rocks were examined at 5 points. Rock samples were collected from 20 points for uniaxial compressive strength test. Siltstones and muddy sandstones form gentle valley-side slope, whereas limestones and sandstones form steep slopes. Recession of Siltstones and muddy sandstones slopes are seems to be caused by rockfall, landslide and creep. While recession of limestones and sandstones slopes are probably caused by toppling failure. Slope angles of siltstones and muddy sandstones valley-side slopes with gentle slope angles, increase with the increase of rebound hardness of the Schmidt Hammer test and point-load strength of slope-forming rocks. Slope angles of limestones and sandstones valley-side slopes with higher than 60° are not correlated to rebound hardness of Schmidt Hammer test,

point-load strength and uniaxial compressive strength of these slope-forming rocks. Slope angles of valley-side slopes with higher than 60° approximately agree with joint angles developing within limestones and sandstones.

Gentle slopes of siltstones and muddy sandstones valley-side slopes are controlled by the strength of slope-forming rocks, while steep slope of limestones and sandstones are controlled by joint angles developing within slope-forming rocks.

Acknowledgments

The auther expresses his appreciation to Prof. C. S. Nelson at the Department of Earth Sciences, the University of Waikato for fruitful suggetions, to Mr. L. J. Gaylor and R. Langridge of the Department of Earth Sciences, the University of Waikato for help with the measurement in the field.

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オークランド南部の第三紀堆積岩がつくる地形と岩石物性

前門　晃*

オークランド南部には第三紀堆積岩が広く分布し，岩石と斜面傾斜との関係が明瞭な丘陵を形成している．5地点で，谷壁斜面の地形測量，谷壁斜面の侵食プロセスの観察，岩石中の割れ目の傾斜の測定，斜面構成岩石の点載荷強度・シュミットハンマー反発値・一軸圧縮強度を測定した．その結果，つぎのことが明らかになった．(1)泥岩と泥質砂岩が緩頃斜の斜面を形成し，石灰岩と砂岩が急傾斜の斜面を形成している．(2)緩頃斜の斜面をつくる泥岩・泥質砂岩は落石・地すべり・土壌匍行で，急傾斜の斜面をつくる石灰石・砂岩は転倒崩落で後退する．(3)谷壁斜面の傾斜と構成岩石のシュミットハンマー反発値，点載荷強度との間には，緩傾斜の斜面をつくる泥岩・泥質砂岩ではこれらの強度が大きくなるにつれて斜面の傾斜が大きくなる傾向があるが，60° 以上の急傾斜の斜面ではこれらの強度が関係しない．(4)石灰岩・砂岩に発達する割れ目の傾斜と60° 以上の傾斜をもつ谷壁斜面の傾斜とはよく一致する．

これらのことから，泥岩・泥質砂岩がつくる緩傾斜の斜面の形成にはそれらの岩石の強度が，石灰岩・砂岩がつくる急傾斜の斜面の形成にはそれらの岩石中に発達する割れ目の傾斜が関係していると言えそうである．

*〒903-0213　沖縄県西原町千原1　琉球大学法文学部