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Editors Note:

This issue introduces a new series to the Hong Kong Geologist: *Hong Kong's Classic Geology*. The series deals with all geological features that are well exposed and located in Hong Kong. Topics will include, for example, geological structures, rock types and type sections. The first in the series deals with columnar jointing. Authors wishing to submit papers to this series should contact the Editor.

Weathering Profile Development Below the Yuen Long Plain, Western New Territories, Hong Kong

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Abstract

Some 2,651 borehole logs have been interpreted and entered in to a computer database, which has been used to model the morphology and depth of the weathering front in the Yuen Long area. The results are used as a basis for correlation between the surface topography, the morphology of the weathering front, and the main structural trends. This study has focused on examining the different weathering characteristics between granitic, volcanic, and metamorphic lithologies, and on the influence of the geological discontinuities. Attention has also been paid to corestone development and distribution, and the thickness and distribution of superficial deposits. The results of this and similar studies play an important role in developing models for interpreting, and ultimately for predicting, weathering patterns over the main rock types in Hong Kong.

摘要

2,651 個鑽孔的資料被解讀，並被輸入電腦數據庫，藉此模擬元朗地區風化帶的形態和風化深度。其結果被用來作為分析地表地貌、風化形態以及主要構造趨勢之間相互關係的基礎。該研究集中探討花崗岩、火山岩及變質岩不同岩性的風化特征，以及地質上的不連續對風化作用的影響。該研究亦特別注意核岩的發展與分佈，以及第四紀沉積物的厚度與展佈。這項研究以及類似研究的成果，對於建立模型以詮釋乃至最終預測本港主要岩石類型的風化模式十分重要。

Introduction

The main objective of most engineering ground investigations is the determination of rockhead, that is the boundary between soil and rock. In Hong Kong, an area of deep subtropical weathering, this boundary is usually the base of weathering, a surface termed the weathering front (Mabutt, 1961). In some areas, rockhead is the base of transported Quaternary superficial deposits. Geologists are commonly required to determine the morphology of the weathering front, the thickness of the weathered mantle, the physical properties of the weathered and unweathered rocks, and the engineering performance of the different degrees of weathered rocks.

Every year numerous engineering ground investigations are carried out at individual sites around Hong Kong. These investigations have resulted in the generation of a large amount of borehole data, much of which is concentrated in particular development areas. Records from approximately 375,000 boreholes are held in the Geotechnical Information Unit of the Civil Engineering Department, Hong

Kong Government. These are commonly used to assist the geological modelling of individual small sites, but few studies have attempted more regional research.

Variations in thickness and physical characteristics of the weathered mantle broadly depend upon the lithology, geological structure, topography, and ground-water conditions. Detailed regional modelling of the depth and topography of the weathering front and determination of the particular geological factors that control extreme local variations in the surface will assist in refining the techniques for planning future ground investigations and increase their reliability. Ultimately, regional models will improve the general understanding of spatial weathering patterns and the magnitude of their depth variations, therefore helping to avoid the unexpected geological conditions that arise at many sites.

In a study of the distribution of buried marble below the designated area in the northwestern New Territories, Frost (1992) compiled contours of the

bedrock surface below the thick superficial deposits. Bedrock contours were shown on the published 1:5,000 scale maps of the area, and diagrammatically in the accompanying Sheet Report. A special solid geology edition, HGM 20S, of the 1:20,000 scale Sheet 2 (GEO, 1994) to the north of the study area shows isopachs of the overlying superficial deposits. Recently, Li (in press) has mapped the weathering front in the Tin Shui Wai area to the north. Shaw (1997) used borehole data to map variations in the weathered mantle over the uniform granite of the undulating Kowloon peninsula. Subsequently, Owen and Shaw (in press) have extended that investigation to assess weathering characteristics over volcanic lithologies in the low lying Tuen Mun corridor. This study has attempted to update the earlier research using more recent borehole records and models the weathering front surface using computer techniques.

Study area limits and methodology

The main study area, centred on the town of Yuen Long (Figure 1), is bounded by the coordinates 815500E to 823000E and 831000N to 835500N (an area of about 132 km²). Two subsidiary areas, in which particularly dense concentrations of boreholes occur, were modelled in greater detail. Area A is bounded by 817700E to 818900E and 834200N to 835500N (1.5 km²). Area B lies between 819500E to 821800E and 833500N to 834600N (2.2 km²).

The low-lying Yuen Long area has a dense concentration of boreholes (Figure 2), though these become less concentrated in more elevated sites. A

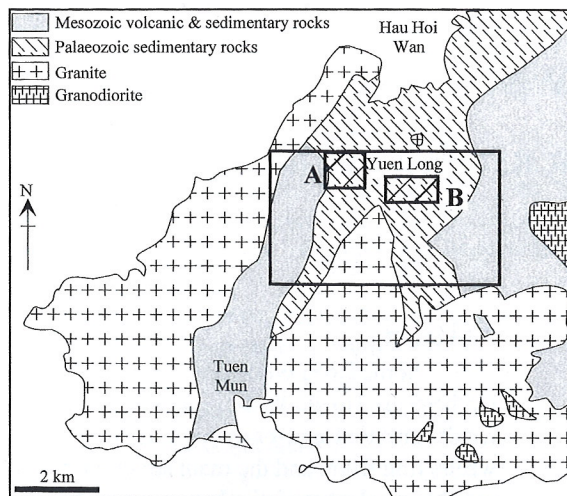


Figure 1 - Location and generalised geology of the main study area (large box). Note also the position of the detailed sub-areas "A" and "B". Map from Langford et al., 1989.

total of 2,651 borehole records were retrieved, of which 1,895 penetrated to the bedrock. Location coordinates and interpreted geological details were extracted from the borehole logs and entered into a computer database. Absolute level of the ground surface, base of superficial deposits or fill, top of the corestone bearing horizon (if present), and base of the weathered mantle were identified. Surface contouring of the weathering front was carried out, and isopachs of the weathering profile thickness or superficial deposits were calculated to establish a model of regolith variations.

Determination of the weathering front (rockhead) for foundation levels in Hong Kong normally requires

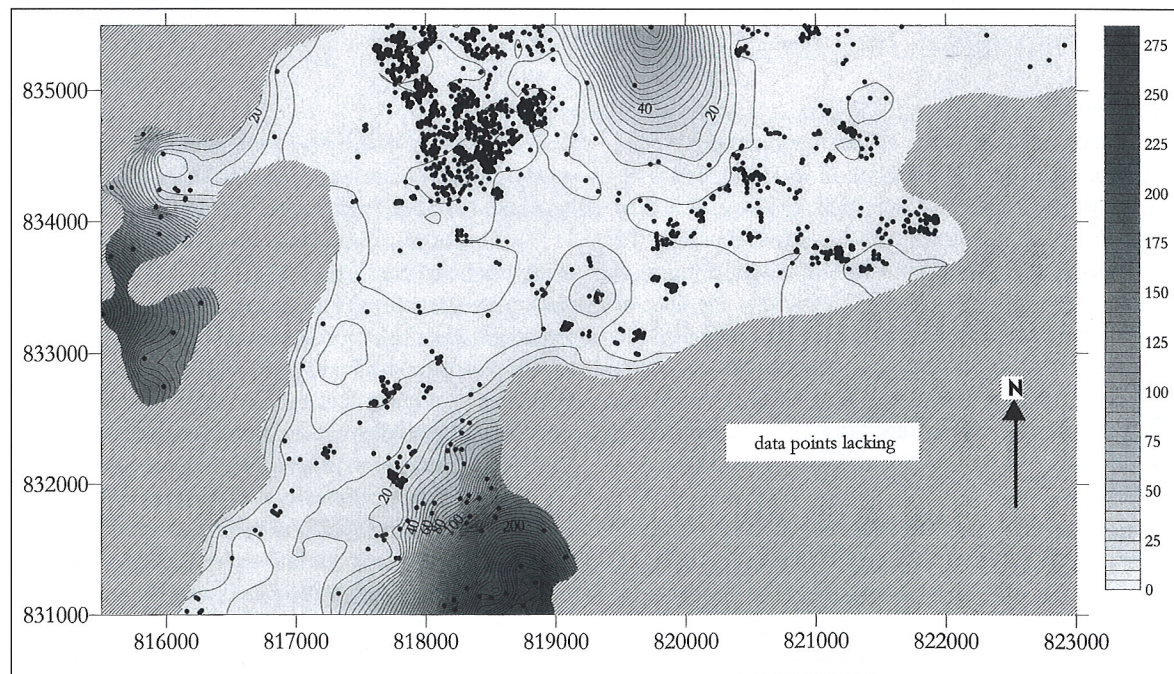


Figure 2 - Surface topography and the distribution of data points in the Yuen Long area. Note that topography is based on borehole data, not topographical surveys. Shaded relief to the right is in metres above principal datum.

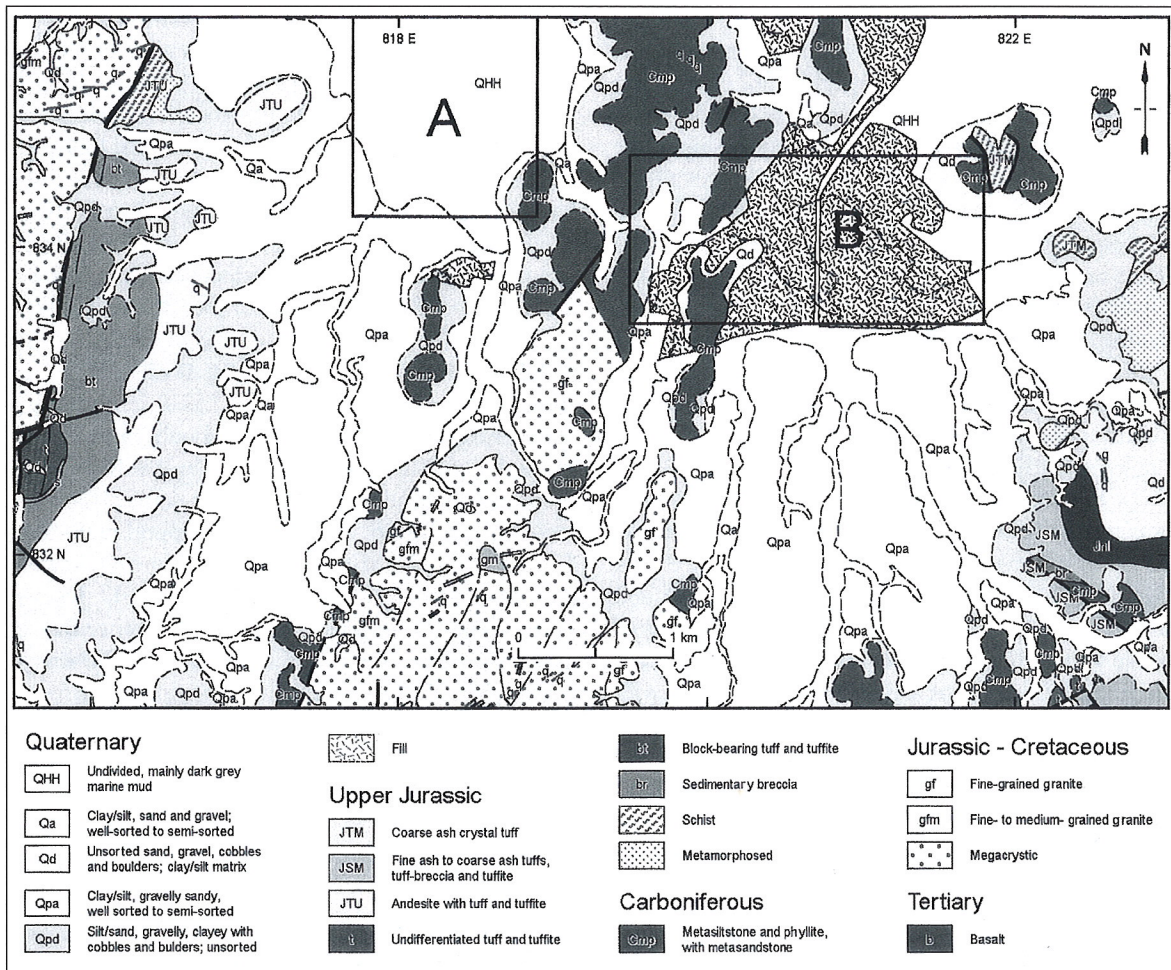


Figure 3 - Geology map of the main study area. Detailed study areas indicated by letters A and B. Much of the surface is covered with superficial deposits formed by north-flowing river systems. Map from Geotechnical Control Office, 1988b and 1988c.

drilling for at least 5 metres (Geotechnical Control Office, 1987) into Grades I to III rock material (Geotechnical Control Office, 1988a). This criterion was also adopted to define the weathering front. Determination of corestones followed the procedure of Shaw (1997) in which corestones in boreholes were defined as occurrences of Grades I to III rock material that were separated from each other, and from the weathering front, by at least 1 metre of weathered rock material. Bands of weathered rock less than 1 metre thick were considered to be widened joints. Bedded or layered, finer grained sedimentary, metamorphic and volcanic rocks do not usually form corestones, therefore in these lithologies the weathered layers are widened bedding planes or the differential weathering of less resistant interbeds.

Geomorphology and geology

The study area includes part of the low lying Yuen Long Plain and the northern Tuen Mun Valley. Elevation ranges from a maximum of 295 m in the south to near-sea level in the north (Figure 2). Streams flow northwards across the area from the Tai Lam massif in the south and discharge into Deep Bay. However,

intensive urban development and flood control measures have ensured that very few natural drainage channels remain. Most streams are confined to concrete nullahs.

The geology of the study area has been described by Bennett (1984), Langford *et al.* (1989) and Frost (1992). Structurally, the western New Territories comprises a Palaeozoic sedimentary basin surrounded by Mesozoic granitic and volcanic rocks (Figure 1). The sedimentary rocks in the basin are mostly of Carboniferous age, belonging to the San Tin Group (Langford *et al.*, 1989). However, these rocks are largely concealed by Quaternary superficial deposits (Figure 3). Post-Jurassic regional metamorphism has affected most of the strata in the area, with local contact or thermal metamorphism identifiable around the granite intrusions.

Carboniferous rocks of the San Tin Group comprise the largely calcareous Yuen Long Formation (CYL) at the base, overlain by the argillaceous and arenaceous Lok Ma Chau Formation (Cmp). Marble and limestone concealed below the Yuen Long area were first recognised by Ha *et al.* (1981) and were later designated

as the Yuen Long Formation by Lee (1985). The Yuen Long Formation comprises a lower Long Ping Member, of over 300 m of dark grey, finely crystalline marble, and an upper Ma Tin Member, of about 200 m of pale grey to white, massively bedded marble. The original limestone has been metamorphosed, so it is entirely recrystallised and all the original structures have been destroyed. The overlying Lok Ma Chau Formation (Cmp on Figure 3) occurs in subcrop below much of the low lying ground between Tuen Mun and Mai Po. The lower Mai Po Member, which is 500 m thick, consists of metamorphosed argillaceous limestones, mudstones, siltstones and sandstones. The overlying Tai Shek Mo Member is a metamorphosed arenaceous sequence with conglomeratic horizons.

Frequently, the boundary between the two formations is difficult to distinguish in boreholes because the top of the marble is karstified (Frost, 1992). This consists of a highly irregular, pinnacled surface and cavities within the rock mass. Poor borehole recovery of marble with silt-filled cavities closely resembles weathered interbedded metasilstone and marble, or tuff breccia with clasts of marble.

Volcanic rocks belong to the Repulse Bay Volcanic Group of Upper Jurassic to Lower Cretaceous age. These are dominated by andesitic lavas and tuffs of the Tuen Mun Formation (JTU on Figure 3). A distinctive sequence of interbedded tuffite and marble-bearing breccia, the Tin Shui Wai Member, underlies a large area in the southwest.

Sedimentary and volcanic rocks are intruded by granodiorite and granite. Granodiorite is the oldest, forming large, irregular, sheet-like masses in the volcanics, and smaller intrusions within the Carboniferous sedimentary rocks near Yuen Long. Granites are mostly fine- and medium-grained, forming major plutons to the south and west.

Northeast-trending faults dominate the structure of the study area (Langford *et al.*, 1989), whereas north- and northwest-trending faults are common in the younger granitic rocks. Palaeozoic sedimentary rocks of the San Tin Group occupy an irregular, curved, fault-bounded basin, a narrow graben between granitic rocks and metasedimentary rocks of the Repulse Bay and Lok Ma Chau formations. The belt, which is up to 4 km wide, extends northeastwards for about 25 km from Tuen Mun in the south, through Yuen Long to Shenzhen and Guangdong Province (Figure 1). The southeastern edge of the marble subcrop is characterised by a sharp, thrust-faulted boundary. Deeply weathered volcanics on the downthrust eastern side contrast markedly with the massive white Yuen Long Formation marble in the west (Frost, 1992). The western boundary consists of the steeply dipping edge of the marble overlain by the Mai Po Formation siltstones.

Thick superficial deposits, 20 to 80 m thick, cover most of the low lying ground, with continuous alluvial floodplains extending from Tuen Mun through Yuen Long to Lok Ma Chau. Late Pleistocene and Holocene debris flow deposits mantle the hillslopes that fringe the plain. Late Tertiary to Quaternary age debris flow deposits have been identified below the alluvium, filling irregularities in the karst marble surface (Frost, 1992). Holocene marine deposits occur adjacent to Deep Bay and the Sham Chun River, below the Tin Shui Wai reclamation.

Weathering in the Yuen Long area

Borehole data

Logging standards vary, and only in the recent ground investigations was there any reference to lithostratigraphical units. As a result, some difficulties arose in classifying lithologies in several boreholes. Selected examples of descriptions in weathered siltstone lithologies over marble are given in Table 1. Despite these difficulties it was possible to compile data on weathering thickness, to distinguish superficial sediments, and to classify bedrock types (Table 2). Lithologies were assigned to one of 24 categories, under the three major groups (granitic, volcanic, and metamorphic), with a minor intrusive group.

The depth of the weathering front encountered in each of the major groups is illustrated graphically in Figure 4. Overall weathering is deepest over metamorphic lithologies, and least over the volcanic and granitic rocks.

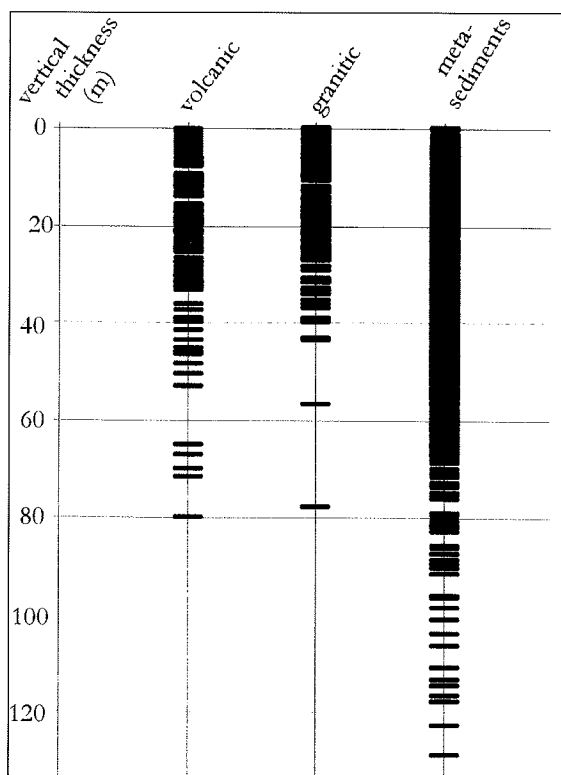


Figure 4 - Weathered mantle thickness for three major rock types. Each horizontal tick represents the thickness of weathered mantle in one borehole.

Table 1 - Examples of borehole data from weathered siltstone lithologies overlying marble.

BH No	GIU No	Location	Depth in Hole	Typical Weathered Rock Description
DH 31	10828	Yuen Long	18.5 – 23.6m (5.1 m)	Greyish dark brown sandy clayey SILT (C.D. Marble)
DH 151	12456	Tin Shui Wai	11.5 – 21.5m (10.0 m)	Dense to very dense, yellowish brownish becoming brownish grey SILT rich in sericite (Extremely weathered meta-SILTSTONE)
H A2	06509	Yuen Long	15.0 – 30.0m (15.0 m)	Medium dense, pale grey, yellowish green SILT, pyrite on core, relict joints, dip 10Y and 50Y with limonite staining (Extremely weathered SILTSTONE)
BH1	11533	Yuen Long	17.0 – 37.1m (20.1 m)	Soft, reddish pink, striped light grey and white, clayey silt (CW META-SILTSTONE)
PS9	10976	Yuen Long	04.0 – 29.0m (25.0 m)	Firm to stiff, white and greyish brown clayey SILT with cobbles and gravel (C.D. VOLCANIC)
DH189	12881	Tin Shui Wai	11.5 – 41.5m (30.0 m)	Dense to very dense, yellowish brown, brown-grey SILT rich in sericite (Extremely weathered meta-SILTSTONE)
BH12	12433	Yuen Long	5.0 – 45.7m (40.7 m)	Very stiff, dark grey, with limonite stained relict joints, SILT (Completely Decomposed Siliceous SILTSTONE)
BH15	13299	Tin Shui Wai	13.0 – 62.0m (49.0 m)	Extremely weak, moist, dark brown, completely decomposed, fine-grained META-SILTSTONE (Dense, clayey, sandy silt with much coarse gravel of quartz)
DH BD47	10406	Yuen Long	11.7 – 62.2m (50.5 m)	C.D. BASALT. Dense to very dense, greenish brown, silty fine sand with relict texture preserved
DH L4/D7	16050	Tin Shui Wai	18.0 – 101.0m (83.0 m)	Brown silt CD META-SILTSTONE
DH H31	11256	Tin Shui Wai	09.5 – 110.0m (100.5 m)	Medium dense, yellowish brown to light grey, mottled pink, sandy silt with gravel CW SILTSTONE
DH21	12950	Tin Shui Wai	18.0 – 148.3m (130.3 m)	Extremely weak, greyish brown, completely decomposed, fine-grained META-SILTSTONE (Firm, fine, sandy SILT with occasional gravel of quartz in some samples)

Table 2 - Bedrock geology, weathered and superficial mantle parameters, and corestone data for boreholes in the Yuen Long study area.

BEDROCK LITHOLOGY	W' FRONT MIN'	(mPD) MAX'	MANTLE THICKNESS MIN'	MAX	SUPERFICIALS MIN	MAX'	BOREHOLES #	COREST'	PERC'
GRANITIC									
COARSE-GRAINED (Gc)	-051.4	+276.3	000.0m	039.9m	000.0m	027.7m	074	009	012%
GRANODIORITE	-089.5	- 012.9	006.6m	078.0m	000.0m	016.3m	047	006	013%
MEDIUM-GRAINED (Gm)	-035.5	+193.2	000.0m	033.3m	000.0m	017.8m	023	003	013%
FINE-GRAINED (Gf)	-029.4	+009.7	000.9m	025.8m	000.0m	011.6m	012	000	000%
MEDIUM-COARSE (Gmc)	-036.6	+165.6	000.0m	025.3m	000.0m	07.5m	010	000	000%
FINE TO MEDIUM (Gfm)	-036.5	+194.1	002.4m	031.5m	000.0m	013.5m	006	000	000%
GRANITE	-013.7	+017.5	000.0m	009.7m	003.0m	023.7m	003	000	000%
PORPHYRY	-019.9	- 019.9	013.8m	013.8m	007.9m	007.9m	001	000	000%
SUMMARY	-089.5	+276.3	000.0m	078.0m	000.0m	027.7m	176	018	010%
VOLCANIC									
VOLCANIC	-055.6	-008.9	006.4m	048.6m	005.5m	017.5m	028	002	007%
TUFF	-031.0	+008.3	009.4m	079.8m	000.0m	013.9m	028	001	004%
JTU	-081.1	+152.3	006.9m	070.2m	000.0m	019.5m	025	004	016%
TUFF BRECCIA	-052.1	+113.1	015.9m	043.7m	000.0m	010.2m	008	003	037%
SUMMARY	-081.1	+152.3	006.4m	079.8m	000.0m	019.5m	089	010	011%
METAMORPHIC									
MARBLE	-142.3	-006.7	000.0m	130.3m	000.0m	053.9m	507	146	029%
METASILTSTONE	-135.4	-010.6	000.0m	129.0m	000.0m	033.2m	793	176	022%
METASANDSTONE	-111.1	+066.7	000.0m	098.5m	000.0m	017.0m	200	050	025%
QUARTZITE	-090.0	-008.3	000.0m	065.3m	004.5m	026.5m	036	008	022%
METAMORPHIC	-028.5	-001.3	004.6m	027.9m	000.0m	018.5m	028	004	014%
METATUFF	-072.6	-019.9	012.6m	069.0m	003.2m	015.5m	020	003	015%
PHYLLITE	-061.9	-010.3	000.2m	050.4m	000.0m	015.0m	010	001	010%
LOK MA CHAU Fm (Cmp)	-065.1	-004.7	004.4m	059.0m	006.0m	012.0m	009	000	000%
METAVOLCANIC	-034.8	+104.0	011.0m	033.0m	000.0m	013.8m	008	000	000%
METACONGLOMERATE	-044.8	-044.8	044.9m	044.9m	002.5m	002.5m	001	000	000%
FAULT BRECCIA	-070.3	-070.3	058.7m	058.7m	013.0m	013.0m	001	001	100%
SUMMARY	-142.3	+104.0	000.0m	130.3m	000.0m	053.9m	1613	389	024%
MINOR INTRUSIVE									
BASALT	-053.2	-025.5	018.5m	046.4m	004.5m	014.5m	007	004	057%

A thick weathered mantle occurs over the Yuen Long Formation marble, and over the metasiltstones and metasandstones of the Lok Ma Chau Formation. Given that marble will tend to dissolve and leave relatively little *in situ* weathered material (mostly the rare impurities contained therein), it is believed that the silty weathered mantle

mostly represents decay of the Lok Ma Chau Formation. Langford *et al.* (1989) noted that the Mai Po Member occurs in the study area. This consists of several hundred metres of metamorphosed siltstones, sandstones and graphite schists, a sequence that could generate the observed weathering profiles (Table 1).

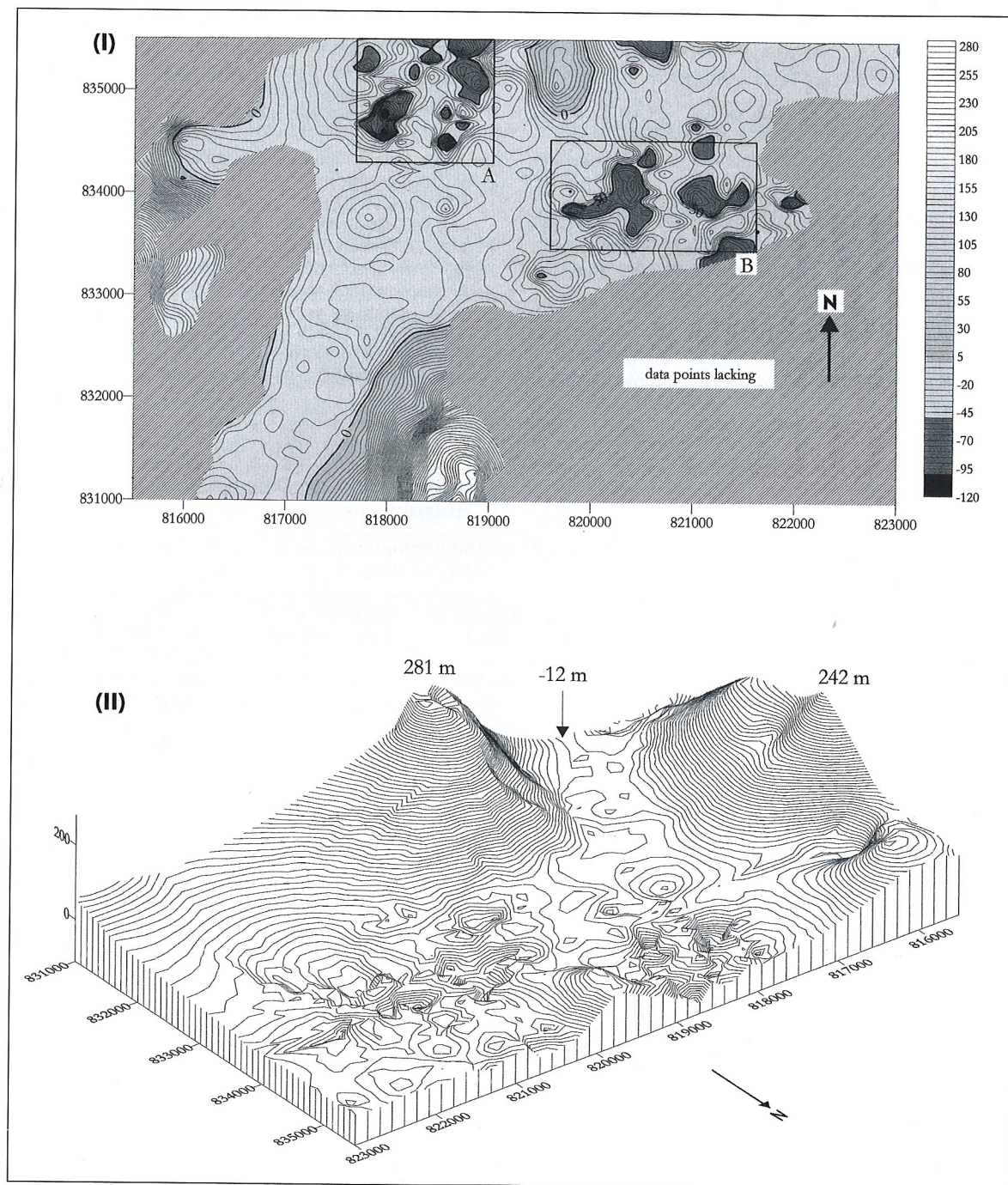


Figure 5 - Height (5 m intervals) of the weathering front (rock head) in the Yuen Long study area. (I) - contour map showing the hummocky, undulating surface. Study areas "A" and "B" also shown; (II) - isometric view of the same area from the northeast (Tuen Mun Valley at top right). Note that the apparently greater frequency of depressions in areas A and B reflect higher borehole densities, and therefore more detailed contouring.

The weathering front

A total of 1,895 boreholes reached bedrock, and further 754 terminated within the weathered profile, providing minimum values for the depth to the weathering front. The data were used to compile contour and isometric maps of the weathering front at 5 metre contour intervals (Figure 5).

Unweathered bedrock reaches an altitudinal maximum of 280 mPD on granite, in the southern part of the study area. The lowest weathering depth was -142 mPD in Area A (818054E, 834553N), over marble and below 130 m of weathered rock and a cover of 18 m of superficial deposits and fill materials. The weathering front has a total altitudinal range of 272 metres in the study area.

The weathering front topography contrasts strongly with that of the surface topography. The latter is a relatively smooth planar surface (Figure 2) bounded by concave slopes rising to the upland areas, whereas the former is characterised by basins and domes, many arranged in linear groups (Figure 6). Broad depressions appear on the contour plots in areas with a low borehole density. Areas A and B, with dense borehole concentrations, show greater detail and a more complex pattern of domes and basins. The margins of these basins are usually steep (Figure 6). Since contouring will smooth out height differences in topography between points (Figure 7), many of these basin edges may actually be near-vertical.

The Tuen Mun Valley follows a NNE-trend, which is broadly reflected in the bedrock topography. At the largest scales, the bedrock contours shows both NNE- and NE-trends, whereas at intermediate scales, these orientations are not as clear. However, where borehole concentrations are high, pronounced northeasterly patterns are apparent (Figure 6), with a less distinct northwesterly orientation also occurring. These trends reflect the dominant fault orientations in the region.

The weathered profile

The average weathering profile thickness (based on all boreholes) is 30.4 metres. Average thickness over volcanic rock is 25.9 m (median = 21.6 m), which compares with 9.7 m (median = 13.4 m) for granite and 32.8 m (median = 25.1 m) for metasediments (Figure 4). Granites tend to form high ground in the study area. However, the overlying weathered material is generally thinner than elsewhere, possibly due to either higher erosion rates at these upland sites, or because of a relatively greater resistance to weathering of the granite itself.

Weathered profiles range in thickness from

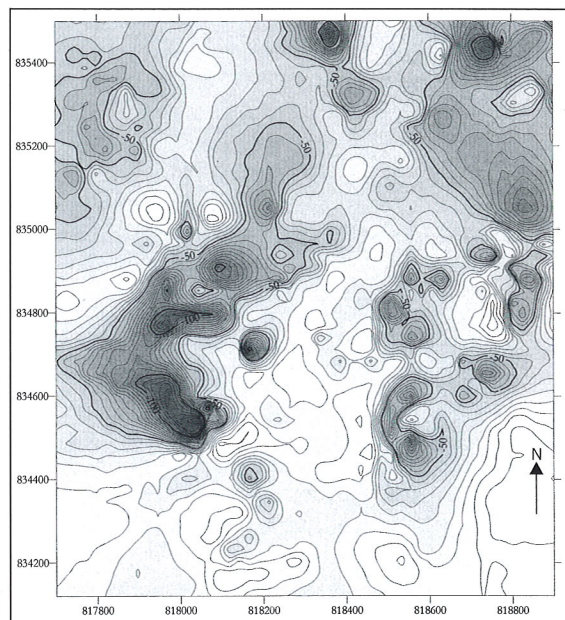


Figure 6 - Detailed weathering front topography in Area A, showing northeasterly aligned domes and basins.

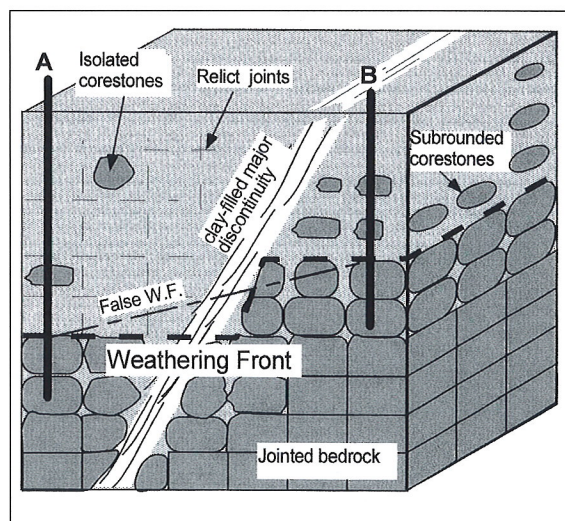


Figure 7 - Weathering front morphology in granitic rocks (after Shaw, 1997) and borehole density. Weathering front morphology is often closely controlled by joints, bedding, foliation and/or faulting giving rise to a stepped and irregular surface. Borehole spacing is critical to the accurate representation of this surface. Note how the average slope between boreholes A and B produce a false apparent surface that is much more gentle than the true topography. Where borehole density varies across a map this will result in apparent changes in contour spacings, as seen in Figure 5 (compare areas A and B with the rest of the map).

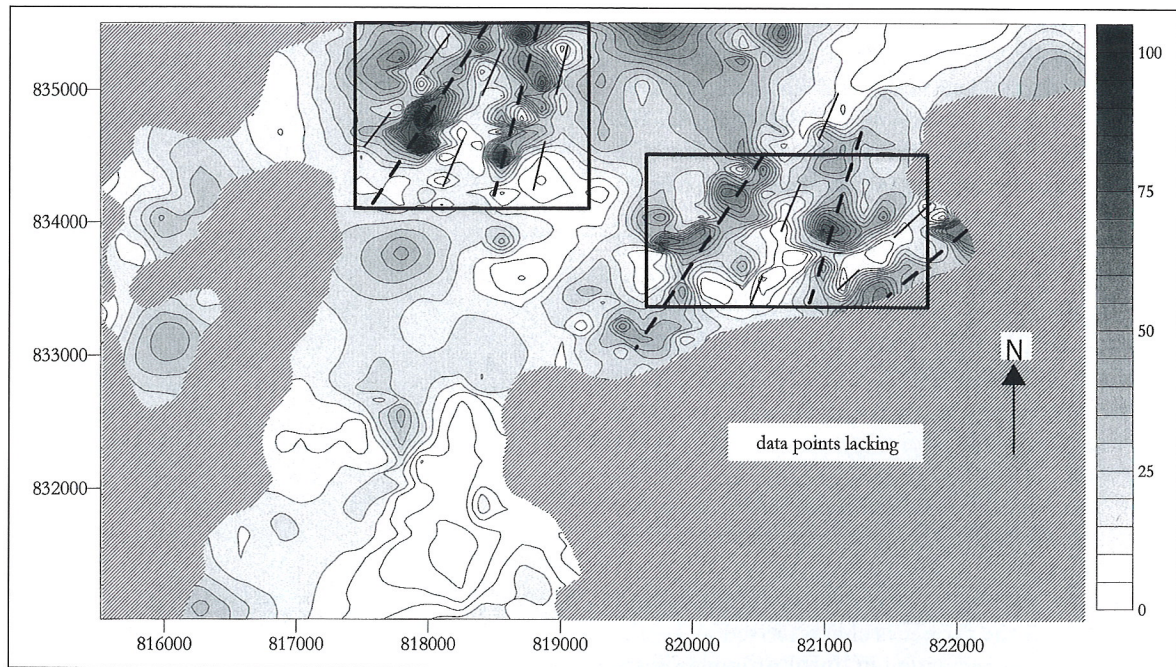


Figure 8 - Weathered mantle isopachs for the Yuen Long area. Note the two areas of apparently greater complexity in the northern part of the study area. These are locations where there are particularly dense concentrations of boreholes that pick out greater detail for the weathered mantle. Note the strong NNE- to NE-trending alignments of the thickest weathered material (heavy dashed lines) that alternate with thinner profiles (thin long dashed lines).

zero to a maximum of about 130 m (Table 2). The thickest profiles occur over metamorphic rocks (Table 2), along the Tuen Mun Valley axis, and in the low-lying northern part of the study area (Figure 8). The thickest weathered mantle occurs in the northeasterly aligned bedrock basins. The thinnest profiles tend to occur on bedrock ridges between these aligned basins, and on the granitic and volcanic lithologies towards the margins of the study area.

Corestone distribution

Weathered profiles over granitic and coarse-grained volcanic lithologies characteristically contain corestones (Figure 7), rounded to subrounded blocks of relatively unweathered rock up to several metres in diameter. True corestones are rare in finer grained volcanic rocks and similar lithologies. Corestones were encountered in only 421 (22%) of the boreholes in the study area. Variations with lithology are evident. On average, 10% of boreholes over granitic rocks contained corestones (Table 1), with a similar percentage (11%) occurring in boreholes over volcanic lithologies.

The pattern changes dramatically to 24% over metamorphic bedrock. However, it should be noted that the corestone definition is based on occurrences of Grades I to III rock material (relatively fresh rock) that are separated from each other, and from the weathering front, by at least 1 metre of weathered rock. It is therefore possible that the 1 m or more of weathered

material that the boreholes passed through simply represents widening of bedding planes, foliations, or the differential weathering of less resistant interbeds. Consequently, this weathering phenomenon is probably different from true corestone development. However, this characteristic has important engineering implications as false bedrock, like corestones, can give rise to problems during site investigation and development.

Figure 9 illustrates the spatial distribution of corestones, or false bedrock, in the Yuen Long area related to the weathering front topography. Although corestones, or widened discontinuities, are widespread across the study area, they lack any clearly discernible distribution patterns at the scales being considered here. There is also no apparent correlation with the thickness of the weathering profile.

Superficial deposits

An isopach map of the superficial deposits in the study area is shown in Figure 10. In general, thick alluvium covers much of the surface of the Yuen Long Plain, with colluvium mantling valley sides and extending as lobes onto low lying areas. Coarse debris flow deposits (Frost, 1992) have been recorded near the base of many superficial sequences. Marine deposits occur in the north the study area.

Thicknesses range from zero to over 53 metres, with the thickest deposits being concentrated along two axes, one northerly and the other northeasterly trending.

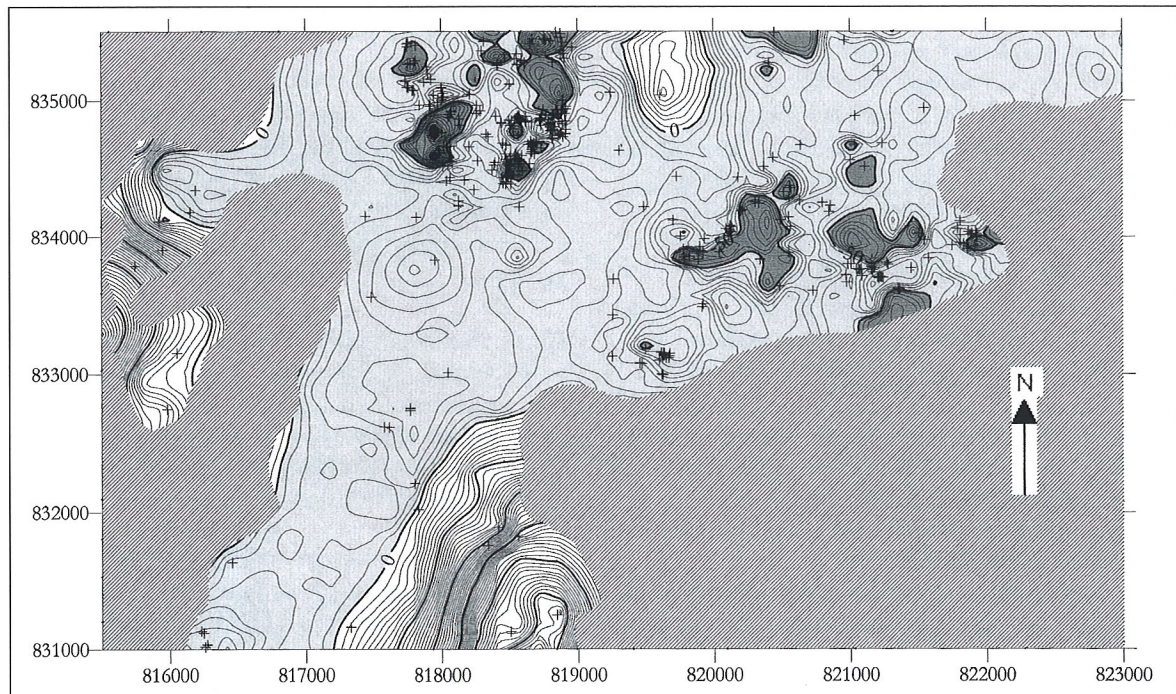


Figure 9 - Corestone locations superimposed on the weathering front topography. Darker shades are low-lying areas, with lighter colours representing highs. No clear corestone distribution pattern is discernible. The high concentrations in the northern part of the map reflect greater concentrations of boreholes.

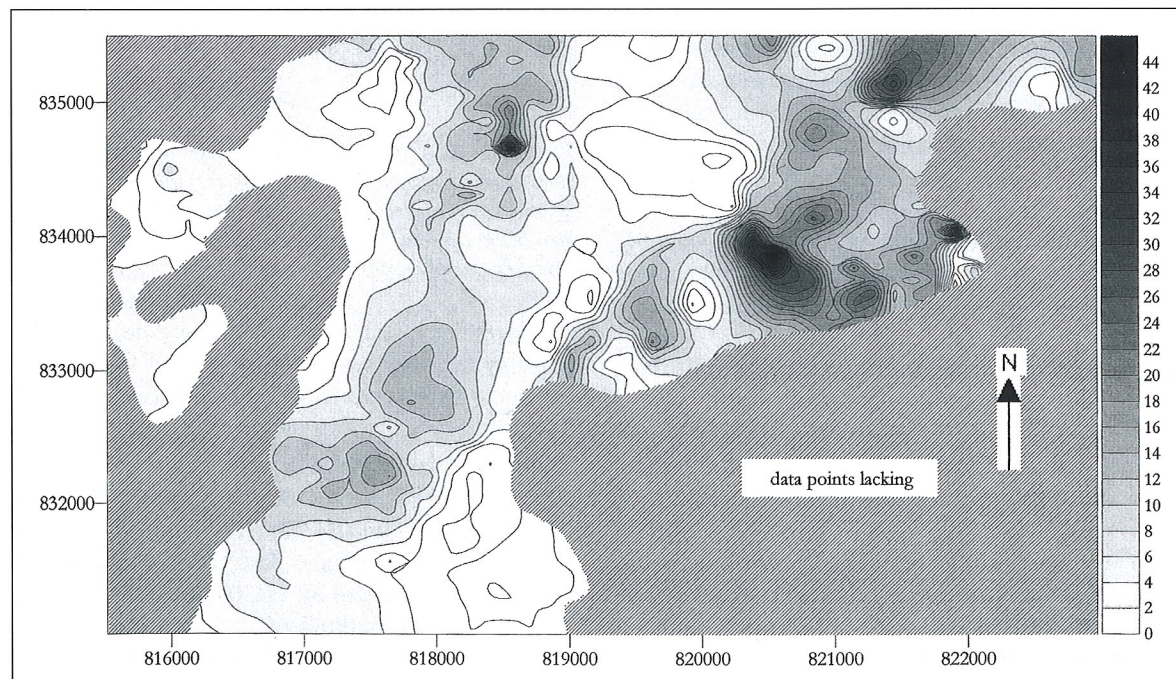


Figure 10 - Isopachs of superficial sediments in the study area. Thick deposits occur in low lying areas forming two major lineaments. One northerly and the other northeasterly. Note that the variations in detail reflect borehole concentrations. Greyscale column at right shows superficial deposit thickness in metres.

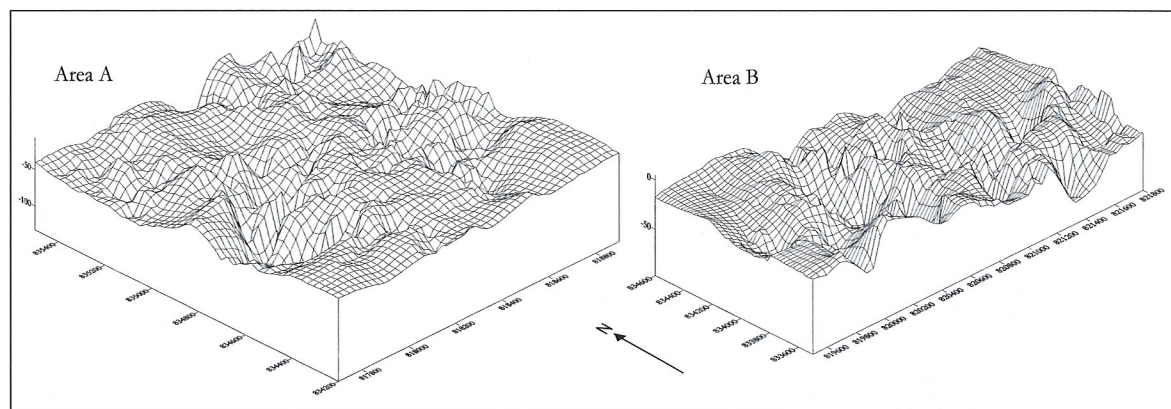


Figure 11 - Detailed isometric views for Areas A and B (see Figure 3 for location). Both block diagrams are viewed from the southwest. Note the basin and dome morphology. In reality, it is likely that the slopes between domes and basins are much steeper in many places (see Figure 8).

Summary and conclusions

The thickness of the weathered profiles and the topography of the weathering front are important characteristics that must be accurately mapped as part of site investigations prior to construction. An understanding of regional weathering patterns is of great value at the early planning stages.

This investigation demonstrates that weathering thickness and the bedrock topography are highly variable at both small and large scales. Nevertheless several general observations can be made:

1. The weathered mantle is thicker over metamorphic rocks and below valley floors. The former observation probably involves *in situ* weathering of the metasiltstones and metasandstones of the Lok Ma Chau Formation rather than the marbles of the Yuen Long Formation (Table 1).
2. The weathering front has a very irregular topography, when viewed on a variety of scales. In detail it consists of a series of aligned basins and domes (Figure 11).
3. The rockhead basin lows are infilled with thick weathering profiles and superficial sequences.
4. Thick deposits of alluvium and underlying debris flows occur and extend over central parts of the plain.
5. Where high concentrations of boreholes allow detailed studies, the basins and domes appear to be aligned along NNE and NE lineaments. A weaker NW trend may also be present. These trends broadly match the regional fault patterns in the Yuen Long area (Figure 12).
5. Faulting exerts an important influence on weathering, creating bedrock lows.

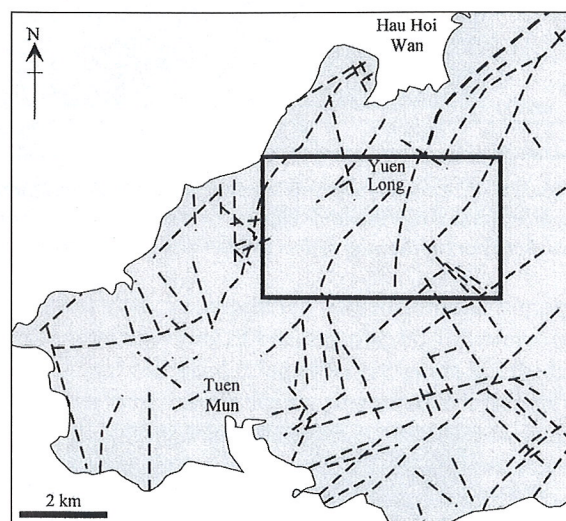


Figure 12 - Simplified fault patterns in the western New Territories show dominant northeasterly and north-northeasterly alignments, with northwesterly orientations also being present. Study area shown in the box. Map modified after Langford et al., 1989.

6. Corestone distributions do not show clear patterns, probably because they are controlled by local factors below the resolution attainable by the borehole data.

Acknowledgements

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Sedimentary Facies of Fluvial Marine Transition Environments at Pak Nai

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Abstract

This paper looks into modern brackish deposits. Pak Nai in the west of Hong Kong is situated on an estuarine tidal stretch where freshwater and salt water meet. The study concluded that there are a variety of depositional interfaces in the area, such as seasonal swamps, mudflats, sandy beaches, sand dunes and river shoals and that the number and variety of foraminifera in the area are relatively small. *Haplophragmoides shenzzhensis*, a kind of textularia, was the major species in the area. Results of particle size analysis, microfossil and chemical composition studies of the deposits suggest that they reflect the characteristics of the depositional interfaces, and can be used to analyse Quaternary depositional environments.

摘要

本文主要研究近代鹹淡水交界的沉積物。位於香港西面的白泥處於鹹淡水交界的河口潮汐漲退帶。研究結果發現該地區有各色各樣的沉積面如季節性沼湖，泥灘，沙灘，沙丘和河灘；並發現該地區有孔蟲的品種和數量比較少。串珠蟲類的深圳擬單樣蟲為此區之主要品種。從沉積物的粒徑，微生物和化學成份的研究結果可反映各沉積面的特徵，有助分析第四紀的沉積環境

Introduction

Deltas encompass a transition from fluvial to marine settings and are associated with many subenvironments of deposition, such as sand bars, pebble and cobble bars, tidal flats, lagoons, littoral zones, spits and beach ridges. Three commonly recognised delta types are: fluvial-dominated, wave-dominated and tide-dominated, each of which are associated with a distinct set of sedimentary facies. Fluvial-dominated deltas are variously associated with mouth bar sands, overbank muds, marsh sediments, crevasse splays, and locally, alluvial fan deposits. Pebble and cobble sands and gravels are common. Wave-dominated deltas are associated with facies formed in mouth bars, beach ridges, spits and linear

sand bodies. Tide-dominated deltas are particularly associated with tidal flat muds, fine-grained sediment and well sorted sands (Walker, 1984). This study attempts to characterise several distinct deltaic facies in terms of grain-size, sediment color, organic matter, sediment pH and salinity, CaCO_3 , and foraminifera content.

Foraminifera live in habitats ranging from shallow coastal to deep sea settings and are often used as marine environmental indicators. In this research, particular emphasis was placed on benthic sediment foraminifera as they are relatively easy to collect and their tests reflect their growth environment. There are three suborders of foraminifera present in the sediments

sampled; *Textulariina* (agglutinated tests), *Miliolina* (porcelaneous tests) and *Rotaliina* (hyaline tests). Several factors control the distribution of foraminifera, including: water salinity, CaCO_3 in solution, temperature, pH and particle size. For example, a low salinity (brackish) environment favors a low diversity assemblage of agglutinated foraminifera. Silty and muddy sediments tend to support large foraminifer populations. Individual species are often adapted to a certain range of temperature, CaCO_3 , oxygen and pH conditions. (Brasier, 1980).

Locally, Sun (1991) suggested that pH is a controlling factor causing differences in the benthic foraminifer species composition in the Shenzhen Bay and Xincun Harbor. Li (1988) found that water depth, salinity, temperature, pH value and the nature of bottom sediment control the distribution pattern of agglutinated foraminifers in the Zhujiang River Estuary.

Methodology

Samples were collected along five transect lines at Pak Nai (Figure 1), within the intertidal zone. Surface and core samples were obtained at 10 m and 50 m intervals, respectively, along each transect. About 2

kg of sediment was collected at each surficial-sediment sampling site. The cores ranged between 60 and 100 cm and were recovered using plastic cylinders driven into the sediments.

Field measurement and mapping were also carried out in order to record facies distribution. During the laboratory phase of work, the grain size distribution, pH value, CaCO_3 , moisture, and organic matter content was determined.

Samples for foraminifera studies were washed through a $63\mu\text{m}$ sieve and dried. Heavy liquid (Sodium polytungstate) was used to separate foraminifera from sediment with a density of 1.4 g cm^{-3} . The samples were then placed under a binocular microscope and individual foraminifera were picked out using a very fine brush. Finally, a scanning electronic microscope was used to obtain images of the foraminifera. The detailed procedures of the separation technique are given by Anderson *et al.* (1995).

Environmental and Geological Setting

The delta at Pak Nai is located on the margin of Deep Bay, which lies in the western part of Hong Kong (Figure 1). Deep Bay is a sheltered shallow marine

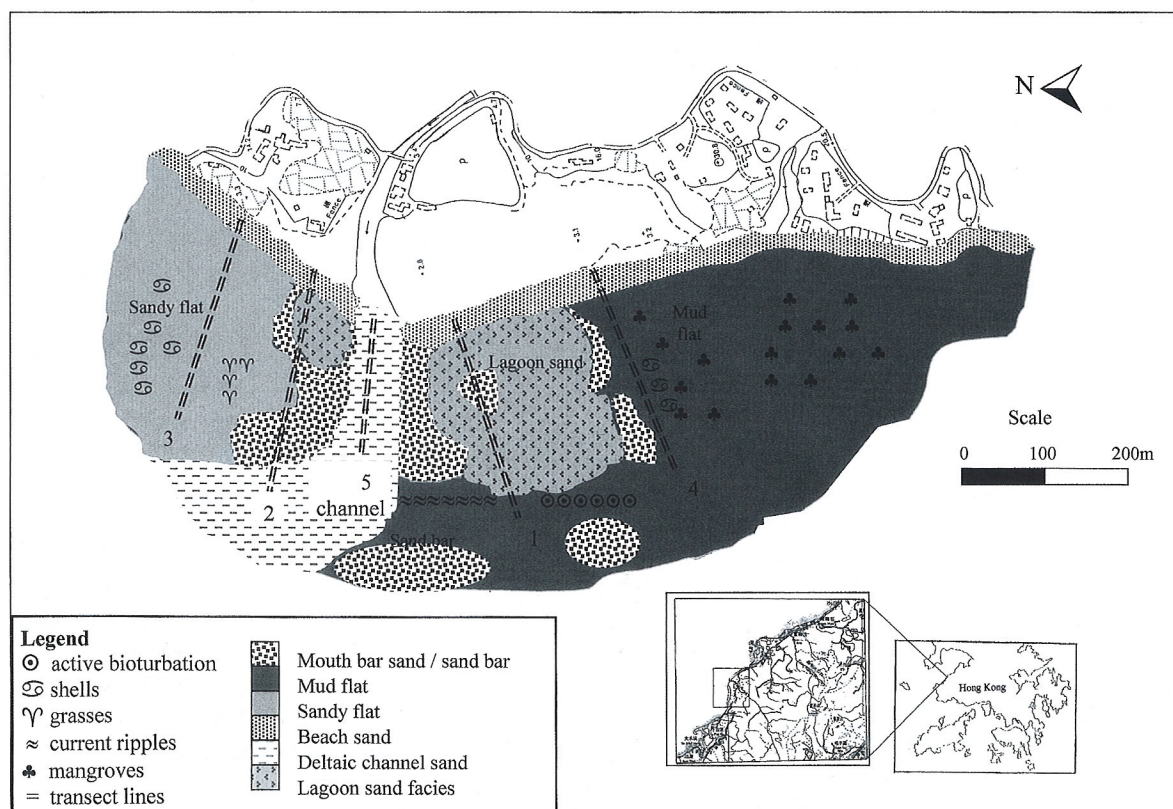


Figure 1 - Geomorphic sketch map of the Pak Nai Delta and location of the study site. The map shows major subenvironments and the position of transect lines noted in the text.

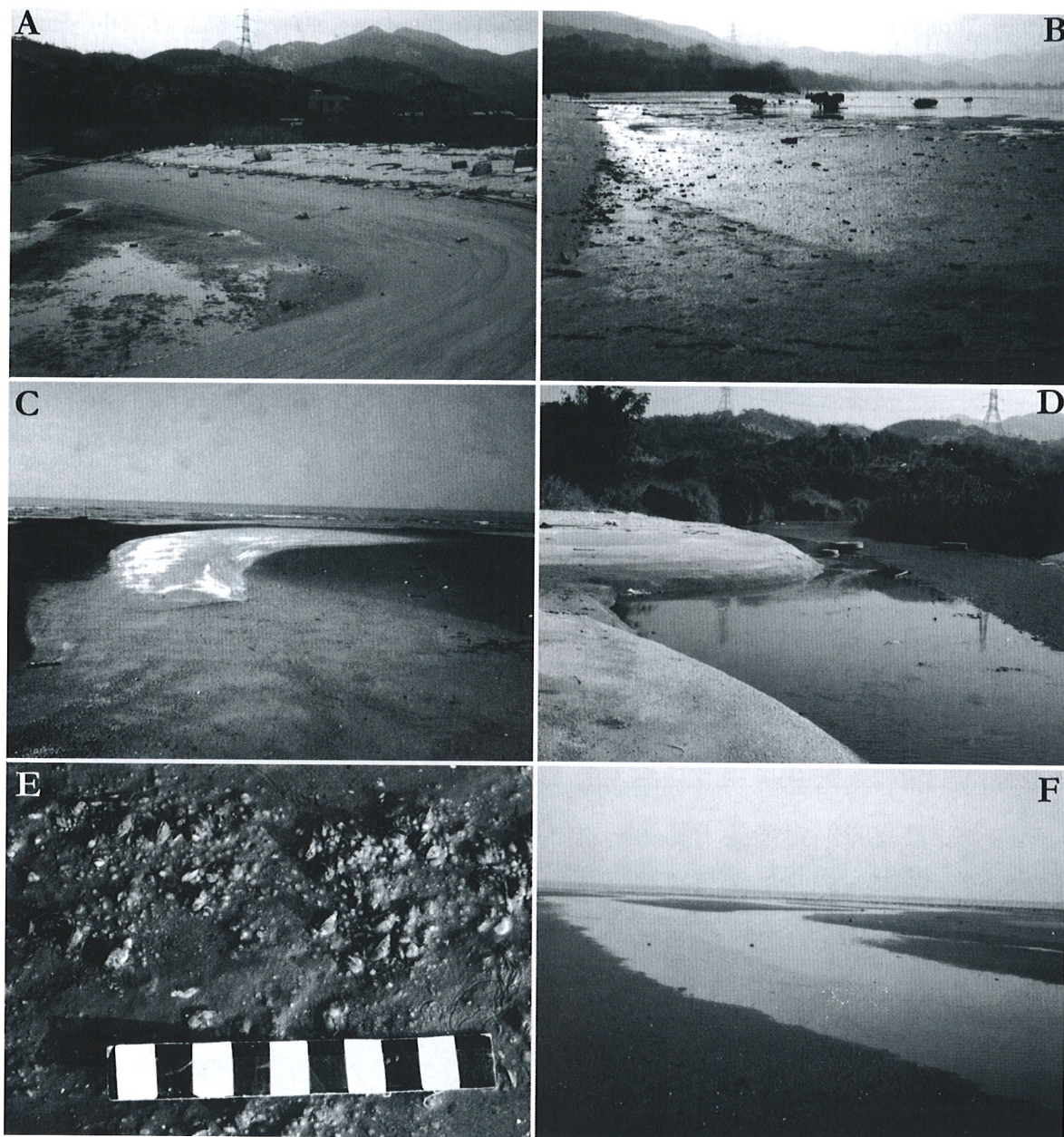


Plate 1 - Subenvironments and facies present on the Pak Nai Delta. A: the flat-lying floor of a lagoon, between a beach and sand bar, shows the lagoon sand facies; B: a mudflat on the southern part of the delta; C: a typical sand bar (62 m long, 12 m wide); D: a sand bar near the river mouth of the Pak Nai Delta; E: a detail of the sandy flat present on the northern delta (note the small bivalves); F: the main channel of the Pak Nai River.

environment (<5 m) with brackish water. The Pearl River, the Shenzhen River, and several small channels from the Gone Shan continuously supply sediment and fresh water to the bay. The climate of the area is wet in summer and dry in winter. During the dry season (October-March) of 1989-1990, the catchment area of the Pak Nai Delta received 211 mm of rainfall. In contrast, in the wet season (April to September), the average rainfall reached a high of 1,340 mm.

The total catchment area of the Pak Nai Delta is about 4,000 m² and is dominated by intrusive igneous rocks (Arthurton *et al.*, 1988). These consist principally

of fine to medium-grained granite, medium-grained granite and aplite. Superficial deposits consist mainly of Holocene well-sorted alluvial clay, silt, sand and gravel, as well as very poorly sorted debris flow materials. Pleistocene terraced alluvium occurs locally and is comprised of well-sorted to semi-sorted clay or silt and gravelly sand. Coastal deposits include beach and marine silty sand.

Results

Several subenvironments and facies occur in the fluvial-marine transition zone of the Pak Nai Delta (Figure 1; Plate 1). These include: lagoons, sandy

flats, mud flats, beaches, deltaic channels, mouth bars and sand bars. The facies types present in each of these environments, and their characteristic foraminifera, are described below.

1. Lagoon sand facies

The lagoon sand facies occurs in depressions between mouth bars and beaches (Plate 1A) on the Pak Nai Delta. The sediments are dark gray and contain abundant organic material. Granules (20-45%) and sands (50-70%) dominate. The mean grain size ranges between coarse and very coarse sand ($\phi 0.22$ to $\phi 0.23$). The sediment sorting is generally poor (1.68), with fine to very fine skewness values ($sk=0.14$ to 0.70) and platykurtic to mesokurtic (0.84 - 1.0) distributions. Sediment pH values are typically 7-7.5 with salinities

generally below $k=27$. Calcium carbonate content is $<2\%$.

Foraminifera (Plate 2) are abundant in the lagoon sand facies, with an average number of 35 forams/g. Figure 2 shows foraminifera data for Transect 1 on the Pak Nai Delta. *Haplophragmoides shenzhensis* and sp. are dominant. Other foraminifera present include: *Ammonia* sp., *Trochammina* sp., *Elphidium* sp., *Textulariina* sp., *Quinqueloculina* sp. and *Brizalina striatula*. Figure 3 shows data from a short core in lagoon sands. The highest abundance of foraminifera in the core occurs at 10-12 cm depth, where the average is 12/gram with *Haplophragmoides shenzhensis* heavily dominating the assemblage. Other foraminifera present in the core include *Trochammina* sp., *Ammobaculites* sp., *Textulariina* sp., *Ammonia* sp., and *Elphidium* sp..

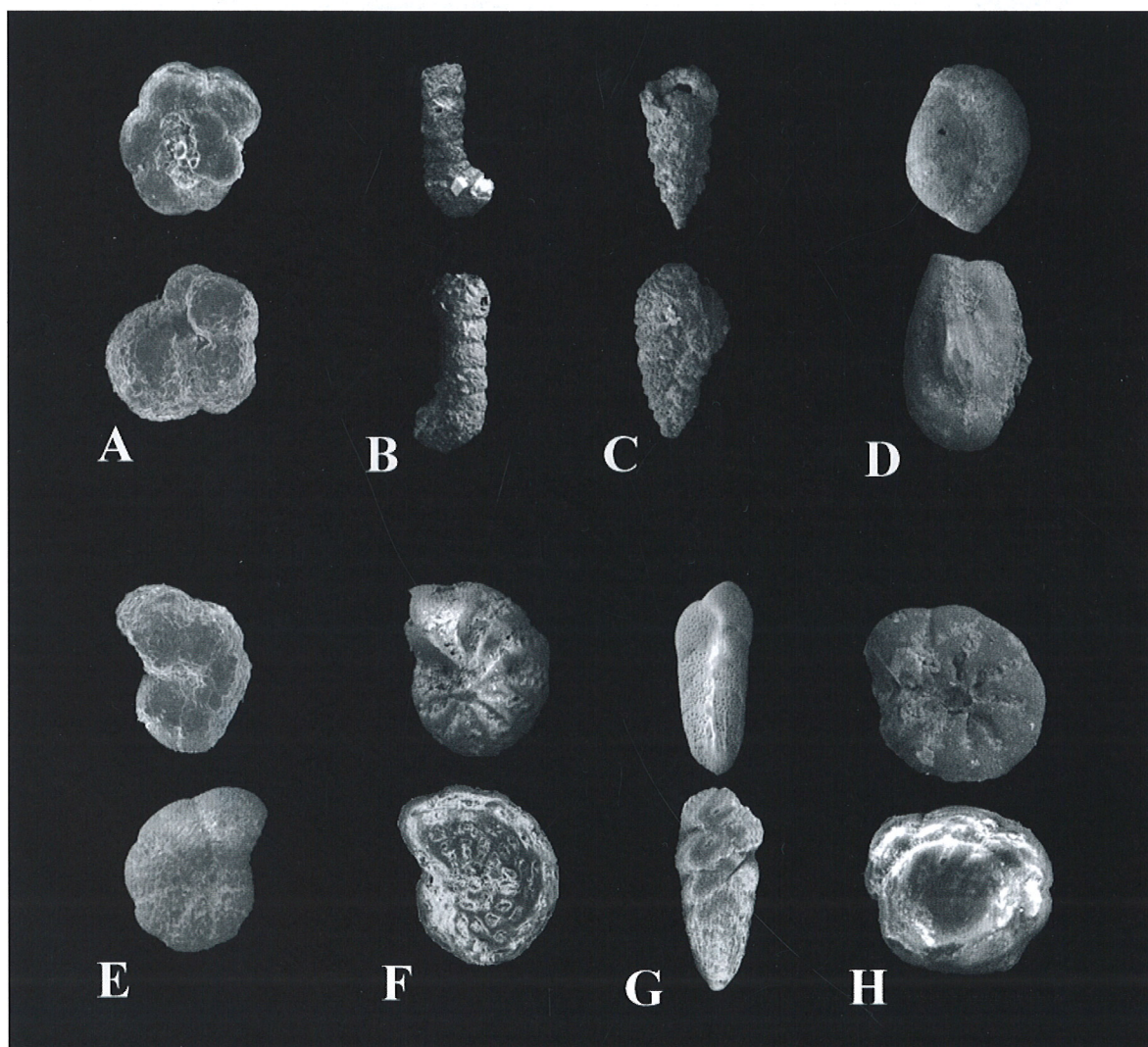


Plate 2-Scanning Electron Microscope images of common foraminifera in the coastal zones of the Pak Nai Delta. A: *Trochammina* sp.; B: *Ammobaculites* sp.; C: *Textularia* sp.; D: *Quinqueloculina* sp.; E: *Haplophragmoides shenzhensis*; F: *Elphidium* sp.; G: *Brizalina striatula*; H: *Ammonia* sp.

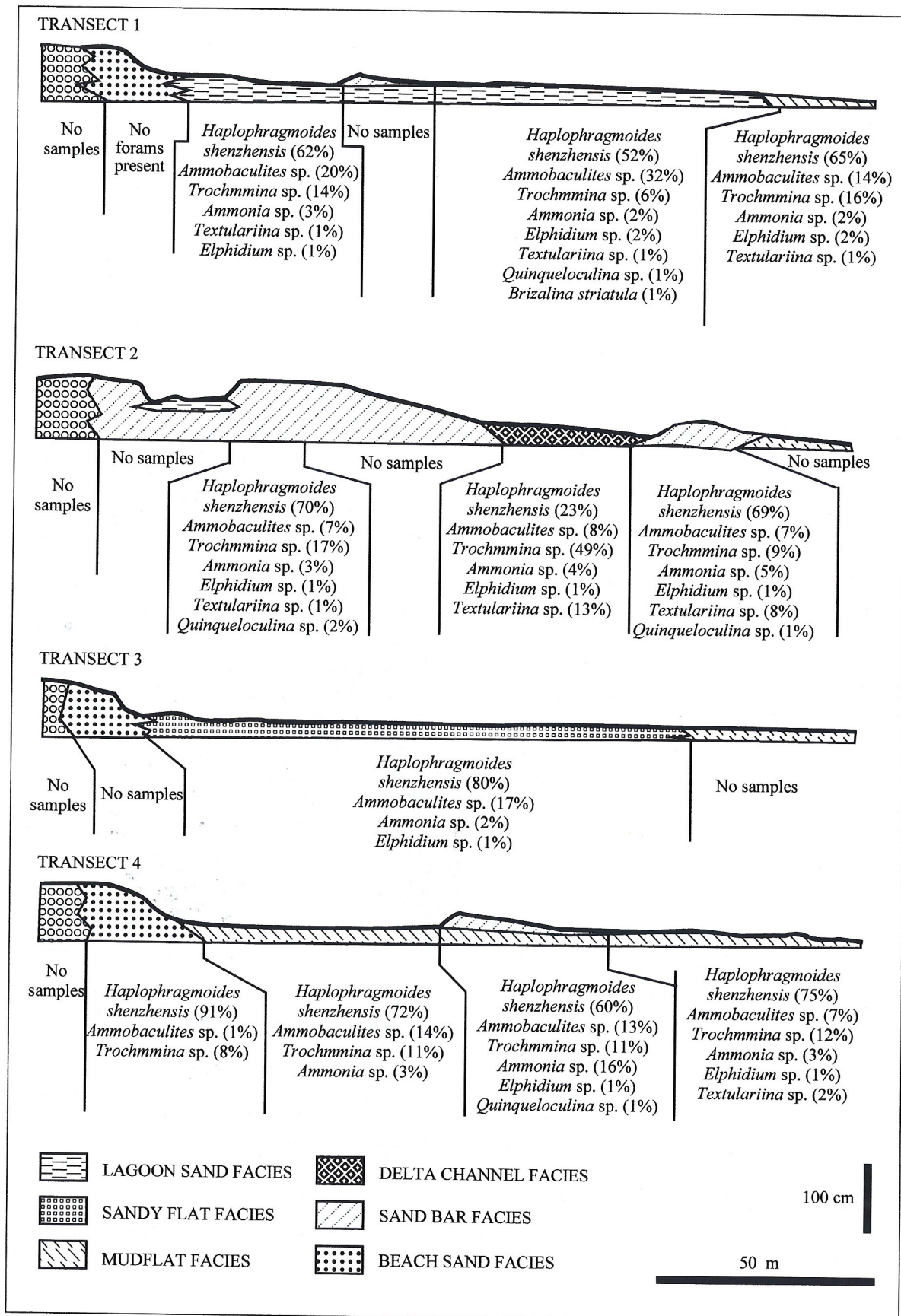


Figure 2 - Facies and foraminifera. Transects (Figure 1) show foraminifera content in selected facies along four transect lines.

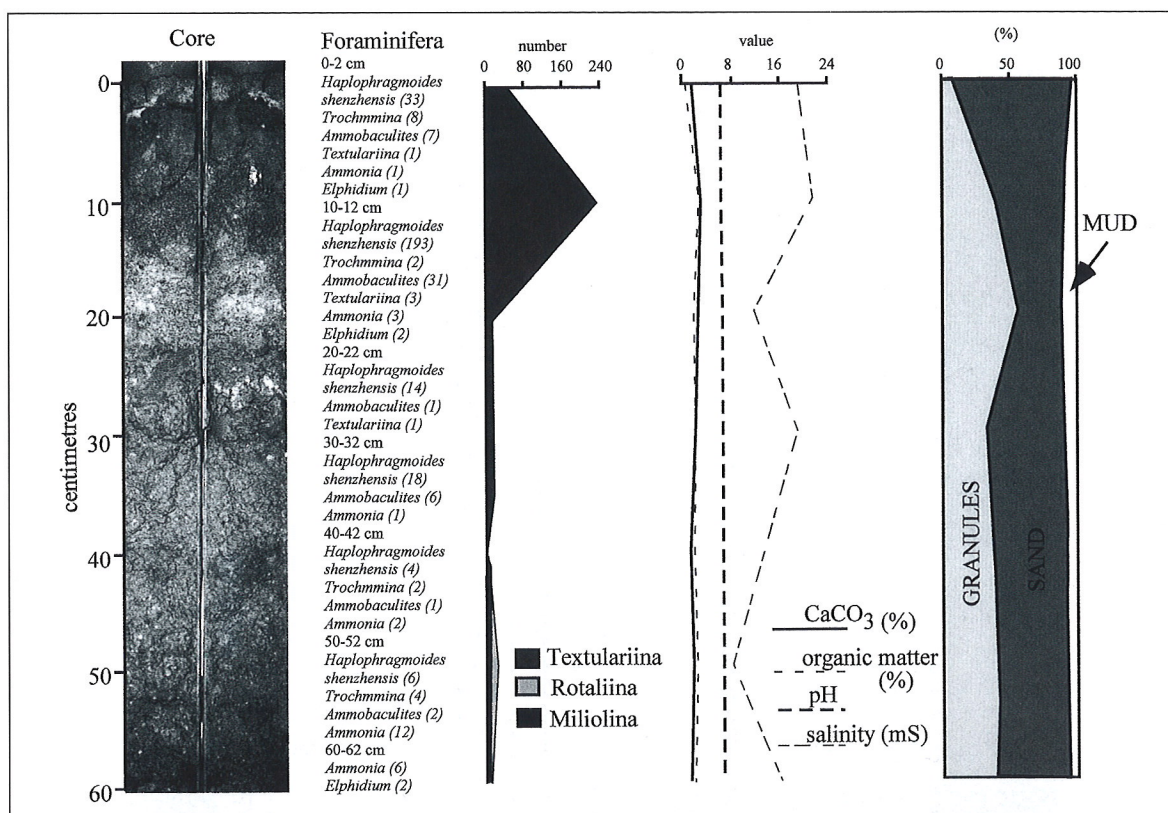


Figure 3—Core data for the lagoon sand facies. Foraminifera collected from 2 cm intervals, with numbers observed per gram shown in brackets. third column shows numbers of major groups per 20 g sample. Fourth column gives geochemical information, with grain size data

2. Sand bar facies

Two types of sand bars are recognised, reflecting geographic location and mode of formation. The first are “mouth bars”, which form where rivers enter the marine environment and dump their sand load. The second are mobile, asymmetric, sand bars that are distributed throughout the delta at Pak Nai. Transect 2 in Figure 2 shows two sand bars, together with their foraminiferal fauna. The left-hand sand accumulation is a mouth bar and the right-hand feature is a mobile sand bar.

The mouth bar sands occur on both sides of the river, are 40–60 m long and 50–100 cm high. Mobile sand bars vary in size with one large crescent-shaped example being 62 m long and 12 m wide. Sand content is high in all types of sand bars. Granule and mud contents are low. The mean grain size is mainly coarse sand ($\phi 0.03$ to $\phi 0.92$). Sorting is moderate (0.81–0.84), with the deposits showing a fine (0.18) to very fine skew (0.71). Distributions are mesokurtic and leptokurtic. The sediment pH values range between 6.9–7.3. Sediment salinity is low ($k=11$ –25), as are calcium carbonate and organic matter contents (1–2%).

Foraminifera abundance averaged 17 forams/g and is similar in both bar types. The most common species was *Haplophragmoides shenzhensis*.

Trochammina sp. and *Ammobaculites* sp. are also present. (Figure 2) together with *Textulariina* sp., *Ammonia* sp., *Elphidium* sp. and *Quinqueloculina* sp..

3. Sandy flat facies

The Sandy flat facies occurs in the northern part of the Pak Nai Delta (Transect 3 in Figure 3). The profile across the area is gentle and flat with well-compacted sediment. Some shells are found near the shore. Many locations have 60–75% sand. Granule contents are constant at 20–35%. Mud content increases seaward, from 2 to 9%. The mean grain size is coarse sand ($\phi 0.01$ to $\phi 0.86$). However, some landward locations are dominated by very coarse sand. Sorting is mainly poor (1.00–1.88), with grain size distributions showing a strong fine skew (0.38–0.71) and being leptokurtic to very leptokurtic (1.12–1.61). The pH values are mainly >7 , with salinity ranging between $k=20$ –30. Calcium carbonate is low ($<2\%$) and organic matter content ranges between 1–3%.

In a short core (Figure 4), foraminifera were most abundant at the top (6 forams/g), with numbers declining down the profile. *Haplophragmoides shenzhensis* dominates throughout. *Ammobaculites* sp., *Ammonia* sp., *Elphidium* sp., *Textulariina* sp.,

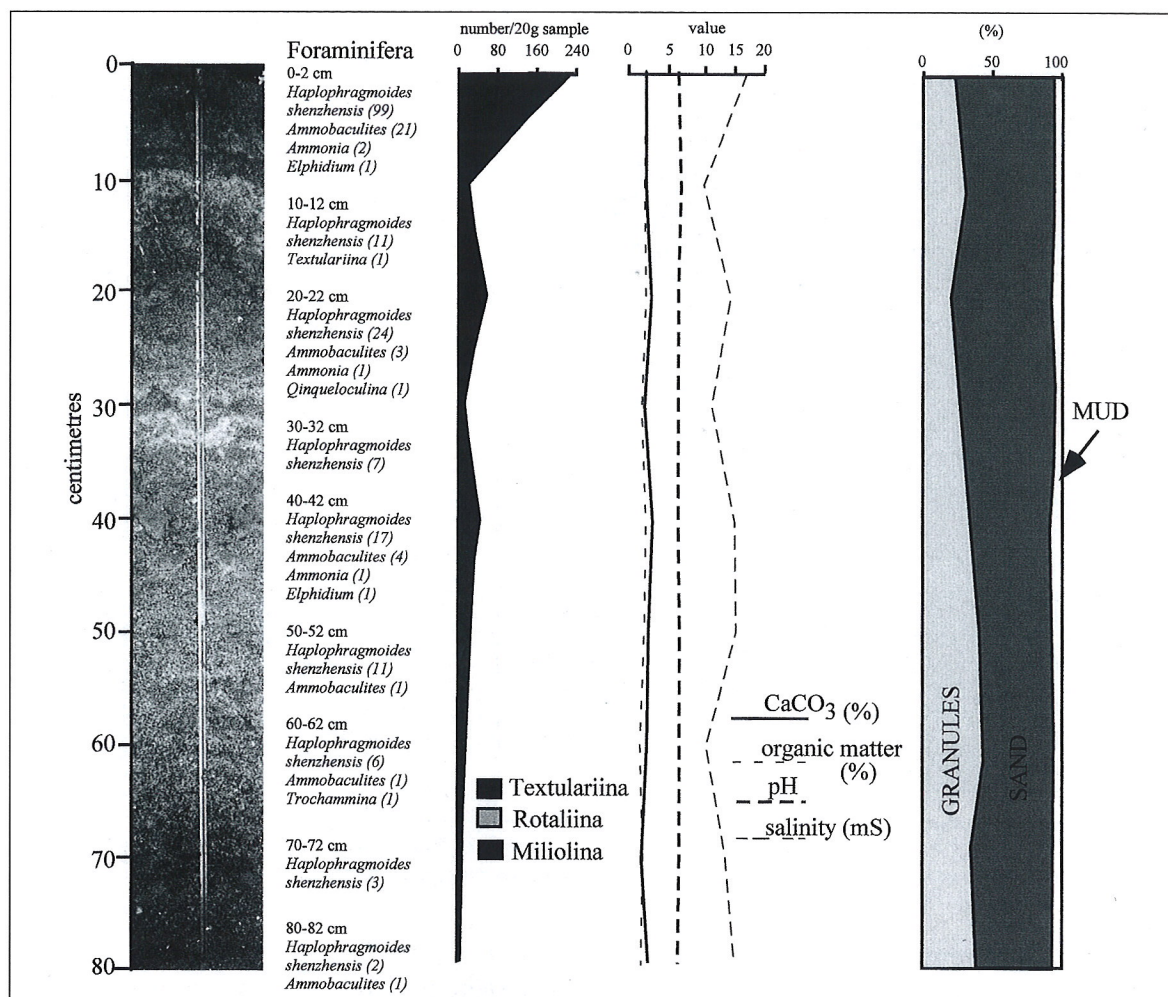


Figure 4—Core data for the sandy flat facies. Foraminifera collected from 2 cm intervals, with numbers observed per gram shown in brackets. third column shows numbers of major groups per 20 g sample. Fourth column gives geochemical information, with grain size data to the right.

Trochammina sp., and *Quinqueloculina* sp. are also present in the core. (Figure 4)

4. Mudflat facies

Extensive gently-sloping mudflats are found on the southern part of delta (Transect 4 in Figure 3) and as a marginal fringe at other locations. Sparse mangroves occur landwards, and the sediment is soft and black in color. The sediments contain a relatively high clay and silt content (9–18 %), with the mean grain size ranging from very fine sand (ϕ 3.31) to coarse sand (ϕ 0.47). Sorting is poor (1.70) to extremely poor (4.51), and the deposits range show strongly fine (0.69) to near symmetrical (–0.07) skewness values. Grain size distributions are platykurtic and leptokurtic. Sediment pH values are 7–7.7. Salinity is below 32. Calcium carbonate content is 1–3 % and organic matter content is relatively high (4%) (Figure 5).

Foraminifera are abundant in the mudflat facies, with an average of 20–24 forams/g. The dominant

foraminifer is *Haplophragmoides shenzhensis*. *Trochammina* sp., *Ammobaculites* sp., *Ammonia* sp., *Quinqueloculina* sp. and *Elphidium* sp. are also found (Figure 3). Foraminifer were most abundant at the top of the short core collected from this facies, with an average of 3 forams/g. (Figure 5) Abundance decreases downward. The most common species was again *Haplophragmoides shenzhensis*. *Ammobaculites* sp., *Trochammina* sp., and *Ammonia* sp. all occur in the core sediments.

5. Deltaic channel facies

The deltaic channel facies occurs along the major channel of the Pak Nai Delta. Sand content is high (65–98 %) and granule content is <33 %. Mud content is low (0–7 %). Grain sizes tend to be coarser than elsewhere, with mean values of ϕ –0.16 to ϕ –0.39. Sorting is moderate (0.71–0.82) to moderately good (0.58–0.67). Grain size distributions are finely skewed (0.35 to 0.54) and leptokurtic to very leptokurtic (1.12–

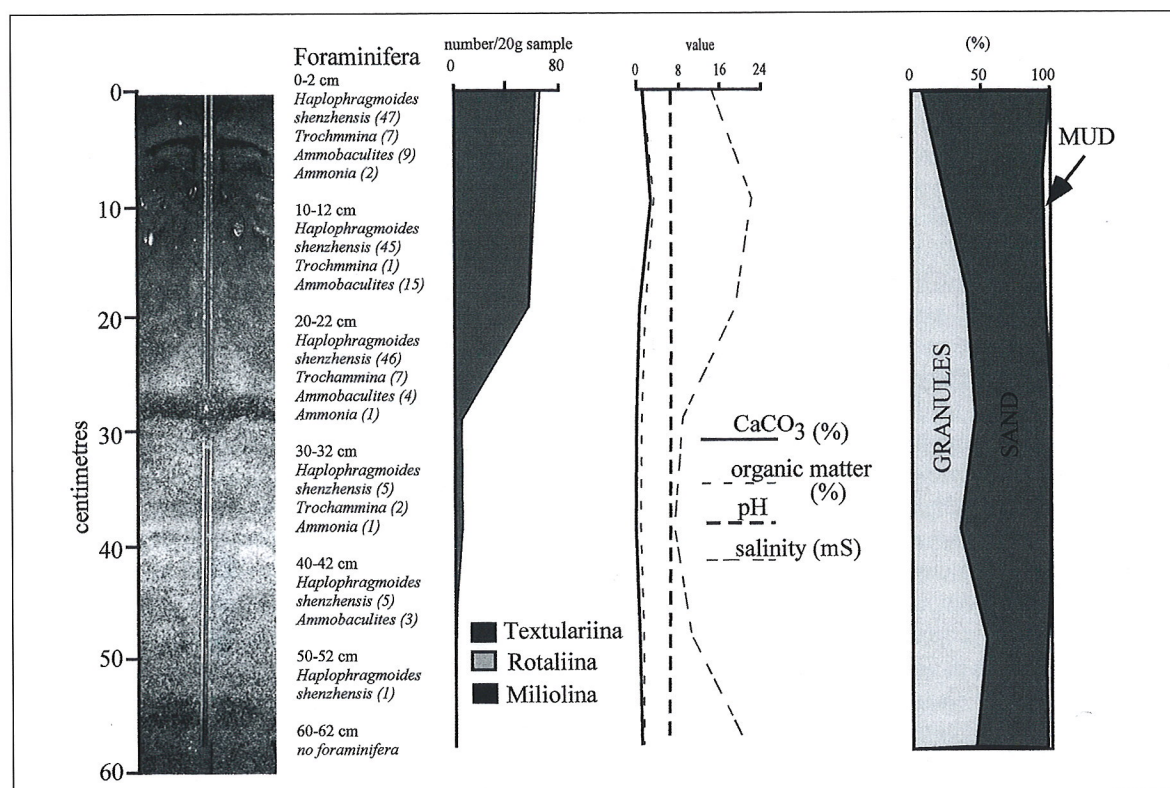


Figure 5 - Core data for the mudflat facies. Foraminifera collected from 2 cm intervals, with numbers observed per gram shown in brackets. third column shows numbers of major groups per 20 g sample. Fourth column gives geochemical information, with grain size data to the right.

1.83). Sediment pH values are 6.4-6.7, with sediment salinities below $k=28$. Calcium carbonate content is low (0.2-1 %), as is organic matter (1-2 %).

Foraminifera average 14 forams/g. (Figure) *Trochammina* sp. dominate. Other forams include *Haplophragmoides shenzhensis*. *Textulariina* sp., *Ammobaculites* sp., *Ammonia* sp., *Elphidium* sp. and *Quinqueloculina* sp..

6. Beach sand facies

The beach sand facies forms a linear deposit parallel to the shoreline (Transects 1, 3 and 4 in Figure 3). The light yellow beach sand facies has a high sand content (98 %), with minor granules (<2%) and mud (<1%). A few shells, mostly broken, are present. The median grain size is coarse to very fine sand (ϕ 0.31- ϕ 3.2). Sorting is moderate (0.75). Grain size distributions are finely to coarsely skewed and platykurtic to leptokurtic. The pH values are <7, with salinity low ($k=8-17$). Calcium carbonate and organic matter contents are also low (<2 %).

Foraminifera are absent or uncommon, averaging 2 forams/g (Figure 2). The most common species is *Haplophragmoides shenzhensis*. *Trochammina* sp. and *Ammobaculites* sp. also present.

Discussion

The data presented provide a model of modern sedimentary parameters (grain size, carbonate, organic matter, sediment pH and salinity) and foraminifera assemblages that should be of value for palaeoenvironmental studies of fluvial-marine transition situations. Sediment pH values range between 6-7. Sediment calcium carbonate content is 0-5%. Sediment salinity is $k=5-38$. Organic matter content is 0.3-4%. In general, lower sediment pH values, calcium carbonate and organic matter contents and salinity occur in the deltaic channel sand, sand bar and beach sand facies. Higher sediment pH values, salinity, calcium carbonate and organic matter contents occur in lagoon sand and mudflat facies.

The delta at Pak Nai is fluvial-dominated in summer and a tide- and wave-dominated in winter. During the summer season, 70-90% of sediment is comprised of granule and sand, which extends even over the mudflat and lagoon areas. Only the beach sand and deltaic channel facies can be identified. Heavy summer rain increases river discharge and coarse sediment load to the delta. In winter, as river discharge is reduced, a greater range of deposits can be identified including: lagoon sand, sand bar, sandy flat, and mudflat facies. This reflects a decreased fluvial load, and a relative increase in tidal and wave influences.

The low diversity and sparse foraminifera distribution is a characteristic of fluvial-marine transition environments. Eight species are identified: (Textulariina) *Haplophragmoides shenzhensis*, *Ammobaculites* sp., *Trochmina* sp. and *Textulariina* sp.; (Rotaliina) *Ammonia* sp., *Elphidium* sp. and *Brizalina striatula*; (Miliolina) *Quinqueloculina* sp. *Textulariina* (91-100%) dominate the foraminifera distribution at Pak Nai. The most abundant faunas are found in the lagoon sand facies (35 specimens/g). Foraminifera are also most diverse in the lagoon sand facies. In contrast, the lowest population abundance occurs in the beach sand facies.

The most common textulariina foraminifer at Pak Nai is *Haplophragmoides shenzhensis* (70-90%), which is also found in the Shenzhen River (Sun, 1991). *Haplophragmoides shenzhensis* is the most frequent foraminifer in each facies, except for deltaic channel sands. *Trochmina* sp. is the most dominant species in the latter facies type and is also common in the sand bar facies. Species of *Textulariina* sp., *Ammonia* sp., *Elphidium* sp. and *Quinqueloculina* sp. tend to be associated with higher sediment salinity and pH, reflecting a greater abundance in the seawards sediment samples. *Ammobaculites* sp. is relatively more common mudflat and lagoon sand facies.

The Shenzhen and Pearl Rivers are also probably influencing the growth, types and distribution of foraminifer at Pak Nai, through mixing as tides rise and fall and due to wave action reworking coastal sediments.

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A Quartz Porphyry Dyke; its Margin, and Hydrothermal Zoning at Peng Chau, near Lantau

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Abstract

On northeast Peng Chau Island, off the eastern coast of Lantau, a quartz porphyry dyke of earliest Cretaceous age intrudes Middle Jurassic granite. There is an increase in the size and percentage of the phenocrysts from the strongly chilled margin to the centre of the dyke. Shredded biotite near the dyke margin indicates that the last stages of movement were piston like. On a microscopic scale, at the margin slivers of fractured granite adjacent to the wall are separated from the rhyolite of the dyke by a thin zone containing granite dust fragments rimmed by feldspar collars forming globulites. The matrix was formerly glassy. Late stage hydrothermal fluids moved up this margin. Again on a microscopic scale, a sequence of albite epidote, epidote, actinolite, and iron ore was deposited. Flow continued until the exit in the very poorly permeable granite was sealed.

摘要

位於大嶼山東面的平洲，其西北角有一石英斑岩的岩脈，年化定為早白堊紀，入侵中侏羅紀的花崗岩中。岩脈中斑晶的大小和數量由冷卻邊緣向內部增加。在邊緣上發現有碎裂的黑雲母，顯示末期的運動是活塞的形式。從微觀的層次來說，圍岩和岩脈是被一很薄的岩體所分開。岩體中發現有極細的花崗岩碎片，其圍邊為長石。基質原本是玻璃質，後期有熱液流入此邊緣，生成一系列的礦物，包括有綠簾，陽起石和鐵礦。熱液的流動直至花崗岩的出口被封閉為止。

Introduction

Basic dykes have been much studied for over a century, but it is only recently that acid dykes have received much attention (Petford et. al., 1993; Petford and Koenders, 1998; Clemens and Petford, 1999). This paper concentrates on the anatomy of one such acid dyke and its margin, which is well exposed on the low cliffed coast of northeast Peng Chau Island offshore from the larger island of Lantau in southwestern Hong Kong (Figure 1).

It is one of a swarm of dilational acid dykes trending east northeast in northern Lantau and is dated at c.146 Ma (Davis et al., 1997). It is an I - type feldsparphyric rhyolite dyke pencontemporaneous with mafic dykes (Darbyshire and Sewell, 1997). The Lantau

granite that it cuts is dated at c.161 Ma and forms the Lantau pluton (Davis et. al., 1997).

The importance of dyke margins in helping to reconstruct methods of intrusion was stressed by Cox et al. (1987). In acid dykes vital evidence is usually lost in the later stages of intrusion where piston type movement scrapes against the wall. In this study intermediate layers between the wall and the dyke are examined in detail.

Local geology was described by Langford et al. (1995), and regional geology by Sewell et al. (1992), Sewell and Campbell (1997), Campbell and Sewell (1997), and Fletcher et al. (1997). A major Jurassic - Cretaceous acid igneous complex with calderas makes up much of Hong Kong and is part of a larger northeast trending belt in

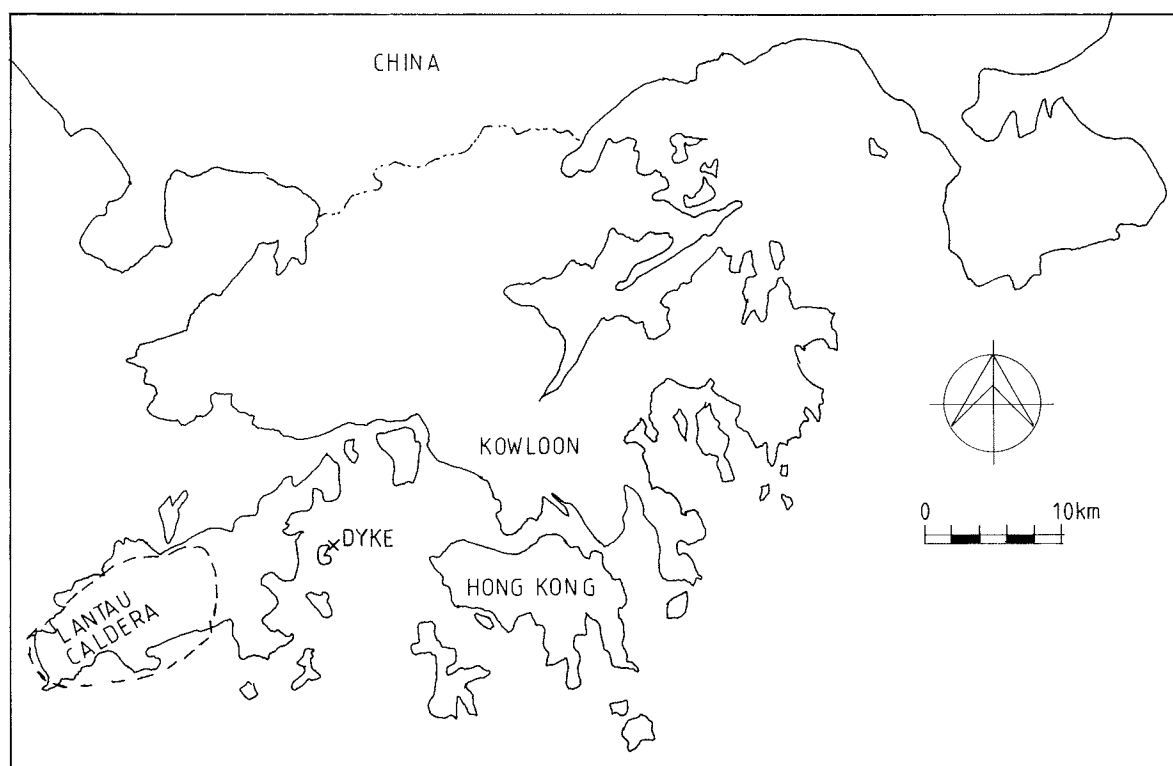


Figure 1 - Location map of acid prophyry dyke in Hong Kong

southeast China. In Hong Kong six pulses of granitoid rocks and five pulses of extrusives were distinguished. The granite and dyke described belong to pulses 1 and 2 respectively.

The Whole Dyke

The Peng Chau dyke is 60 m in width with flow banding on the strongly chilled margins, and shredded biotite, up to 10 m from the wall, showing some late stage piston movement. Phenocryst type and content were counted across half the width of the dyke and selected results are shown in Table 1. The percentage of phenocrysts increased rapidly inwards from the contact and tailed off asymptotically, approaching 24 % at the centre (Figure 2). The larger orthoclase continued to grow at the expense of the smaller orthoclase crystals. The central concentration of phenocrysts could be due to dispersive pressure (Komar, 1972), but the fluidity may not have been

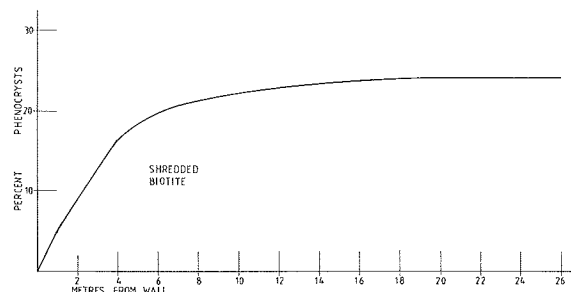


Figure 2 - The percentage by volume of the phenocrysts inwards from the dyke wall

Table 1. Percentage of phenocrysts at two intervals inwards from the wall

	% Quartz	Biotite	Small Orthoclase	Large Orthoclase	(long axis mm) Orthoclase
20m from wall	3.3	2.4	4.5	13.8	7
27m from wall	3.9	2.8	3.4	13.9	21

sufficient to allow this. Yet the smaller plagioclase crystals occur in clumps (syneusis) signifying a low viscosity. Gradual cooling inwards from the margins, allowing large euhedral orthoclase phenocrysts to develop in the centre, is the preferred theory of origin, in accordance with more recent work (Marsh, 1988).

Dyke Margin

In thin section, the equigranular (0.5 to 3.0 mm) granite is made up of equal parts of quartz, microcline and plagioclase with some biotite (altered to chlorite). At the presumed top (Figure 3), it has a sharp planar contact with the devitrified glass of the quartz feldspar porphyry. Below this, two thin (1 mm) layers intervene (Plate 1). First, a sliver of fractured granite lies adjacent to the wall, separated by a well defined fault. Second, and in sharp contrast, is a mixed layer adjacent to the dyke containing globular structures 3 to 40 mm in diameter with a less sharp margin (Figure 4). The fractured granite sliver has moved against the wall showing in places cataclasis and a smearing out of the chloritised biotite. The cores of the globulites are small fragments of comminuted granite. These are surrounded by rims of

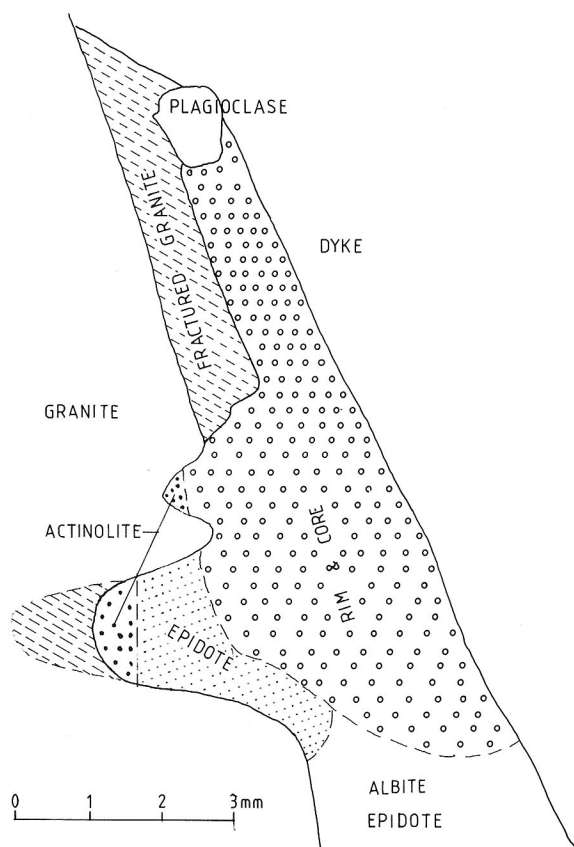


Figure 3 - Slightly simplified section of the margin of the quartz feldspar porphyry dyke showing two embayments in the wall



Plate 1 - The margin of the quartz porphyry dyke showing the fractured granite sliver and the "globulite" layer, which are together 2 mm wide. On rotating the stage more globulites come into view. Crossed nicols, blue filter.

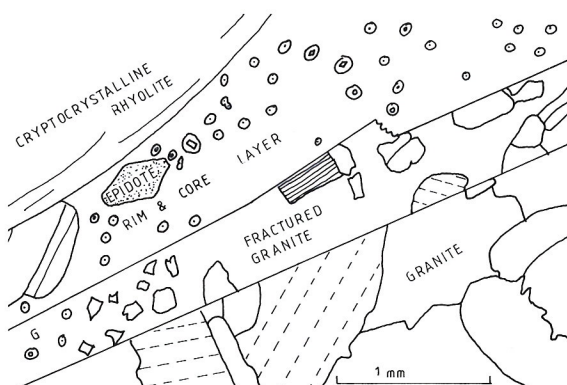


Figure 4 - Part of the top third of the section of Figure 3 showing the epidote clot pseudomorphing after an amphibole crystal giving the right way up.

feldspar in a groundmass of finely granular feldspar, quartz and chlorite. Relict perlitic cracks show that the groundmass was at least partly glassy. An embayment in the wall has microbrecciated granite, with a jigsaw-fit breccia showing a crack and seal texture (Ramsay, 1980) adjacent to actinolite and epidote infills. A stringer from the embayment bores into the granite wall for 3 mm ending in a pool of iron ore (Figure 5). At the base is a mass of albite and epidote with some chlorite.

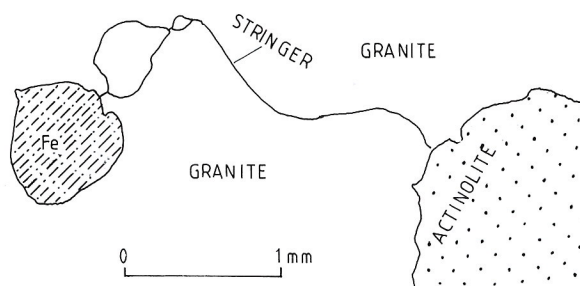


Figure 5 - Showing the stringer connecting the large embayment (actinolite) to the iron ore pool

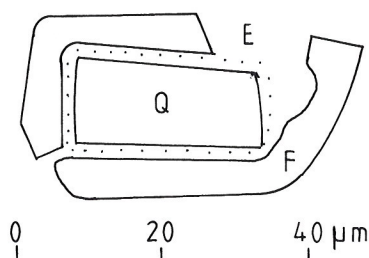


Figure 6 - A large core and rim "globulite", F - potash feldspar, E - epidote, Q - quartz,. Note the partial peeling off of the feldspar collar.

In the globulites (Plate 2) the whole collar is in optical continuity and extinguishes as one, whereas the core has variable extinction. Where the cores are quartz or feldspar a thin layer of epidote granules intervenes between the core and rim (Figure 6). Biotite cores are altered to chlorite. The larger collars of feldspar show open crack patterns due to shrinkage reminiscent of the so called collocrysts of Elliston (1966) where a colloidal stage was envisaged. Quenched melt of glass around cool granite fragments would hydrate, devitrify and recrystallise to epidote and feldspar and give structures similar to the "globulites" present in pulverulites of New Zealand (Marshall, 1935). Condensation around pulverised fragments of wall rock is also a variant (cf. Smith,

1974), as is the detachment of small pieces of rhyolite from the melt (Wohletz 1986).

Close packing of globulites less than 3 mm in size is seen in reconstituted sediment in a contact metamorphic aureole in Antarctica (Krynauw et al., 1988). Original close packing of globulites at Peng Chau occurs near the top of the slide (cf. Drake, 1990; Plate 1). Later pulses of volatiles have broken up some of these, and other clusters, where polygonal boundaries were present. Later pulses may have been hotter than the original melt in chilled margins (Cox et al., 1987; Maaloe, 1987). Close packing of globulites suggests a parallel with ball bearings where sizes of 3: 4:5 in ratios of 5:3:2 cause mass movement (Boerner and Sclater, 1992). Even cogwheel structures have been suggested (Scott, 1996). The drag on the walls of Petford and Koenders (1998) hypothetical acid dyke is around 14.7 kPa and, at Peng Chau, probably caused some rotation of the globulites with each pulse. The last pulse causing some peeling off of the collar of a large globulite (Figure 6). The granular epidote clot is a pseudomorph after amphibole which has come up from below the area of the thin section.

The globulite film was thus a hybrid melt or fluid that, when slowed down or blocked, was under sufficient pressure to drill into the wall through quartz and feldspar crystals to form a stringer (1-2



Plate 2 - Photograph (1 mm wide) shows the close packed globulites.

mm diameter) leading to a pool of iron ore. In the laboratory, the boring of stringers into walls occurs at high temperatures (600°C) and pressures (2,000 bars) (Murrell and Ismail, 1976), which would indicate significant depth. In peperites at shallower depths drilling is a common phenomenon (Busby-Spera and White, 1987); the granite may have been damp.

The pool of iron ore is either a replacement of the granite or the infilling of a miarolitic cavity or due to an explosion caused by decompression. The latter is most unlikely because there is no shattering or signs of compression around the margin. The siting of a miarolitic cavity in this position would be a remote chance and so replacement by hydrothermal fluids seems most likely.

Hydrothermal Zoning

There is a metasomatic fringe of chlorite and epidote in the granite wall and margin of the dyke (1 to 2 mm). Beyond this the rocks are nearly free of alteration products except for the chloritization of the biotite.

Within the metasomatic fringe epidote and chlorite make up 4 % of the granite and 9 % of the dyke, whereas epidote is over 25 % of the whole in parts of the hydrothermal pathway, shown in the lower part of the diagram (Figure 3). Zoning in thin section is shown by the sequence:

5. Iron ore pool in the granite
4. Actinolite margins to two embayments
3. Epidote - actinolite seal, minor clinozoisite
2. Epidote - feldspar network
1. Epidote - feldspar - chlorite

The changes take place from the base upwards diverting into and through the large embayment ending via a stringer to the iron ore pool.

The permeability of granite is very low and decreases with elevated temperature (Moore et al., 1994). In time an impermeable seal is formed and flow ceases. Flow, however, lasted long enough to precipitate the ore; momentary in geological time but perhaps thousands of years in real time (Cathles, 1977).

In the epidote - feldspar network (stage 2) the spongy albite crystals have intricate grain boundaries. Intergranular fluid pulses of formation and dissolution are suspected. Albite replacing alkali feldspar, due to late stage residual fluids, in Hong Kong granites was noted by Peng (1970). Actinolite, feldspar and ore minerals filling fractures and forming a seal in basalt in Iceland were formed at 370°C to 400°C (Fournier, 1991). At lower temperatures (250°C to 300°C) chlorite forms too (Nicholson and Black, 1998). Epidote forms above 260°C. Temperatures vary with pressure. Fluid transport and zoning can occur on a microscopic scale and on a grand scale of tens of kilometres (Boulter, 1996), from a humble stringer 1-2 mm in diameter to huge percolation networks (Gueguen et al., 1991).

The Sequence of Events

Table 2 suggests the probable sequence of events to explain the dyke margin. A rhyolitic magma stage at sufficient pressure to bore a stringer into the wall is followed by a hydrothermal stage where fluids from below took advantage of the pathway into the granite wall. This is a type of dark margin (Bishop, 1963), where more basic material has come up from below. This was probably a plagioclase hornblende mixture which is now

Table 2 - a suggested sequence of events at the dyke margin, oldest at the base

Hydrothermal stage	Formation of epidote, albite and chlorite on margin
	Crystallisation of actinolite and epidote in embayments
	Sealed by reduced permeability, froth at contact
	Sufficient flow to precipitate iron ore pool
	Volatiles, including water, up wall diverted to embayment
Magma stage	Quenching, cooling, shrinkage cracks
	Rotation of granite fragments causing partial peeling off of rims
	Xenocryst blocking, stringer bores into wall forming pool
	Fluidised marginal film 3mm wide with evenly spaced fragments
	Cataclasis or shock pulverises fractured granite to dust
	Dragging up wall fractures asperities and weak spots
	Cracks, dyke injection, speed the order of 10cm sec ⁻¹

altered essentially to albite - epidote. A subjacent lamprophyre (spessartite).

The gradation from melt to hydrothermal stage seems to have taken place in one episode of cooling punctuated by partial remelting and dissolution phases because some lamprophyres are cut by members of the acid igneous complex (Ruxton, 1960). In this instance both appear to be consanguineous. During annealing the polymerising albite developed void structures in the colloidal aggregates resulting in spongy crystals. When the granite was sealed off frothing occurred at the impermeable contact; some of the bubbles nucleating around dust fragments.

Also synchronous are three examples of oscillatory (sinusoidal) cracks: two along the main margin between granite and fractured granite and one at the proximal end of the stringer. They indicate a speed of crack formation in glass of over 5 cm sec^{-1} (Yuse and Sano, 1993) comparable with theoretical speeds of acid dyke injection of 9 cm sec^{-1} (Petford and Koenders, 1998: see below).

Discussion

Core and rim textures are common in igneous rocks. They vary from mantles and overgrowths to reaction rims and rotational rims. The core is a favourable site for nucleation or reactions. The smaller bits of colloidal size may act as seeds. Microexplosions probably occurred because there is, in places, a pressure fringe of flattened microlites between the core and rim structures and the rhyolite dyke. Shock is probably necessary to produce colloidal sizes. Rapid decompression, rapid quenching and hydraulic brecciation are invoked to cause explosions. One can then speak of pulverisation to dust. The grade size distribution of the sizes that can be seen under high power microscopy would support a mechanical fragmental origin (cataclasis). There are no thermal or chemical changes in the granite wall. Basic dykes in granite in Hong Kong cause a thin rim of fused wall rock, which is not present in the acid dykes, and so the temperature of the rhyolite probably did not exceed 1000°C . That it was very hot is shown by the fluidity of the margin despite ingesting the cool granite dust.

Dyke Margins

Dyke margins are usually assumed to be sharp, planar, often chilled, and sometimes with a hybrid intermediate layer (Cox et al, 1987). Some irregular or "damaged" walls have been ascribed to forcible intrusion (Noble, 1952; Meriaux et al. 1999), whereas brecciation and globular textures are often due to peperite formation upon emplacement in wet rock. Some authors (Maaloe and Wyllie, 1975) believe that exsolved gases stream along the contact

between magma and wall rock. Fluidisation occurs when the drag exerted by the moving pore fluids exceeds the effective weight of the grains. The particles and lumps are lifted and the strength is reduced to near zero (Lowe, 1975). At Peng Chau fluidisation (i.e. turbulence; Kokelaar, 1982) is suggested both by the moving up of the epidote clot and by the even spacing of the granitic grains. A type of slurry flow is possible, with suspension shearing where particles are forced to avoid one another and to roll and translate (Petford and Koenders, 1998).

The rhyolite of the dyke probably intruded into a wall of granite with damp patches where internal "peperite" formed due to sudden overpressures of vapour (Blanpied et al, 1992). Upward dyke movement was then by stick and slip on bare wall surfaces (Brace and Byerlee, 1966), fluidisation with a rotary dust of globulites, or by cushioning of gases, in order of greater speed.

Genesis of Dykes

Theoretically an acid magma (70 % SiO_2) with viscosity of 10^5 Pa's and buoyancy of 0.3 g cm^3 can flow freely at a mean velocity of 9 cm sec^{-1} as a 6m wide dyke (Petford and Koenders, 1998). The Peng Chau dyke is ten times as wide. Micro-oscillatory cracks along the margin suggest a comparable speed (Yuse and Sano, 1993).

Rock and others (1988) wrote of possible small hot spots in the mantle producing lamprophyres and volatiles that provided the heat for the melting of granite in the upper crust to form swarms of granitoid porphyries and associated gold deposits. The "andesitic" source of the hydrothermal fluids may in fact be the volatiles from a lamprophyric intrusion below. Whereas D'Lemos and others (1992) proposed crustal granite porphyry dykes as intermediaries in granite batholith formation within transpressional orogenic zones, Campbell and Sewell (1997) suggested crustal transtension as the control for the placement of Hong Kong granitoid-porphyries. The dyke swarm covers an elliptical area of 300 km^2 and contains some dykes up to several kilometres in length and up to 100 metres in width.

A subsolidus assemblage in Hong Kong where albite replaced potash feldspar in granite was reported by Peng (1970). The Peng Chau assemblage is more evolved and has some similarities with peperites in California (Brooks, 1995; Hanson and Schweikert, 1982), where matrices are profoundly recrystallised under conditions of greenschist facies yet original fabrics are preserved (palimpsest).

Dykes, Faults and Earthquakes

At the piston stage along the wall of a dyke even a slip of 1 mm would be expected to generate intense heat and perhaps local remelting (Kanamori et al., 1998). But where data is available frictional heat on sliding (e.g. as on the San Andreas fault) is negligible and has been explained in several ways (Scholz, 1996):

1. movement on ball bearings (Scott, 1996),
2. interlinked cogwheels freely rotating (Boerner and Sclater, 1992),
3. overpressured fluid compartments (Blanpied et al., 1992; Byerlee, 1993), with hydrofracture,
4. acoustic fluidisation (Melosh, 1996) and
5. movement on a compressed vapour film (cf. Mills, 1984).

The presence of the stringer at Peng Chau boring into the wall would favour the overpressured fluids theory.

The presence of fractured granite and granite dust formed by cataclasis at the dyke margin has parallels with fault gouge (Indraratna et al., 1999). Both may facilitate slipping with some globulites acting as rotating ball bearings. That sliding takes place is shown by the smearing out of biotite on the margin of fractured granite at Peng Chau. Movement may be upward, oblique or even sideways; some dykes elsewhere have horizontal channelised indented ripples apparently in the direction of flow (Percival, 1985).

The latest suggestions in Hong Kong geology (Sewell et al., 1992; Campbell and Sewell, 1997) include a Lantau caldera of acid volcanic nature adjacent to the granitoid dyke swarm. If this is correct then a major inversion of relief has occurred in the denudational history because the acid volcanics now form the high peaks of Lantau. Several kilometres of erosion from off the top of the quartz - feldspar porphyry dyke is implicit and this was suggested by Ruxton and Taylor (1997) in their dynamic model of the denudational history of Hong Kong.

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Sedimentology of Double Haven (Yan Chau Tong), New Territories, Hong Kong

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Abstract

This paper aims to obtain a better understanding of the sedimentology of Double Haven by investigating the inter-relationship between sediment characteristics, bottom dynamics and coastal morphometry. The particle sizes of 8 short sediment cores have been studied for spatial and vertical variability. The samples mainly consist of silt with only a very limited amount of clay and sand, indicating that Double Haven generally is a low energy sedimentary environment with restricted tidal circulation. Since there is an absence of major rivers introducing large quantities of detrital sediments into the Haven, sedimentation is mainly contributed by pelagic processes. Spatial variations in the particle size of surface sediments suggest that fine particles are re-distributed by weak bottom currents. Bioturbation results in the homogenization of basal and surface sediments.

摘要

本文旨在通過研究沉積物特徵、海底動力學和海岸形態學的相互關係去了解印洲塘的近代沉積型態。從八個沉積物鑽芯樣本的結果得知，印洲塘的沉積物主要由粉砂所組成，粘土和砂的成份甚少，顯示印洲塘在平常的情況下，是一個低能量的沉積環境，潮汐所做成的海水循環微弱。因為沒有大型的河流帶動碎屑物進入印洲塘，沉積物的組成主要來自海水本身的沉積物產生。微弱的海流將海底的表面細小的沉積物從新分配，做成顆粒大小在空間上輕微的分別。另一方面，生物混動卻使底層與表層沉積物混和而使沉積物在垂直上趨向一致化。

Introduction

Recently, many paleoenvironmental studies of sea floor sediments have been carried out in Hong Kong. Most have attempted to reconstruct sea level change for the Holocene and Pleistocene. However, their conclusions are contradictory. For example, while Yim (1994) proposes a multiple transgression model, Owen et al. (1998) argue that only two major transgressions are preserved in the sedimentary record. Such arguments may be due to a lack of local models that describe modern sedimentation patterns and their controlling factors. By means of a systematic examination of sea floor sediments obtained from Double Haven (Yan Chau Tong), this paper attempts to fill this gap. The investigation examines the inter-relationship between sediment characteristics, bottom dynamics and coastal morphometry.

Study Area

Double Haven is located in the north eastern part of the New Territories (Figure 1). It is bounded by the mainland coast in the west, Double Island in the south and Crooked Island in the northeast. The geology of the Hong Kong mainland is dominated by the Cretaceous Pat Sin Leng Formation, which consists of sandstone and siltstone with conglomerate at its base. Several small creeks flow into the Double Haven. The islands are composed of coarse ash crystal tuff of the Upper Jurassic Tai Mo Shan Formation (Lai et al, 1996).

Double Haven was chosen because of its lagoon-like embayment, which is enclosed almost completely by outlying islands. It is believed that, in such an enclosed area, the causal relationship between sediment types, bottom dynamics and coastal morphometry can be best documented because the environmental conditions are strictly controlled.

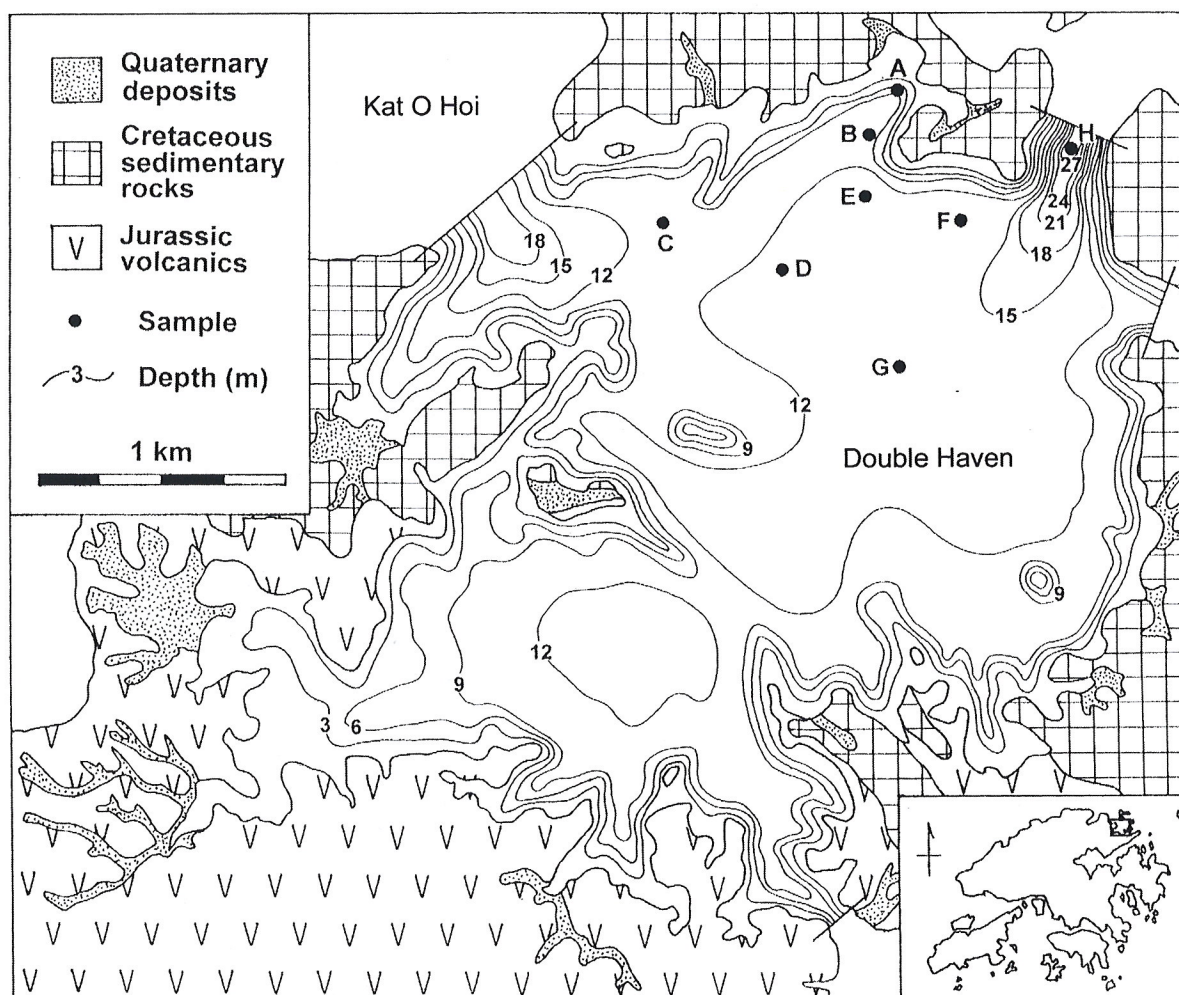


Figure 1 - Map of Double Haven showing geology, sampling sites and bathymetry.

Today, Double Haven has been designated as a marine park. Bottom sediment is an essential component of the marine ecosystem as it provides a habitat for a variety of marine organisms. An understanding of sedimentation is therefore important for the future protection of the park.

Methodology

Coastal Morphometry

A system developed by Håkanson (1981) was adopted for quantitatively describing the coastal morphometry of Double Haven. Bathymetric maps were constructed from a hydrographic survey and 1:20,000 topographic maps. Size parameters (such as the area of the water surface, volume, maximum depth, fetch, etc.), form parameters (such as bottom roughness and shore development, etc.) and exposure were calculated.

Sediment sampling

Eight short sediment cores were recovered in September and October 1998. One advantage of core samples over grab samples is that the stratigraphic variability of the sediment can be demonstrated. These cores were collected at several locations representing different sedimentary environments, such as tidal channels, littoral areas and unrestricted offshore regions (Figure 1).

Cores were logged while wet and were examined using the Troels-Smith (1955) procedure. Subsamples collected from the outermost layer and from the base of each core were examined with a Coulter LS130 Particle Size Analyzer. The analyzer can precisely determine sediment grains ranging from 0.4 mm to 900 mm. For the analysis, approximately 0.5 g of sample were immersed in 10 g NaOH with 25 ml distilled water, in order to break down aggregates. Then, the mixture was drained into a fluid module system and the

distribution of various particles were determined automatically by computer. Various descriptive statistics such as sorting coefficient, skewness and kurtosis were determined using the method of Folk & Ward (1957).

Results and Discussions

Coastal morphometry

A detailed bathymetric map of Double Haven was constructed using available topographic and field hydrographic data (Figure 1). Subsequently, a number of coastal morphometric parameters were determined for Double Haven (Table 1). This showed that the water surface of Double Haven is 8.778 km² in area, with a water volume of 77.09 x 10⁶ m³. The maximum depth and mean depth are 27 m and 8.78 m.

The most striking characteristic of Double Haven is its topographical enclosure. Exposure is only 9.48 %. There are two implications. First, the local circulation of

Table 1. Coastal morphometry of Double Haven

Water area (A), km ²	8.778
Water volume (V), m ³	77.09x10 ⁶
Exposure (E),	9.48
Maximum length (L_{max}), km	4.52
Maximum effective length (L_e), km	4.08
Maximum effective fetch (L_f), km	2.56
Maximum width (B_{max}), km	3.12
Mean width (B_{mean}), km	1.94
Maximum depth (D_{max}), m	27
Mean depth (D_{mean}), m	8.78
Medium depth (D_{medium}), m	11.11
1 st quartile depth (D_{25}), m	4.44
3 rd quartile depth (D_{75}), m	12.50
Mean slope (x_m), %	3.14
Shoreline length (L_o), km	28.33
Shore development (F), dimensionless	2.6974
Bottom roughness (R), dimensionless	2.6951
Volume development (V_o), dimensionless	0.9756

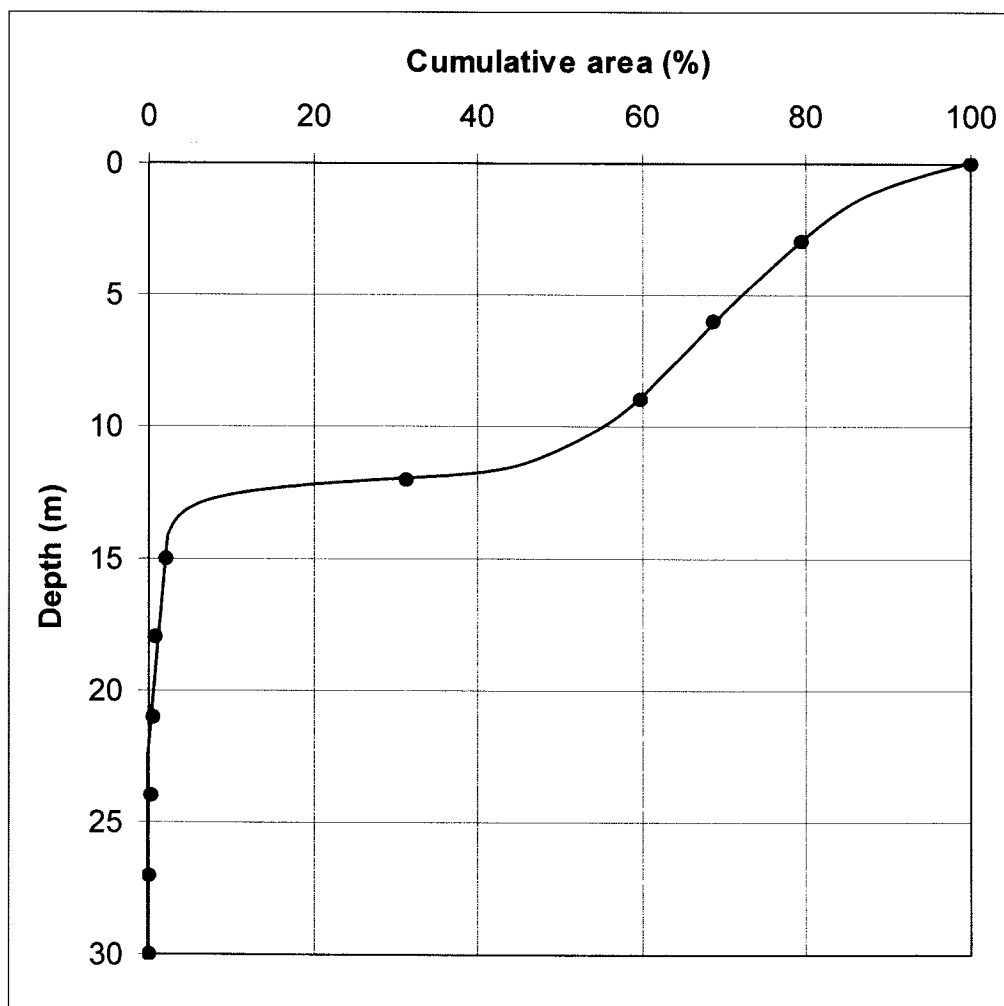


Figure 2 - Hypsographic curve of Double Haven

water would be not only dependent upon the tidal current, but also the local environmental factors such as wind direction, salinity contrasts and temperature differences within the Haven. Second, the maximum effective fetch is very short, only 2.56 km. Since a low fetch effectively prevents the development of high waves, wind/wave induced erosion should be significantly lower than for other open marine environments.

In Hong Kong, the mean wind speed is 3 m s^{-1} and maximum gusts can be as high as 70 m s^{-1} during a typhoon (Tam, 1987). An empirical study of the inner bay of the Pearl River Estuary reports that the mean wave height is less than 0.5 m and the maximum wave height is less than 2.5 m (Yang & Chen, 1987). It is expected that similar wave patterns will be found in Double Haven. Therefore, the influence of wind/wave action will extend to a depth of approximately 2 m in normal conditions, but may extend to 10 m in extreme conditions. Consequently, fine-grained sediments would tend to accumulate in waters deeper than 2 m, with continuous deposition occurring in areas deeper than 10 m.

By plotting cumulative area (in %) versus depth, a hypsographic curve (Figure 2) can be used to show how area varies with depth. Geomorphologically, Double Haven consists of steep coastal shallows (0 - 9 m), very flat mid-depth areas (9 - 18 m), and limited but deep troughs (> 18 m). While the steep littoral areas are characterized by coastal erosion due to wind/wave action, the

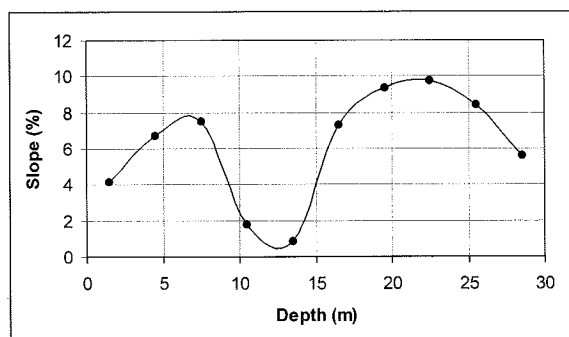


Figure 3- Sea slope angles in Double Haven

deeper areas are gentle and of sufficiently low energy for deposits to settle and stay in place. Between 9 - 15 m, the slope is less than 4 %, the minimum being 0.88 % (Figure 3). More than half of the area of the Haven is both deeper than 10 m and gentle in relief.

Irregularities of shoreline and bottom tend to reflect erosion, whereas deposition and infilling by sediments tends to correlate with smooth regions. Therefore, shoreline development and bottom roughness can be used to represent the energy setting of an environment (Håkanson, 1981). For Double Haven, the values of shoreline development and the bottom roughness are not high, 2.6974 and 2.6951 respectively, indicating a quite smooth shoreline and bottom. This is

Table 2. Particle size characteristics of sediments in Double Haven

Site	Water depth (m)	Sediment depth (cm)	Mean size (μm)	Mode (μm)	Skew	Sort. coef.	Kurtosis	Texture	Sediment distribution		
									clay (%)	silt (%)	sand (%)
									<2 μm	2-60 μm	>60 μm
A	7	0	31.7	26.2	0.39	1.36	1.17	Silt	2.66	88.02	9.33
		11	135.3	20.0	-0.68	2.51	0.88	Sandy silt	2.55	66.69	30.76
B	9.5	0	33.7	26.2	0.38	1.34	1.15	Silt	2.51	89.27	8.22
		22	27.2	22.2	0.45	1.34	1.17	Silt	3.28	90.40	6.32
C	11.3	0	29.6	26.2	0.45	1.33	1.15	Silt	2.63	89.58	7.79
		18	34.5	27.6	0.44	1.35	1.18	Silt	2.47	88.36	9.17
D	12.3	0	32.2	19.0	0.02	1.43	1.30	Silt	2.92	88.62	8.47
		11	35.0	26.2	0.22	1.38	1.20	Silt	2.24	87.47	10.30
E	13.8	0	26.3	17.0	0.03	1.38	1.31	Silt	2.93	89.74	7.34
		21	33.2	29.1	0.53	1.35	1.18	Silt	2.85	88.37	8.79
F	14.5	0	30.3	27.6	0.52	1.32	1.10	Silt	2.47	89.31	8.22
		28	36.0	22.2	0.14	1.44	1.33	Silt	3.06	88.22	8.73
G	14.9	0	31.0	23.5	0.27	1.40	1.20	Silt	2.72	88.46	8.82
		11	31.7	29.1	0.55	1.35	1.15	Silt	2.80	88.82	8.38
H	27	0	17.5	11.7	-0.09	1.33	1.20	Silt	4.05	91.43	4.52
		27	32.8	24.8	0.41	1.38	1.23	Silt	3.01	88.82	8.17

consistent with the above notion that Double Haven is a low energy environmental setting.

Sedimentology

Eight cores were recovered from various locations in Double Haven. Their lengths range from 11 cm to 28 cm. The results of the sedimentological analyses are summarized in Table 2. Except for a core from site C, which throughout consists of black (5Y/2.5/1) mud, all cores consistently consist of olive grey (5Y/3/2) surface sediments, overlying very dark grey (5Y/3/1) basal material. Broken shells are scattered through the lower part. Laminations are absent.

The lack of laminations may be due to continuity of sedimentation, i.e. the rate of sedimentation does not change with time (Håkanson & Jansson, 1983). However, such an explanation seems not to be the case, because significant seasonal variations of temperature and precipitation should generate differential sedimentation rates. The most probable explanation is bioturbation. Although the environment is a low energy setting, the oxygenated bottom conditions should allow various benthic organisms to be active. Stratigraphic features, even if

formed, are destroyed because of continuous mixing of the upper and the lower sediment layers. By means of underwater images, Sin (1999) showed that deep feeding voids and burrowing holes are common in the topmost layer of the sediment, indicating that bioturbation is frequent in Double Haven. Furthermore, the trawling activities of fishermen would also cause mixing of the sediment layers. Since a continuous mixing of the upper and lower layers of sediment is taking place, the resolution of the paleoenvironmental record would become reduced. This would preclude possibilities of detailed seasonal environmental reconstruction.

The sediments consist predominantly of silt; clay and sand are only minor components. Silt ranges between 67 % and 91 %. In most samples, sand and clay usually constitute less than 10 % and 4 % respectively. Plotting on a ternary diagram classifies the samples as silt, except for the basal sample of site A which is sandy silt. Since there is a lack of major rivers introducing large quantities of terrestrial detrital sediments into the Haven, the sediment sources are limited. Sedimentation is mainly constituted by pelagic deposition, involving either chemical flocculation, clay

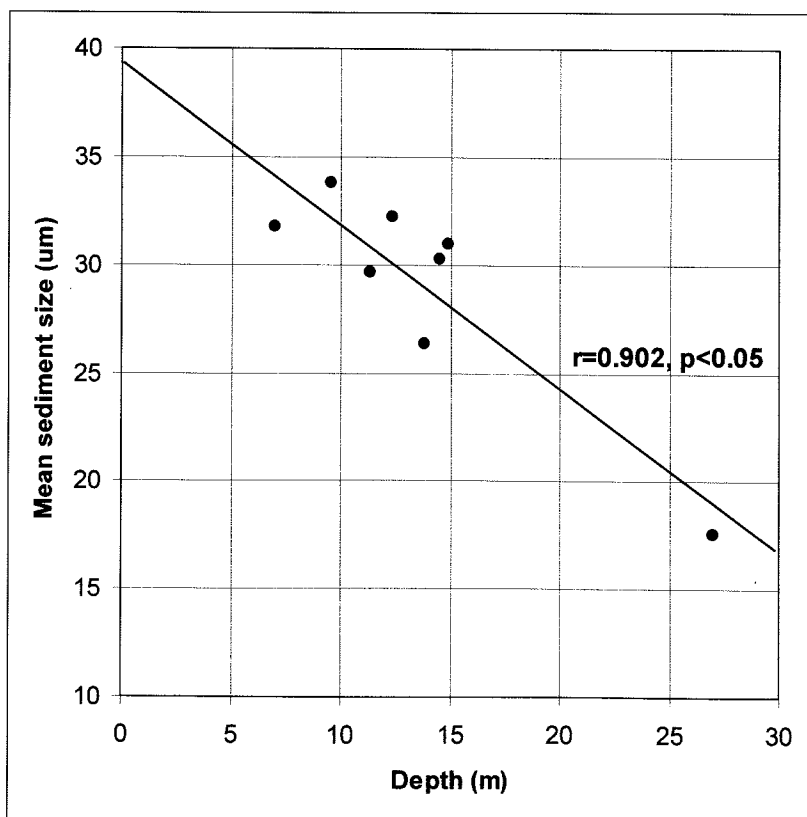


Figure 4 - Plot of mean sediment size against depth.

and silt setting or bio-production. Consequently, sediments of Double Haven are generally dominated by fine particles with a positive skewness.

The mean particle size of surface sediments varies between 17.5–33.7 mm (medium silt). The mean particle size of surface sediments tends to decrease with depth ($r=0.902$, $p<0.05$) (Figure 4). This is probably related to a weak bottom current contributing to the redistribution of fine particles. At a greater depth, lower energy conditions allow the settlement of finer sediments. The bottom current velocity predicted by Stokes Law is approximately 2 cm s^{-1} for the greater part of Double Haven.

The mean particle sizes of basal sediments are exceptionally uniform, in a narrow range of 27.2–36.0 mm (medium silt), except for a sample from site A, which is exceptionally coarse (135.3 mm, fine sand). The lack of a statistically significant difference between the surface and basal samples ($t=1.32$, $p=0.228$) may reflect homogenisation of sediment layers by bioturbation in the greater part of Double Haven. At site A, the inhomogeneous distribution of particles (mean sizes are 31.7 mm and 135.3 mm in the surface and the base respectively), can be explained by the fact that the site is shallow (only 7 m) and near the shore. The surface sediments may represent the initial deposition layer, which is then subject to alteration in extreme situations, such as during a typhoon. While fine materials may be washed away, coarser particles are left to accumulate.

All samples are poorly sorted and leptokurtic, except for the basal sample at site A, which is very poorly sorted and platykurtic, reflecting the fact that the mean size of sediment is increased when fine particles are removed (Folk & Ward, 1957).

Conclusion

This paper shows that the coastal morphometry of Double Haven controls the pattern of wind/wave action and bottom dynamics, which in turn determines how Double Haven functions sedimentologically. Double Haven is dominated by poorly sorted medium silts, indicating that Double Haven generally is a low energy sedimentary environment. Limited wind/wave erosion occurs in shallow coastal areas, but continuous deposition can be found in areas deeper than 10 m. The deposition is subject to reworking by bottom currents and homogenization of basal and surface sediments through bioturbation.

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Hong Kong's Classic Geology, No. 1

Deformation and Slope Failure Modes in Columnar Jointed Tuffs of the High Island Formation - Hong Kong

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Introduction

Columnar jointing is a common characteristic of massive igneous rocks. It is a polygonal (typically hexagonal) system of joints, usually developed at right angles to the cooling surface of the igneous body. The phenomenon results from relatively rapid cooling and contraction of a rock body that has solidified directly or indirectly from its magmatic state. Well developed columnar jointing is often associated with lavas of basaltic composition. However, it can develop in rocks formed from magma of any composition, can occur in intrusive as well as extrusive rocks, and is even a feature of some tuffaceous rocks, most notably those of rhyolitic composition.

Columnar jointing is widespread in the eastern New Territories of Hong Kong. The cliffs between Clear Water Bay and High Island (Plate 1), and those around several of the islands such as Kau Sai Chau and the Ninepin Group provide many outstanding examples of vertically continuous groups of columns. Individual columns are usually several metres in height (Plate 2) but they may extend up to 30 m in height. Their long axes generally plunge to the west at approximately 80°. The columnar joints are inferred to have been sub-vertical at the time of their formation and that their steep westerly plunge is due to later tilting to the east (Plate 3). This has resulted in the present easterly dip of the strata of approximately 10°.

The High Island Formation

The High Island Formation is a very uniform, massive, crystal-bearing, fine ash vitric tuff with small-scale eutaxitic fabrics. The tuffs are of high-silica rhyolite composition (Sewell & Campbell, 1997). The pyroclastic nature of these deposits was first recognized by Tam (1970). The formation unconformably overlies lavas, tuff and tuffite of the Clear Water Bay Formation and occurs principally as a widespread sheet, up to 400 m thick. The thickest development of the formation appears to be to the south of an inferred westerly-trending structure, passing through the High Island Reservoir and Sai Kung. The thickness variations suggest that the formation occupies a complex caldera



Plate 1 – Columnar jointing within the High Island Formation in the sea cliffs on Fu Tau Fan Chau, eastern New Territories.



Plate 2 – Columnar jointing within the High Island Formation on North Ninepin Island (Pak Kwo Chau, SE New Territories).

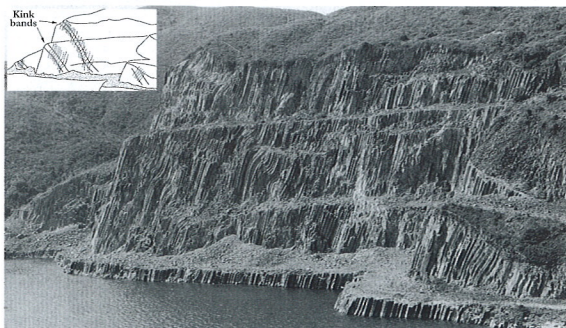


Plate 3 – Kink bands developed within the columnar-jointed High Island Formation, in the disused quarry face north of the East Dam, High Island Reservoir, eastern New Territories.

(Campbell & Sewell, 1997). Although much of the formation probably developed as a single cooling unit, it appears to comprise several pyroclastic flow deposits. The very fine-grained matrix contains *c.*20% of crystals dominated by small euhedral alkali feldspars, with some larger broken fragments of quartz and feldspar. High precision U-Pb dating of single zircon crystals has yielded an age of 140.9 ± 0.2 Ma for the formation (Davis *et al.*, 1997). This suggests that the formation is Early Cretaceous in age and forms part of the final of four episodes of rhyodacite and rhyolite volcanism in Hong Kong (Campbell & Sewell, 1998).

Deformational Features

Folding of the columnar joints is developed at many locations within the High Island Formation. The folds occur in discrete zones, up to about 3 m wide (Plate 3), that dip at a moderate angle, mainly to the east but also occasionally to the west. The folds are variably open monoclines to tight kinks. At one location northeast of the East Dam at High Island Reservoir, a basaltic dyke has exploited a kink fold (Plate 4) indicating that the folds are clearly ancient features. Low angle limb shears have developed along some of the tighter kinks and slickensides can be seen on some of these shear planes. These planes are locally potential

planes of weakness with respect to present slope stability. The mesoscale kink bands are considered to have developed during the cooling and contraction of the tuffs.

Slope Failure Modes

A variety of failure modes affect the High Island Formation. These can be seen in the sea cliffs, as well as in quarry faces and other man-made slopes.

Individual column slumping (collapse)

This characteristic mode of failure affects individual joint-bounded columns (Plate 5). It occurs where low-angle joints have developed towards the bases of columns. The low-angle joints can develop as a result of stress relief associated with weathering, or shearing related to kink band development. Failure results when lateral shearing occurs on the low-angle joints and causes the bases of the columns to kick out. As a result, the columns collapse guided vertically by the bounding joint structure. Several examples of this mode of failure can be seen on the track leading northwards from the East Dam at High Island Reservoir towards a disused quarry. Although failures of this type are generally of small volume, they may trigger larger scales of instability as a result of loss of toe support in a rock slope.

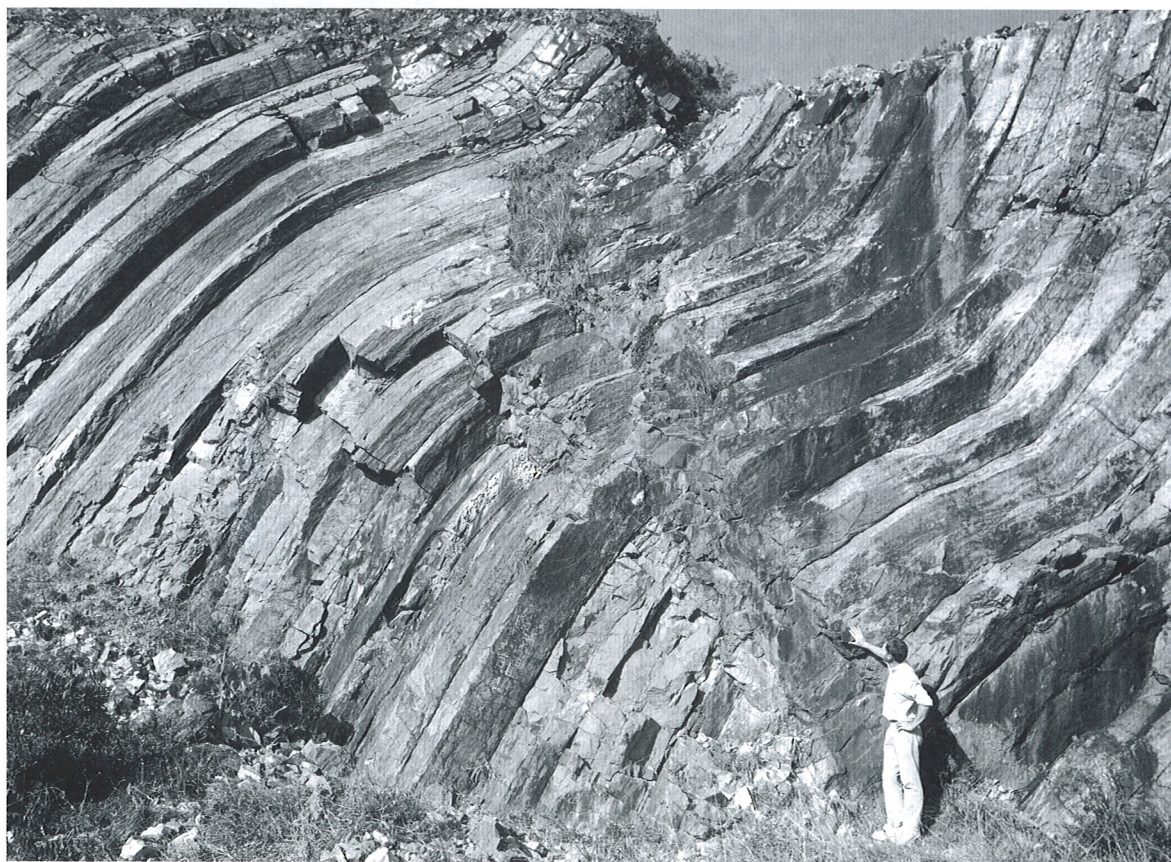


Plate 4 – Basalt dyke intruded into kink band developed within the columnar-jointed High Island Formation, in a cut slope east of the East Dam, High Island Reservoir, eastern New Territories.

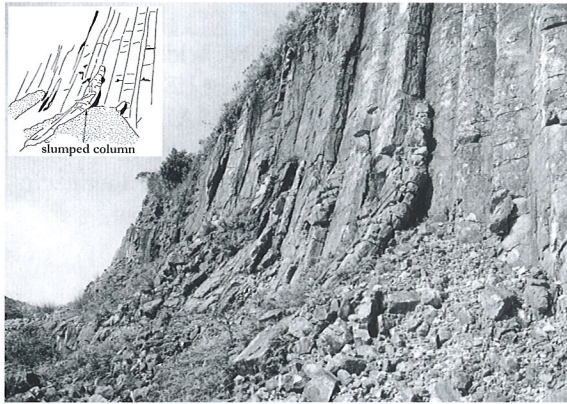


Plate 5 – Slumped (collapsed) cooling column within the High Island Formation, in a cut slope along east side of track leading to disused quarry north of the East Dam, High Island Reservoir, eastern New Territories.



Plate 6 – Columnar-jointed phonolite intrusion, Devils Tower, Wyoming, USA.

For comparison, the same mode of failure can be seen at one of the worlds best known geological localities where columnar jointing is present, Devils Tower in north-east Wyoming, USA (Plate 6). This 382 m-high, 40 million year-old phonolite intrusion was made famous world-wide as a backdrop in the film “Close Encounters of the Third Kind”. Whilst the Native American Indian legend tells of a giant bear’s claw’s forming the well developed vertical joints, the more mundane explanation is that they are columnar cooling joints. A characteristic feature of the columns is their tendency to fail at their bases (Plate 7) in the same way as those in the High Island Formation.

Toppling

Good examples of toppling failure of individual columns and group of columns can be seen on the Ninepins Group of islands in the southwest of Hong Kong (Plates 8 and 9). The toppling is evident in this example in the main scarp of a failure that probably involved translation failure of a rock mass also. The resultant main scarp is highly serrated in plan view.

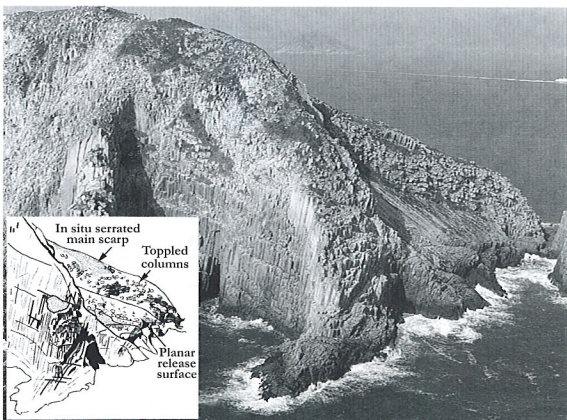


Plate 8 – Toppling of columns and planar release surface suggesting translational failure within the columnar-joint High Island Formation on North Ninepin Island (Pak Kwo Chau, SE New Territories).

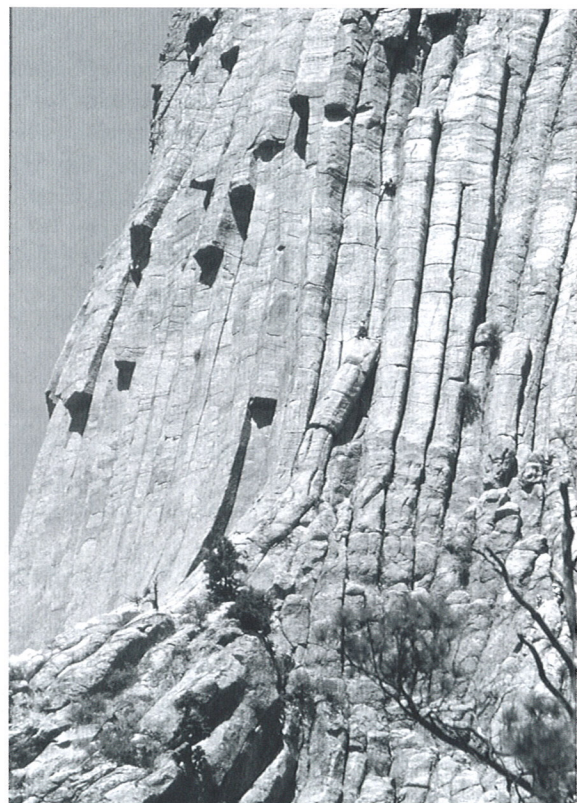


Plate 7 – Column slumping within phonolite intrusion, Devils Tower, Wyoming, USA (note climbers for scale).

Rock slumping and translational failure

Translational failures may nucleate on pre-existing low-angle joints or shear planes (Plate 9). Rock slumping (Kieffer, 1998) is similar to translational sliding in that it involves release (Plate 10) on a low to very low-angle plane which may either be pre-existing (joint or shear plane) or, may be initiated as a new shear plane within the rock mass. In addition, a sub-vertical joint (or other discontinuity) set dipping out of slope is also generally present. A consequence of this mode of

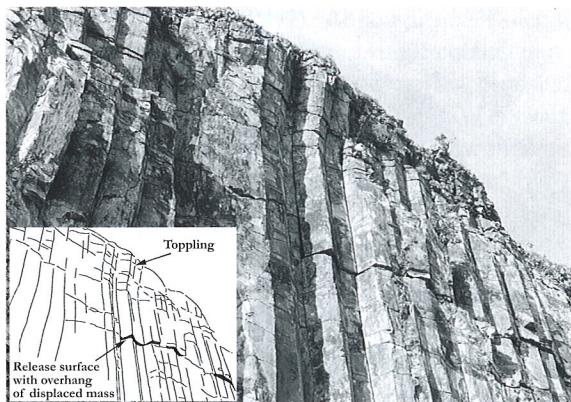


Plate 9 – Low-angle release surface, evident from displaced columns and overhang of the displaced mass, and incipient toppling within the columnar-jointed High Island Formation, in a disused quarry north of the East Dam, High Island Reservoir, eastern New Territories.

failure is the rotation of the sub-vertical joint-bounded blocks of rock and the opening of voids (A-frame voids) within the rock mass (Plate 10). Whereas tension cracks typically taper downwards from the surface (Plate 10), A-frame voids increase in width downwards towards the main low-angle release plane (Plate 10). Once developed, these voids may flood rapidly during subsequent rainstorms allowing cleft pressures to develop which may in turn cause further instability.

Near-surface hill creep

Down slope hill creep can be seen in some cliff-top exposures (Plate 10). A notable feature of the High Island Formation is the very thin soil profiles that are preserved. The lack of thick mature weathering profiles in many places is likely to reflect relatively frequent landsliding causing detachment of soil profiles at and close to rockhead.

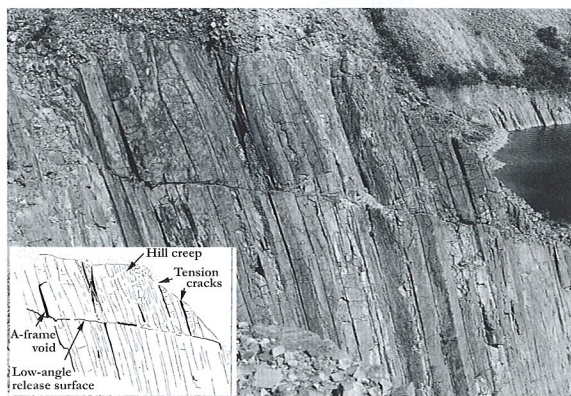


Plate 10 – Evidence of rock slumping including low-angle release surface (evident from displaced columns) and the development of an A-frame void, and near-surface tension cracks and hill creep within the columnar-jointed High Island Formation, in a disused quarry north of the East Dam, High Island Reservoir, eastern New Territories.

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