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The Dangan Basin - a fault-bounded Tertiary basin off southern Hong Kong

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Abstract

The Dangan Basin is a northeast to southwest trending, fault-bounded Tertiary depositional basin on the northern coastal margin of the South China Sea. The basin underlies the northeast aligned Dangan (Lema) Channel which is situated 10 km south of Hong Kong Island and north of the Dangan Islands. The Dangan Basin is about 24 km long and up to 3 km wide and is overlain by a cover of over 170 m of Quaternary sediments. The Tertiary strata recovered from five boreholes within the basin mainly comprise grey to dark grey, thinly-bedded calcareous and dolomitic siltstone and mudstone, which are characterized by thinly laminated detrital and chemical cycle deposits. The sediments are rich in dolomite, calcite and albite with variable amounts of quartz, illite, pyrite, siderite, apatite, and carbonaceous matter. The fossil spore-pollen and ostracods indicate the strata are of early Tertiary age and they are correlated with the Ping Chau Formation of Hong Kong. Seismic reflection data indicates the Tertiary sediments are a well bedded sequence folded into a series of shallow synclines and anticlines dipping at angles of $<6^{\circ}$ to 20° . The limited evidence suggests that the Tertiary sequence is over 300 m thick.

摘要

担桿盆地位於香港島以南 5 公里，担桿列島西北 4 公里，埋於担桿水道海底的第四紀沉積物下。經物探資料證明該盆地全長 24 公里，寬 2.6 公里。出露地層屬平洲組。經鑽探只揭露了 64 米地層厚度，仍未見底部。主要由湖相的灰色至灰黑色薄層鈣質、白雲質粉砂岩和泥岩組成。其顯著特徵為有紋層狀碎屑沉積和化學沉積的交替韻律層。岩石富於白雲石、方解石、鈉長石和石英，並有數量不等之伊利石、黃鐵礦、菱鐵礦、和含碳物質。上部漸變為河流相的砂岩夾礫岩。從已發現的孢粉和介形蟲化石證據說明其年代屬早第三紀。

Introduction

A preliminary geological investigation of the area between Po Toi Island and Dangan Island included field visits to the Dangan and Po Toi Islands, an outline interpretation of Sparker seismic reflection records, and examination of drillcores, with the emphasis on stratigraphic and palaeontological studies. The investigation discovered a northeast-trending fault-bounded sedimentary basin approximately 24 km long and 3 km wide, located 4 km northwest of the Dangan Islands (Figs. 1 & 2). This also confirmed previous interpretation of a fault zone passing through the Dangan Channel (Lai, 1985). The

basin is flanked by Mesozoic granites and contains sedimentary rocks that are interpreted to be of early Tertiary age and correlated with the Ping Chau Formation of Hong Kong. The Lower Member of the Formation consists of dark grey to black, thinly bedded dolomitic siltstone and mudstone overlain by greenish grey, calcareous sandstone, with chert and conglomerate interbeds, of the Middle to Upper Members. From its structure and setting the Dangan Basin may be interpreted as a pull-apart depositional basin.

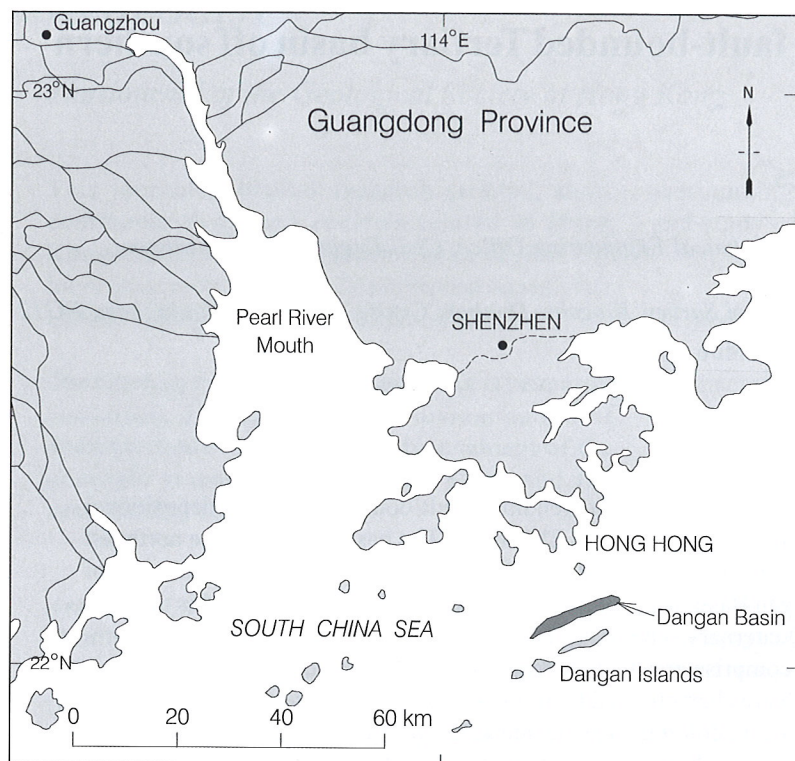


Fig. 1 - Location of the Dangan depositional basin

Stratigraphy

Cores from five boreholes (Fig. 2) in the Dangan Basin were examined. The cored Tertiary sediments indicate dips of about 20°. The sediments are divided into three members (Figs. 2 & 3). The Lower Member occurs in boreholes ZK3B and ZK5P/18579 (following the borehole number is the Geotechnical Information Unit report number), between -161.7 and -215.8 mPD and consists of dark grey to black, laminated dolomitic siltstone and calcareous mudstone (Plates 1 & 2). Some carbonized fossil plant

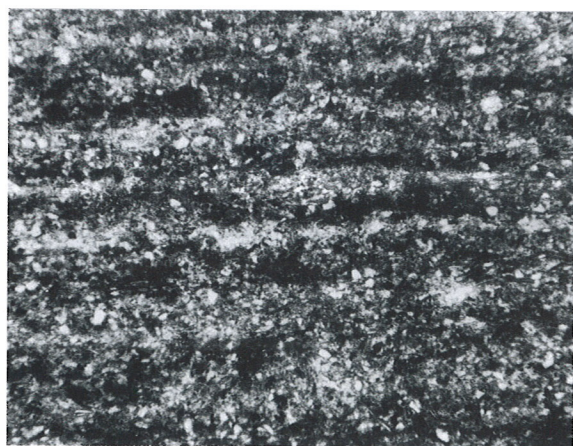


Plate 1 - Thin section of carbonaceous mudstone showing well developed very thinly laminated detrital deposits. Sample HK11800 of Borehole ZK5P at x20 magnification.

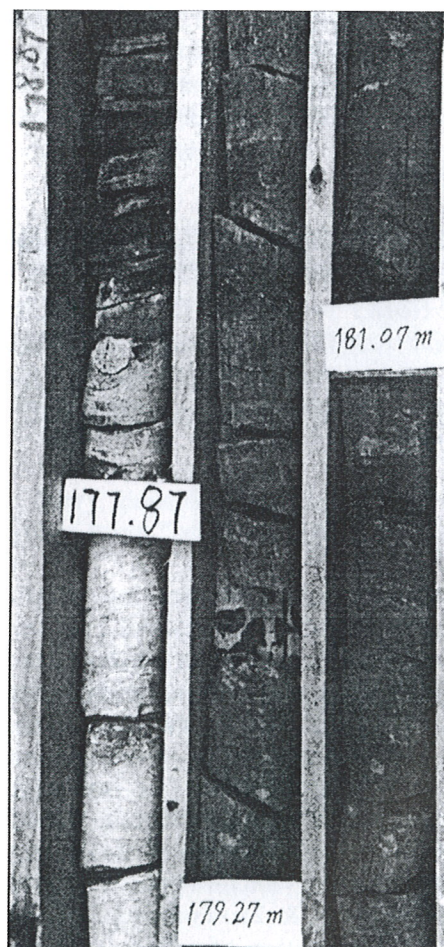


Plate 2 - Dark grey mudstone and greyish white calcareous siltstone core sample of borehole ZK3B from 177.6 m to 181.27 m.

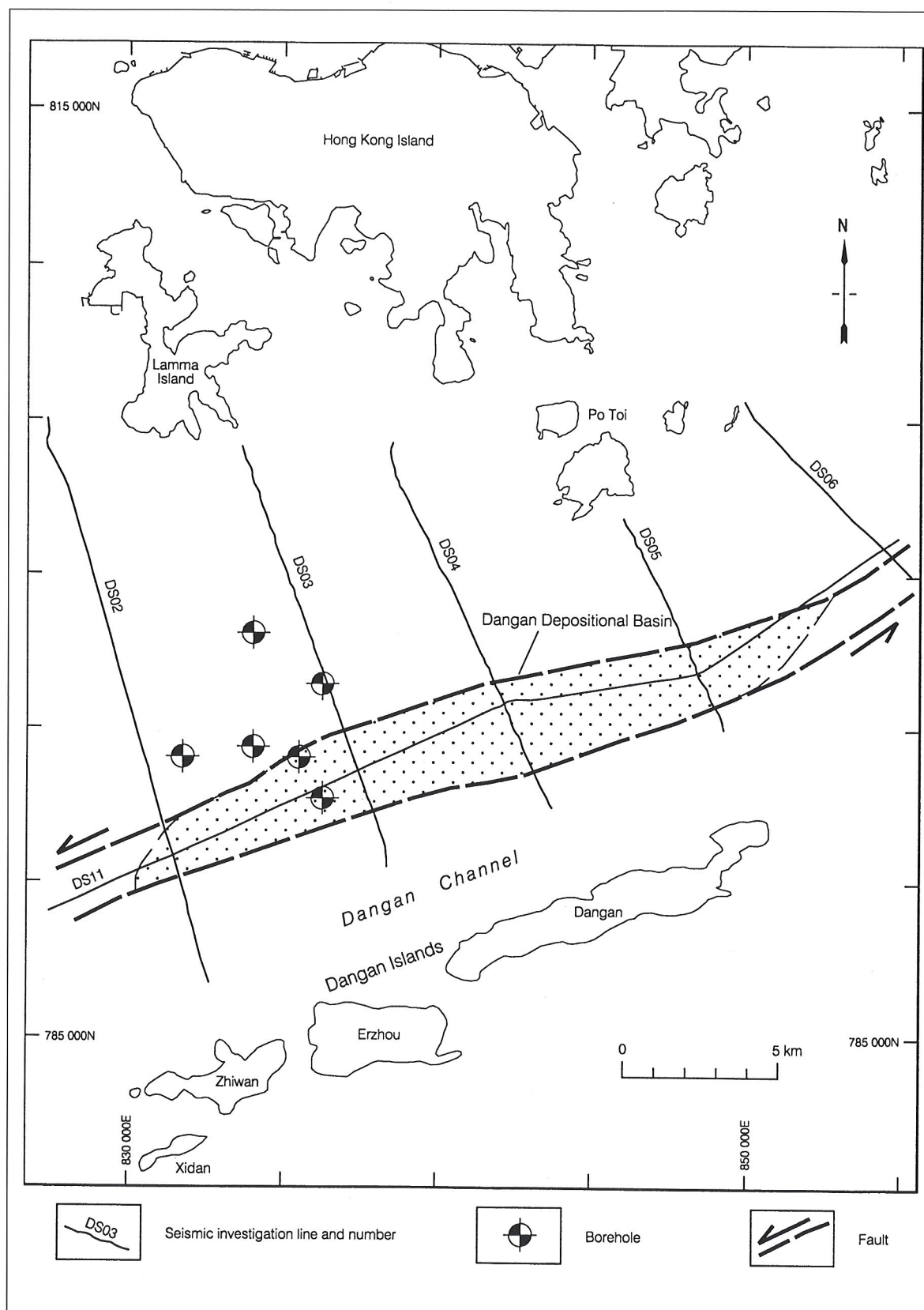


Fig. 2 - Site investigation of the Dangan depositional basin

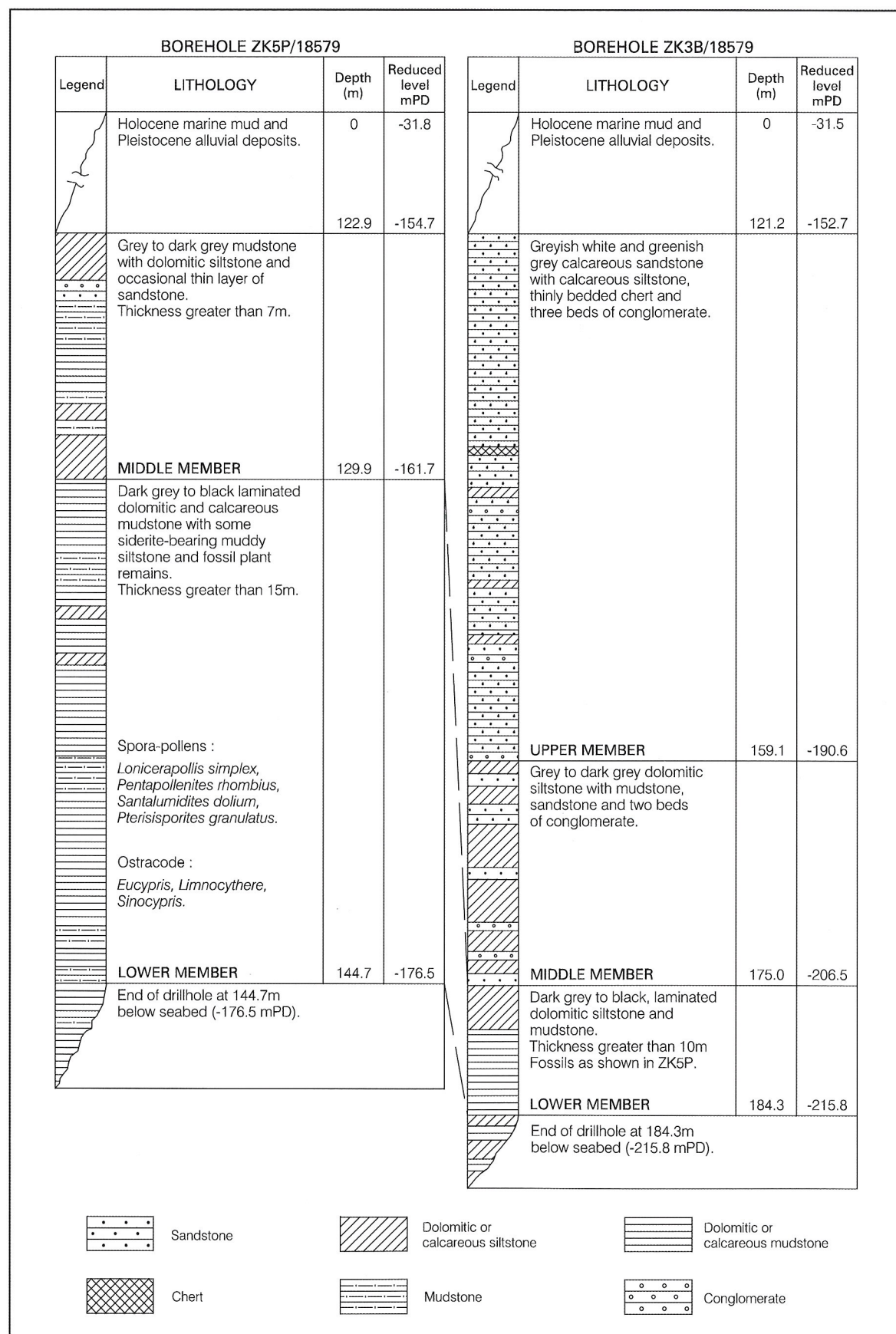


Fig. 3 - Lithostratigraphy of the Dangan depositional basin

fragments and microfossils are present. The base of the Lower Member was not reached in the boreholes and the thickness is >15 m. The lithology of the Lower Member is very similar to rocks of the Ping Chau Formation exposed at Ping Chau Island, Tai Pang Wan (Mirs Bay), Hong Kong (Peng 1983).

The Middle Member comprises grey to dark grey dolomitic siltstone with grey to greyish-white sandstone, mudstone and two layers of conglomerate. The cored thickness is 16 m. The sediment in Borehole ZK5P/18579 is generally finer than in other boreholes.

The Upper Member is only exposed in Borehole ZK3B/18579 and is composed of grey to greenish grey, fine- to coarse-grained sandstone with calcareous siltstone, thinly-bedded chert and three layers of conglomerate. The cored thickness is >38 m.

Structure

Boreholes and shallow Sparker seismic reflection data indicates that the Tertiary sediments lie within a faulted basin flanked predominantly by granites. The widely spaced seismic reflection records (Fig. 2) reveal that the sediments are a well-bedded sequence folded

into a series of shallow synclines and anticlines. The strike of the folds appears to generally run parallel, or at a slight angle, to the long northeast trending axis of the basin. Dips are relatively shallow, with apparent dips of <1° to 12°, the limited true dip measurement ranges from <6° to 10°. The low intensity of the folding is evidenced by the fact that only six fold axes are seen on seismic line DS11, which runs along the entire length of the Basin (Fig. 2). Of the four lines which cross the short axis of the basin, the two western lines, DS02 and DS03, only show beds dipping south towards the Dangan Islands. The beds in line DS04 also dip south with a synclinal axis only seen at the southern margin of the basin. The eastern line, DS05, has a single synclinal axis in the centre of the basin (Fig. 4).

The limited borehole evidence suggests in the north side of the basin the rock type is fine grained with more mudstone, whereas to the southeast it appears coarser with more sandstone and conglomerate. This may indicate sediment sources to the south, possibly high ground in the vicinity of the present Dangan Islands. The basin is bounded by ENE trending faults, which may be characterized not only by vertical but also by strike slip movement. Most strike slip faults found in the Hong Kong area are sinistral (Lai &

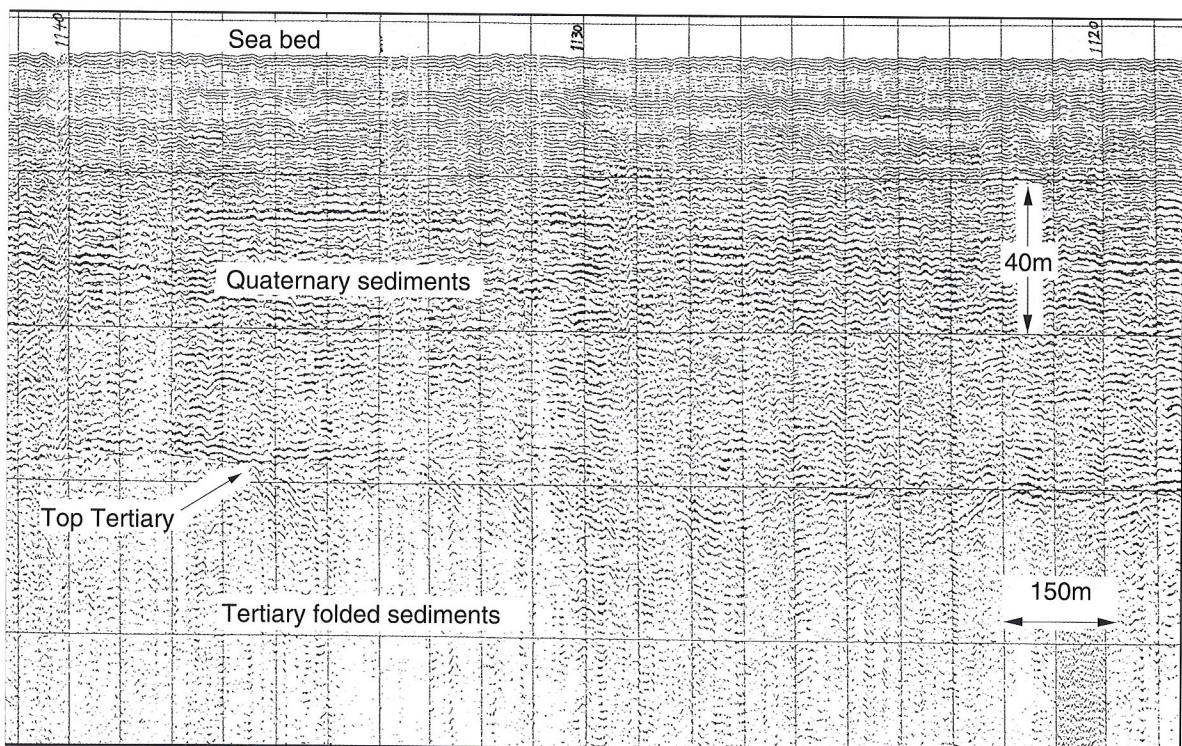


Fig. 4 - A sparker seismic profile on line DS05 across the Dangan Basin showing a synclinal fold in tertiary sediments beneath a thick sequence of Quaternary sediments

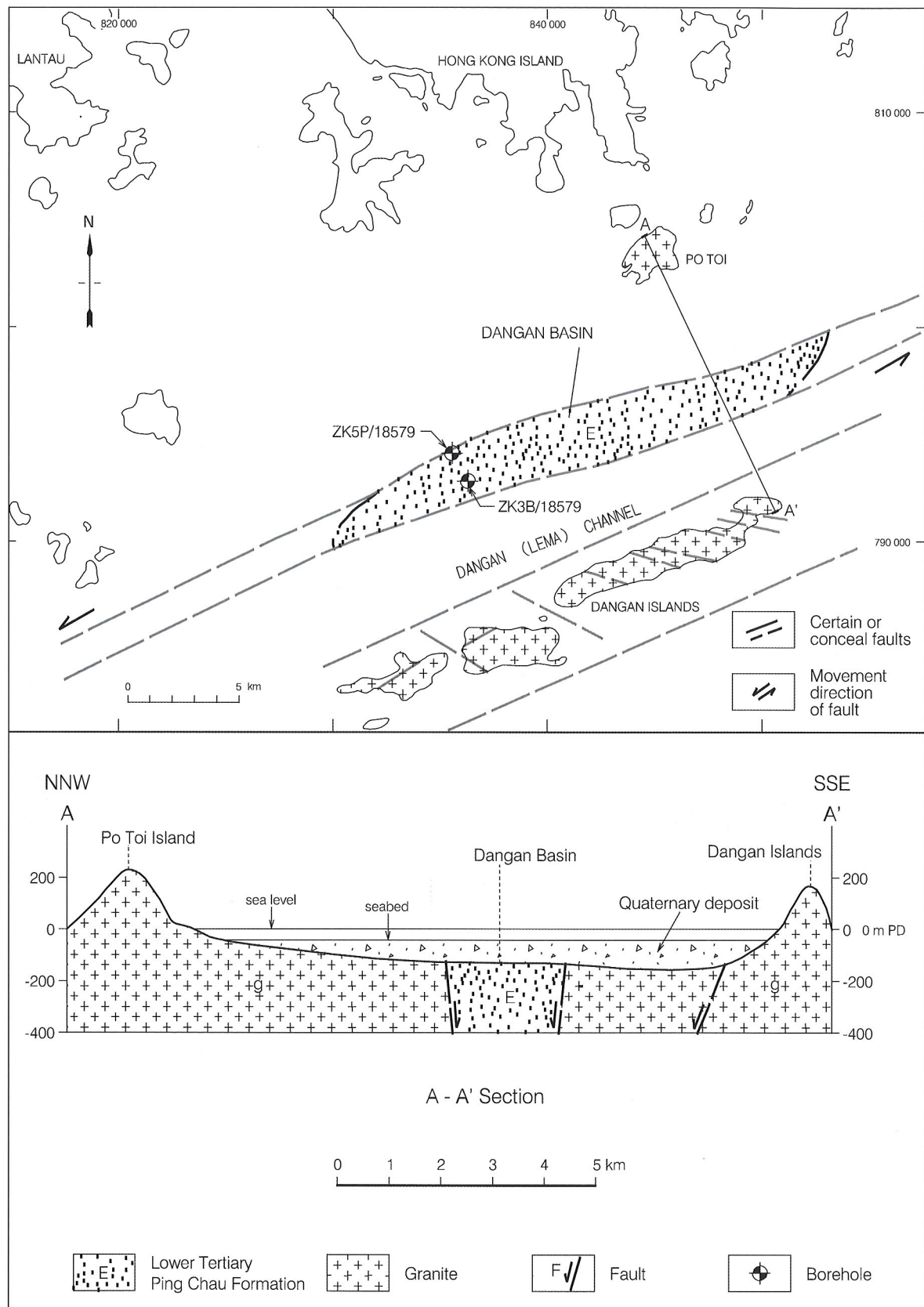


Fig. 5 - Geological structure of the Dangan depositional basin

Langford, 1996). It is possible that the Dangan depositional basin is a pull apart type and associated with strike slip movement (Fig. 5).

To the south of the Dangan Islands the tectonic features of the Pearl River Mouth Basin are different from the South China Folded Belt system on which Hong Kong and Guangdong are situated. The fault system in the Pearl River Mouth Basin trends east-northeast with tensional features, whereas the major fault system in the South China Folded Belt trends northeast, mostly with a compressive property. The east-northeast trend of the Dangan Basin and its structure and setting indicates that it should be regarded as part of the Pearl River Mouth Basin system.

In this area of the Pearl River Mouth Basin some strong earthquakes have occurred on east-northeast trending faults, with epicentres thought to be associated with junctions with NW trending faults (Ding & Guo, 1989). According to historic records the epicentre of the 1874

earthquake (Magnitude $M_s=5\frac{3}{4}$) was located close to, and east, of the Dangan Islands. (Ding & Lai, 1977). The seismic intensity at the epicentre was VIII, which affected Hong Kong at VII. The area has exhibited moderate seismic activity (Fig. 6).

Petrography

Dolomitic siltstone is common in the Dangan Basin. It has a mineral component consisting mainly of dolomite, calcite, quartz, and illite with albite and pyrite. Minor sericite and siderite are present. The grain size ranges from 0.01 to 0.03 mm. The albite forms subhedral crystals, whereas the dolomite is euhedral. The rocks generally contain approximately 30 to 35% dolomite. The rocks in thin section are characterized by thinly interlaminated detrital deposits, including feldspathic siltstone, mudstone, carbonaceous matter, and chemical sediments (mainly clayey dolomite). The laminae vary from 0.5-3 mm thick.

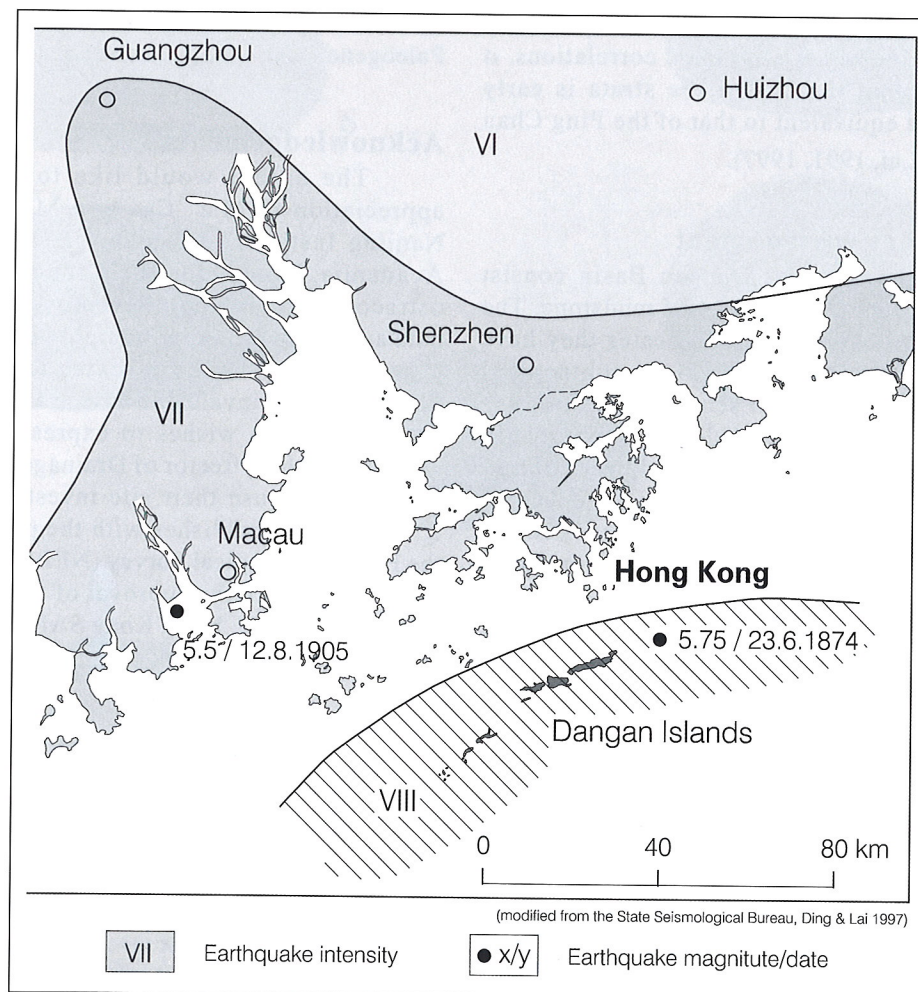


Fig. 6 - Seismic intensity zoning map of the study area

Chert also occurs in the basins. It is greyish green, massive, and very hard. In thin section, it consists mainly of anhedral intergrowths of quartz (more than 90%). Most quartz is fine- to very fine-grained (0.01 mm) and probably recrystallized from opal. Rhombs of dolomite also occur, and are a secondary development of late diagenetic origin. Albite is scattered as clastic grains (0.015 mm).

Palaeontology

The fossils found in the Dangan Basin include the ostracoda assemblage: *Sinocypris curtovata* (Zhang), *Eucypris curta* (Zhang), *Eucypris cf. sanshuiensis* (Zhang), and *Cypris cf. buxinensis* (Zhang) (Plate 3). The spores of the pteridophyta are dominated by *Verrutetraspora* and *Pterisisporites*. Gymnosperm pollen are mainly *Classopollis*. Angiosperm pollen consist of various tricolporate grains such as *Pentapollenites*, *Rhoipites*, *Rutaceoipollis*, *Lonicerapollis* and *Nuxpollenites* (Plate 4). Based on the most recent fossil evidence and stratigraphic correlations, it is believed that the age of the strata is early Tertiary and equivalent to that of the Ping Chau Formation (Lai, 1991, 1997).

Sedimentary environment

The strata in the Dangan Basin consist mainly of dolomitic siltstone and mudstone. The composition of these rocks indicates they have been deposited in a tropical to subtropical brackish water lake under semi-arid conditions.

The Lower and Middle Members are characterized by well-developed, very thinly laminated detrital and chemical cycle deposits. In the detrital cycles, the presence of carbonaceous matter and siltstone layers reflects a relatively humid period. In the chemical depositional cycles, the carbonate layers indicate dry periods. The interlaminated layers are interpreted as reflecting seasonal fluctuations of lacustrine water level and salinity. The Upper Member of the strata in the basin mainly consists of sandstone and conglomerate, reflecting fluvial deposition which may locally be a colluvial deposit.

The abundant flora present in the strata, however, indicates that a relatively warm and humid climate must have existed, contrasting with the hot and arid climate predominating in the late Cretaceous.

Stratigraphic comparison with strata of depositional basins in south Guangdong

The sporopollen assemblage from the strata comprises *Lonicerapollis simplex*, *Pentapollenites rhombius*, *Santalumidites dolium*, *Pterisisporites*, *Verrutetraspora*, *Inaperturopollenites*, *Ulmipollenites*, *Ulmoidipites* and *Subtriporopollenites*.

Palynological comparison of the deposits with strata of the Sanshui Basin, Guangdong, indicates that the Dangan Basin sediments are the equivalent of the Paleogene Buxin Group. The Dangan Basin and the Sanshui Basin have similar rock types and are situated between the same latitudes (22° to 23°N) and are only 120 km apart. Therefore, they are likely to reflect the same palaeoclimate in their sediments. In the Sanshui Basin, the dark grey fine-grained clastic sedimentary rocks of the early Tertiary reflect a relatively warm and humid climate and a stable crust. The nearby Dongguan and Xinhui basins also contain the same early Tertiary sedimentary rocks. A lithostratigraphic comparison of the strata with those of the Sanshui Basin also indicates that the strata are equivalent to the Paleogene Buxin Group (Lee *et al.*, 1991, 1997).

Acknowledgements

The author would like to express his appreciation to M.Z. Cao and M.Y. Li of the Nanjing Institute of Geology & Paleontology, Academia Sinica, for their identification of ostracoda and sporopollen, provision of their data and cooperation in the fieldwork.

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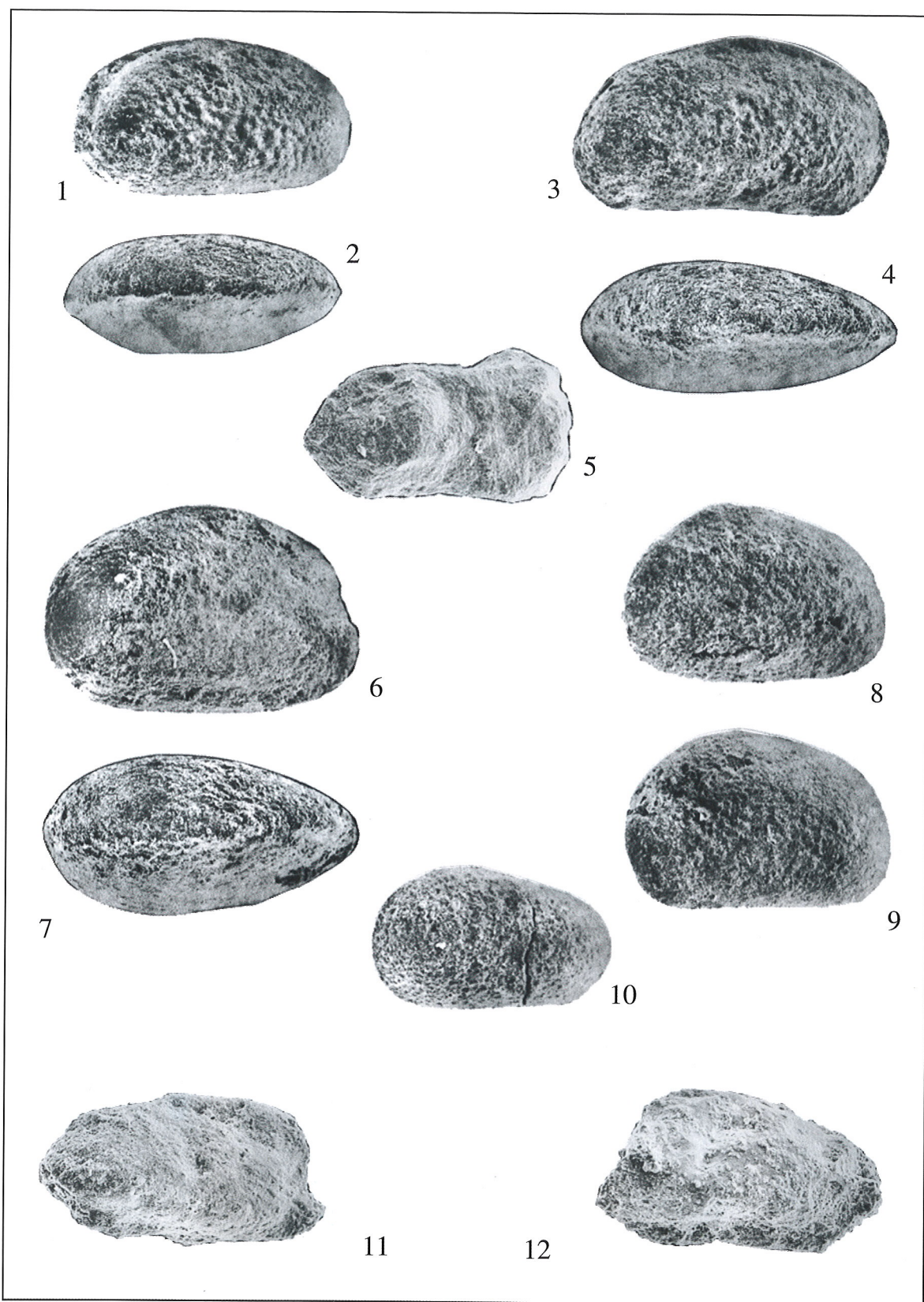


Plate 3 - Ostracoda. Identified by M.Z. Cao of the Nanjing Institute of Geology & Paleontology, Academia Sinica. Magnification: 1-4, 6-9 x 60; 5, 10 x 80; 11-12 x 100. 1 - 2. *Sinocypris* sp.; 3 - 4. *Eucypris* cf. *Sanshuiensis* (Zhang); 5. *Limnocythere* sp.; 6 - 9. *Sinocypris curtovata* (Zhang); (from Sample HK11789 of Borehole ZK3P/18579, -198.96 mPD); 10. *Sinocypris* sp. (from Sample HK11800 of Borehole ZK5P/18579, -160.38 mPD); 11-12. *Limnocythere* sp. (from Sample HK11803 of Borehole ZK5P/18579, -169.78 mPD)

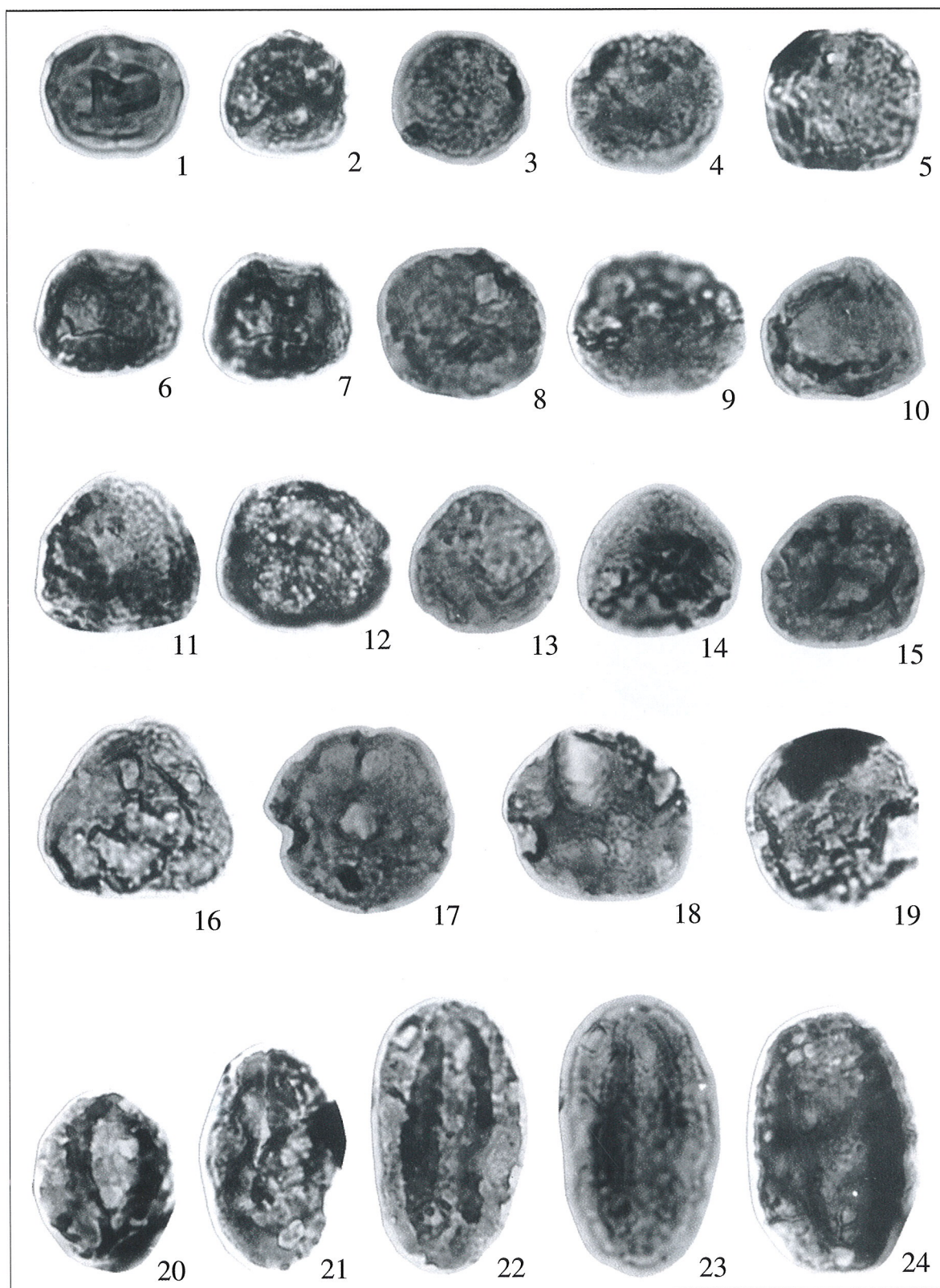


Plate 4 - Sporopollen. Identified by M.Y. Li of the Nanjing Institute of Geology and Paleontology, Academia Sinica. Magnification x800. 1. *Alnipollenites* sp.; 2 - 5. *Ulmipollenites* cf. *granulatus* (Stone); 6 - 7. *Ulmoideipites* cf. *granulatus* (Song, Li & Zhong); 8 - 9. ?*Ulmipollenites* sp.; 10. ?*Plicapollis* sp.; 11-12. *Subtriporopollenites granulatus* (Sung & Lee); 13. *Subtriporopollenites tuberosus* (Sung & Lee); 14-15. ?*Subtriporopollenites* sp.; 16. *Triporopollenites* sp.; 17-19. *Tiliaepollenites* sp.; 20. *Quercoidites solidus* (Song, Li & Zhong); 21-24. *Tricolporollenites* spp. (all from the Sample HK11801 of Borehole ZK5P/18579, Depth -160.48 mPD).

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The application of CIC and CRS models for the determination of sediment ages and sedimentation rates in two marine parks, Hong Kong

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Abstract

This paper discusses the use of Constant Rate of Supply (CIC) and Constant Initial Concentration (CRS) models for the determination of sediment ages and sedimentation rates. Two short cores were collected for palaeoenvironmental studies from Yan Chau Tong and Hoi Ha Wan Marine Parks in northeastern Hong Kong. The CRS and CIC models were used to determine the ages of core deposits and the rate of sedimentation, based on the deposition of ^{210}Pb . The results show that depositional mechanisms vary in the two marine parks. In general, the CRS model can be applied to infer sedimentation patterns when extreme events have occurred during deposition, whereas the CIC model is more applicable for stable environmental situations.

摘要

本文解釋位於香港東面的印州塘和海下灣海岸公園沉積環境演變。本文量度了兩枝岩柱芯的 ^{210}Pb 放射性同位素，並利用 ^{210}Pb 恆定補給速率(Constant Rate of Supply, CRS)模式和常量初始濃度(Constant Initial Concentration, CIC)模式，進行了海底沉積物的沉積速率和沉積年代測定，從而討論CRS和CIC模式作為計算印州塘和海下灣的岩柱芯沉積之可能性。

Introduction

Seabed sediments are the final depositional sites for pollutants, weathered debris and eroded material derived from coastal and inland areas. They also preserve a record of environmental change at the depositional site. A variety of techniques are available for dating seafloor sediments, but the choice of technique depends on their precise age. For Holocene and later Pleistocene deposits ^{14}C methods are commonly used. However, very young (decadal) sediments require a different approach. For example, the activity of ^{210}Pb in deposits was used to determine modern sedimentation rates and sediment ages during investigations of trace elements and heavy metals in Deep Bay (Wong, 1989) and Sai Kung (Lo, 1992). This paper examines environmental change at Yan Chau Tong and Hoi Ha Wan Marine Parks, and focuses on the use of Constant Rate of Supply (CRS) and Constant Initial Concentration (CIC) ^{210}Pb models in the determination sediment age and accumulation rates.

Physical environmental setting

The Agriculture Fisheries and Conservation Department, AFCD, established the Yan Chau Tong

and Hoi Ha Wan Marine Parks to protect the local marine ecosystems and habitats. In both areas, water depths exceed 10 m (Fig. 1). Volcanic rocks surround Hoi Ha Wan, but only occur to the southwest of Yan Chau Tong, where sedimentary rocks dominate elsewhere. Sampling sites are shown in Figure 1.

The Yan Chau Tong Marine Park is comprised of two separate parts, with a total sea area of about 680 hectares. The portion at Yan Chau Tong (Double Haven) is bounded by the coastline of the mainland in the west and Wong Wan Chau (Double Island) to the east. The northern and southern boundaries of the marine park is demarcated by lines linking Sha Ngam Tau to Sai Lau Kong and Lo Sha Tin to Tong Pau Tau, respectively. The portion next to Lai Chi Wo is bounded by a line linking Chung Wan Tsui and the northern tip of Kau Lo Tau. All the landward boundaries are demarcated by the high water mark. The water depth in Yan Chau Tong is up to 20 metres deep. A major creek enters the sea on the south-western shoreline. The surrounding islands and mainland are dominated by volcanic (Tai Mo Shan Formation) and sedimentary (Pat Sin Leng Formation) rocks.

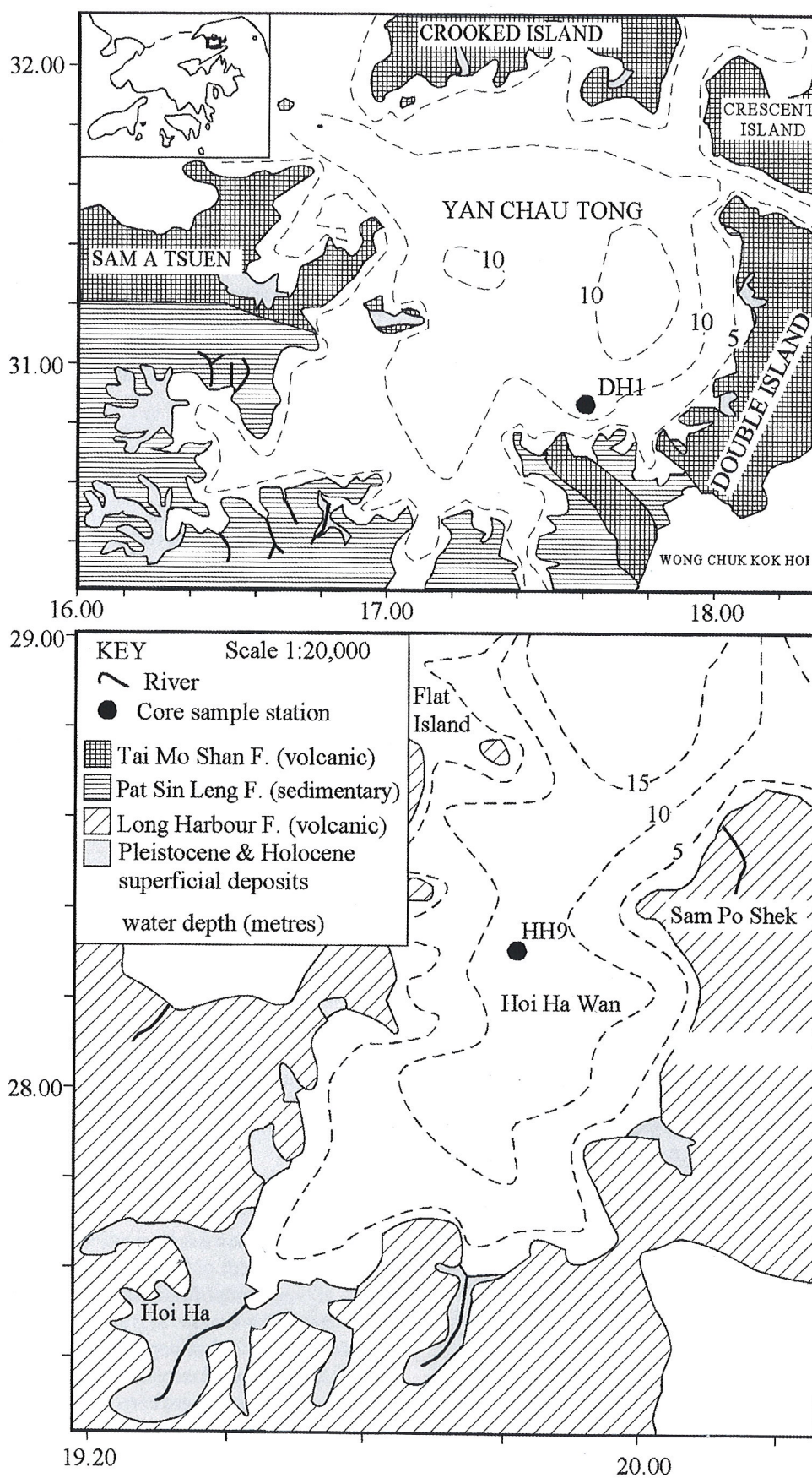


Fig. 1 - Core sample stations in Yan Chau Tong and Hoi Ha Wan

The Hoi Ha Wan Marine Park lies in a sheltered bay situated along the northern coastline of the Sai Kung Country Park. The marine park covers an area of about 260 hectares, with its seaward boundary being delineated by a line linking the tip of Heung Lo Kok to the tip of Kwun Tsoi Kok. The landward boundary follows the high water mark along the coastline. The water depth ranges between 0-16 metres. One major creek enters the bay from the south. Late Pleistocene and Holocene superficial deposits occur near rivers. The bedrocks are composed of volcanic tuffs of the Long Harbour Formation.

Sample Collection and Tests

Core DH1 and HH9 (Fig. 1) were collected from Yan Chau Tong and Hoi Ha Wan by a gravity corer system in 1996-97. The measurements of ^{210}Pb activity were performed by the Nanjing Institute of Geography and Limnology in 1997, using alpha ray counting. The determination of rates of sedimentation and sediment ages were based on Constant Rate of Supply (CRS) and Constant Initial Concentration (CIC) models.

The Principles of ^{210}Pb dating

The measurement of ^{210}Pb deposition is of central importance for environmental reconstructions for decadal time periods. Measured ^{210}Pb activities reflect core depth and sediment age, as well as sediment accumulation rates (Oldfield & Appley, 1984).

^{210}Pb , with a half-life of 22.26 ± 0.22 years (Goldberg 1963), is one of several short-lived daughter isotopes that are produced from the decay of radon. Atmospheric radon (^{222}Rn) is, in turn, a naturally occurring radioactive gas derived from the decay of radium (^{226}Ra), the daughter radionuclide of uranium (^{238}U) contained within the Earth's crust. The general residence time of ^{210}Pb in the atmosphere is between 5 and 10 days before it is deposited onto the Earth's surface (Krishnaswami & Lal, 1978). Having settled, ^{210}Pb is then quickly absorbed by soils on land, or is stripped from oceanic or lacustrine waters by sediment deposition. The situation described above is further complicated by the presence of uranium and radium in sediments, with *in situ* decay of these elements continuously supplying ^{210}Pb to deposits at all depths.

In this way, the decay of ^{210}Pb within sediments is comprised of two components termed the "background" and "excess" activities. The "background" activity reflects *in situ* sediment production of ^{210}Pb , whereas the "excess" activity is derived from the decay of ^{210}Pb deposited from the atmosphere. Consequently, the calculation of ^{210}Pb activity, as used for deducing chronologies, is based

on the following general assumptions:

- 1) Atmospheric fallout of "excess" ^{210}Pb into sediments is constant,
- 2) the deposition of excess ^{210}Pb into sediments is rapid, and involves minimal dispersal within the water column,
- 3) the concentration of excess ^{210}Pb within sediments reflects only its exponential decay.

These assumptions either relate to delivery of ^{210}Pb to the sediments or to sedimentological processes that may affect ^{210}Pb concentrations. Two alternative models may be used in ^{210}Pb dating:

- 1) *^{210}Pb dating chronology by the Constant Initial Concentration (CIC) model.*

An initial concentration of ^{210}Pb exists at A_0 (dpm/g) to A_z (dpm/g) depths, so that a decay ratio of excess ^{210}Pb at depth z (g/cm²) is obtained by assuming a constant of ^{210}Pb activity at depth 0 against excess ^{210}Pb within the depositional sequence:

$$T_z = \lambda^{-1} \ln(A_0/A_z) \dots \dots \dots \text{(equation 1)}$$

Where: λ^{-1} = decay constant of ^{210}Pb (0.031a^{-1})
 A_0 = excess ^{210}Pb activity at depth 0
 A_z = excess ^{210}Pb activity at depth z
 T_z = difference in ages between depth 0 and depth z in years

- 2) *^{210}Pb dating chronology by the Constant Rate of Supply (CRS) model.*

The CRS model assumes a constant flux of excess ^{210}Pb to the sediment system, but allows the rate of sedimentation to vary over time. The CRS model calculates ages based on the total activity of excess ^{210}Pb in the sediment column:

$$T_z = \lambda^{-1} \ln(\Sigma(A_z)d_z / (\Sigma(A_t)d_t)) \dots \dots \dots \text{(equation 2)}$$

Where: λ^{-1} = decay constant of $^{210}\text{Pb}_{\text{ex}}$ (0.031a^{-1})
 d_t = depth of the whole sediment core
 d_z = depth of sediment core at depth z
 $\Sigma(A_z)d_z$ = excess ^{210}Pb activity of sediment below depth z
 $\Sigma(A_t)d_t$ = total excess ^{210}Pb activity in the sediment core
 T_z = difference in ages between depth 0 and depth z in years

Results

The Levels of ^{210}Pb activity in Yan Chau Tong and Hoi Ha Wan

The background level of ^{210}Pb activity is 1.01dpm/g at Yan Chau Tong, and 0.97dpm/g at Hoi Ha Wan. These variations may be due to differences between local bedrock sources of ^{210}Pb , or could be related to differences in atmospheric fallout rates. The ^{210}Pb activities for core sediments from Yan Chau Tong and Hoi Ha Wan are plotted in Figure 2.

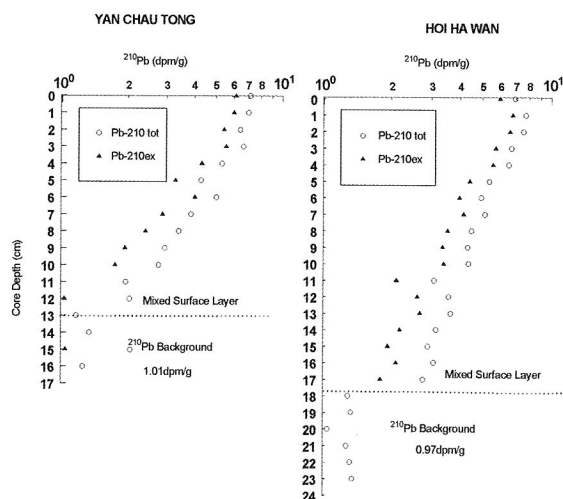


Figure 2 - Profiles for total and excess Pb-210 activity in Yan Chau Tong and Hoi Ha Wan

The ^{210}Pb activity profiles for cores DH1 (Yan Chau Tong) and HH9 (Hoi Ha Wan) represent the upper 16 cm and 24 cm of the seafloor sediments, respectively. For core DH1, total ^{210}Pb activity lies between 1.25-7.17dpm/g, with excess ^{210}Pb activity ranging from 0.16 to 6.16dpm/g. The ^{210}Pb activity falls to background levels at 13 cm depth. The levels of ^{210}Pb activities display a clear pattern of decline within the 5-13 cm depth interval, which suggests a constant sedimentation pattern.

Total ^{210}Pb activity and excess ^{210}Pb activity in core HH9 ranges between 1.05-7.73 dpm/g and 0.08-6.76 dpm, respectively. ^{210}Pb activity displays a clear decline between 2 cm and 18 cm, with constant background levels characterising the lower 6 cm. In contrast, variable profiles occur in the upper 5 cm of core DH1, with ^{210}Pb rising between 0 and 1 cm in HH9. The upper profile variability may be caused by mixing or disturbance of the sediment column. In the offshore areas of Hong Kong this may be caused by bioturbation, but trawling effects may be having a significant impact as well. A further possible source of error might relate to the act of sampling, which can

cause a mixing of loose surficial sediment or even loss of upper sediment layers as the corer impacts the seabed.

Correlation between excess ^{210}Pb and core depth

Though the total levels of ^{210}Pb activity display an exponential decline with depth, the determination of sediment age and deposition rates derives from an examination of excess ^{210}Pb activity. The results of correlation between excess ^{210}Pb activity and core depth for cores DH1 and HH9 are plotted in Fig. 3. The results, for both cores, show over 0.9 coefficients at $p=0.01$ for excess ^{210}Pb activity. The linear distributions of coefficients for excess ^{210}Pb (Fig. 3) suggests that CIC and CRS models can be used to determine sediment ages and sedimentation rates in the two marine parks.

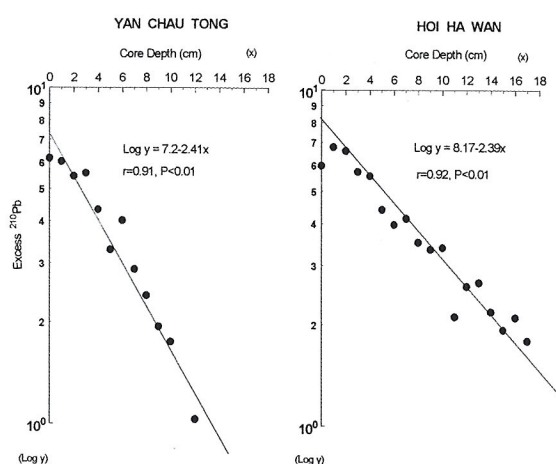


Figure 3 - Correlation test for excess Pb-210 activity in Yan Chau Tong and Hoi Ha Wan

^{210}Pb dating chronology using CIC and CRS models

Sediment ages determined by the CIC and CRS models are shown in Fig. 4 for cores DH1 and HH9. The distribution of sediment ages in both profiles, using the CIC model, are discontinuous. Four breaks can be observed in terms of profile gradients in DH1. The upper part of the curve (0-3cm depth) for sediment ages is the steepest. The largest potential error occurs in the basal part of the core between 12-16 cm. These results show that age determination by the CIC model tends to be more appropriate for the upper layers than in the basal parts of the profile. Using this model, the bottom of the core is dated at 104 years. In contrast, the CRS model generates a concave upwards curve. Errors decrease constantly up the profile, with the gradient being steepest in the upper layer (0-9 cm) and almost linear between 0-6 cm. The oldest sediments, using the CRS model, are dated at 65 years, which is significantly less than the age determined by the CIC model.

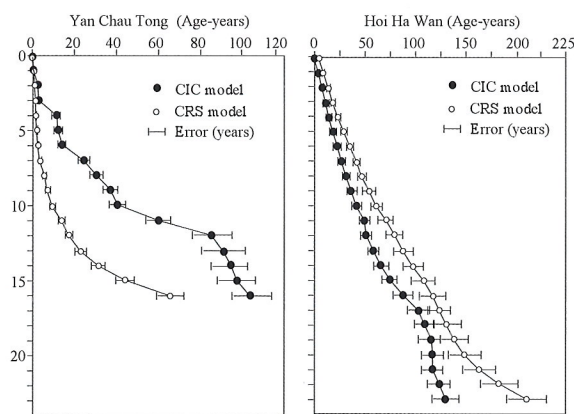


Figure 4 - Pb-210-inferred (CIC) and (CRS) sediment ages for core DH1 (Yan Chau Tong) and HH9 (Hoi Ha Wan)

The sediment age profile inferred by the CIC model for core HH9 (Fig. 4) is discontinuous with the age/depth gradient being relatively steep in the upper layers. The base of the core is dated at 130 years, which contrasts strongly with the age derived by from the CRS model (211 years). Sediment ages display a linear profile. The ages are expressed with an uncertainty of ± 1 SD (standard deviation). The uncertainties include errors involved in measuring isotopic activity, in determining the half-life of ^{210}Pb , in modeling variations in excess ^{210}Pb activity with sediment depth, and also the propagation of these errors at each stage of the calculation.

The chronology of the sedimentation rate at Yan Chau Tong and Hoi Ha Wan

Sedimentation rates for core sediments at Yan Chau Tong and Hoi Ha Wan determined by the CIC and CRS models are plotted in Fig. 5. At Yan Chau Tong, the sedimentation rates based on the CRS model ranged between 0.06-1.47 g/cm², while the CIC model suggested values of 0.04-0.34 g/cm². The highest sedimentation rate determined by CRS is >4 times greater than that indicated by the CIC model. Sedimentation rates fluctuate greatly in the upper profile (0-5 cm) dating to about 1980-1997 for both models. The difference between the two profiles may result from the different assumptions that form the basis for determining the sediment chronology. Furthermore, the sedimentation rates for recent surficial deposits may reflect modern human impacts on sedimentation. These include trawling activities and mass mortality events at Yan Chau Tong.

At Hoi Ha Wan, the sedimentation curves determined by CIC and CRS are quite different. The rates obtained from the CRS model lie between 0.051-0.57 g/cm², while for the CIC model they range from 0.061-0.149 g/cm². Both the CIC and CRS models indicate a peak sedimentation rate at 1 cm depth (=1995).

The CRC model also indicates two levels (at 6-7 cm and 17-18 cm) characterised by very low sedimentation rates, representing 1962 and 1873. These sharp changes in the CRS sedimentation rate may indicate the occurrence of storm events at Hoi Ha Wan.

Discussion

Application of ^{210}Pb dating chronology

An obvious difference exists in sediment ages determined by the CIC and CRS models. Generally, sediment ages determined by the CIC model are younger than those derived from the CRS model, with the exception of two possible disturbances in the deposition rate. Differences in the errors for CIC and CRS sediment ages show that age determination is dependent on the model being used, and reflects the specific premises and assumptions involved. Variations between the two sites may be attributed to the different sedimentary environments in the respective marine parks.

One of the major assumptions is that atmospheric fallout of excess ^{210}Pb activity is constant through time. This premise is not strictly valid as demonstrated by several studies located at a variety of sites worldwide (Krishnaswami & Lal, 1978). However, given that seabed sediments accumulate over periods of several years, interannual variation of ^{210}Pb deposition is likely to be averaged out, so that this premise looks reasonable. Another assumption is that ^{210}Pb deposition into the seabed sediments is rapid and that dispersal within the deposits is minimal. This premise is also acceptable as dispersion in shallow marine regions have been found to be negligible (Koide *et al.*, 1972). Furthermore, significant amounts of excess ^{210}Pb are also assumed not to be eroded from

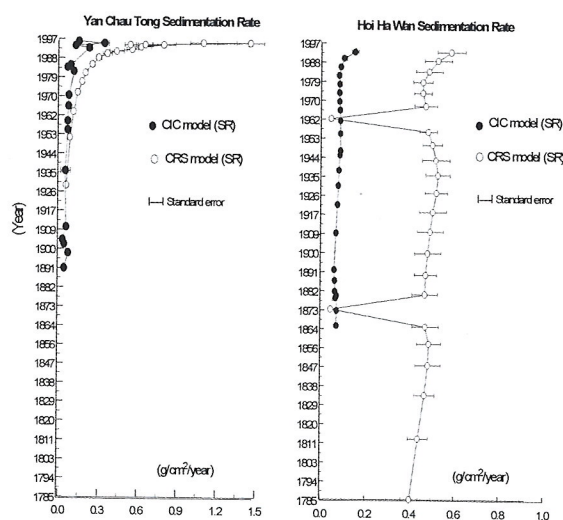


Figure 5 - The chronology of sedimentation rates found in Yan Chau Tong and Hoi Ha Wan

the adjacent catchment area (Gale *et al.*, 1995). The concentration of excess ^{210}Pb within sediments is therefore assumed to only depend on its exponential decay.

In summary, background ^{210}Pb activity is assumed to be constant with depth, and the ^{210}Pb is assumed to not diffuse within sequences or be reworked by wave action, bioturbation, or by the act of sampling. If redistribution of ^{210}Pb by diffusion or mixing is suspected the dating procedure should be evaluated by independent dating methods and it may be necessary to use complex mathematical models that are based on further assumptions about the width of mixing or diffusion depths (Joshi, 1989).

Yan Chau Tong Sedimentary Environment

The ^{210}Pb dating results show that Yan Chau Tong is more likely to have experienced bioturbation in the depositional sequence. Abrupt changes in the rates of sedimentation in the uppermost layers may be due to burrowing organisms or trawling activities. The depositional sequence is highly disturbed and unsuitable for estimation of sediment ages and sedimentation rates as shown in CRS model, which shows relatively young sediment ages and high sedimentation rates.

The break in sediment ages at around 1990-1995 (2-8 cm depth) suggests that the depositional

sequences may be mixed by burrowing organisms. The occurrence of disturbance is in accord with the presence of shell fragments and feeding voids observed in REMOTS images (Geotechnical Engineering Office of Hong Kong, 1993) from stations at Yan Chau Tong (Plate 1). The REMOTS images also display extremely dark-coloured sediments with black patches indicative of reducing (anoxic) conditions. Bioturbation clearly occurs in the area and influences the depositional sequence.

Hoi Ha Wan Sedimentary Environment

The profiles for the sedimentation rates determined by the CRS and CIC models at Hoi Ha Wan are similar. The sedimentation rates estimated by the CRS model are higher than the estimates by the CIC model. The average sedimentation rate ($0.08\text{g}/\text{cm}^2/\text{year}$) determined by the CIC model is lower than the average rate ($0.5\text{g}/\text{cm}^2/\text{year}$) estimated by the CRS model. Also, sediment ages are younger when determined by the CIC model than by the CRS model for the same depth interval. This result is opposite to that determined by CRS modeling at Yan Chau Tong. The REMOTS images from stations at Hoi Ha Wan (Plate 2) show that the burrowing activity of organisms is less significant at Hoi Ha Wan than at Yan Chau Tong. Thus, it is possible that the deposits are less disturbed by burrowing organisms.



Plate 1. Remots images taken from station SK-21 and SK-22 at Yan Chau Tong. Left image shows originally dark-coloured sediments with black patches, suggesting reducing (anoxic) conditions. Shell fragments and feeding voids are common. The right image shows a void at depth (arrow) formed by burrowing activities. Scale = image width is 15cm. Geotechnical Engineering Office of Hong Kong, 1993.

The sedimentation rate profiles estimated by both CRS and CIC models show more consistent trends at Hoi Ha Wan, with the exception of two extreme values dated at about 1964 and 1875. The records of climatic events in Hong Kong (Year Book of Hong Kong 1954-1996, Hong Kong Government Publishers), show that 5 typhoons occurred in 1964. Heavy rainfall from Typhoon Ida and Typhoon Dot induced landslides in August and October of 1964. It is possible, though not provable, that at sea these extreme events may have resulted in storm erosion. The occurrence of typhoons and storms can induce a redistribution of sediment on the sea floor. Therefore, a single event could explain the decreased sedimentation rates at 6-7 cm depth in the CRS sedimentation profile. Unfortunately, there is no record of a climatic event that might explain the presence of the second distinct low in sedimentation rate for 1875.

Conclusion

Although the CRS model is a less effective means of displaying all extremes in the deposition sequence, the profile of CRS sedimentation rates is more likely to correspond to the events of sedimentation sequence in the two marine parks. It is hard to use a

single chronological method to determine sediment ages and sedimentation rates in depositional sequences. Analysis of dating chronology will be more effective if used in conjunction with good documentary records or other chronological markers. To some extent, the CRS model can be applied to estimate the sedimentation rates for the short cores when variations exist in the depositional sequence, while CIC model tends to be applicable in a stable environment.

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Plate 2 Remot images taken from station SK-15 at Hoi Ha Wan. The left image shows black patches and small scars resulting from the burrowing activities of organisms. The right image shows sediment clumps and shell fragments on the seabed surface. Scale = image width is 15cm. Geotechnical Engineering Office of Hong Kong, 1993.

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Mangroves as land builders

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The role of mangroves as land-builders has interested geographers, geologists, foresters, botanists, ecologists and even agriculturalists for many decades. This paper reviews and critically examines this question from a world-wide perspective, using a wide range of existing data together with some new information from Hong Kong and New Zealand. The geomorphological role of mangroves as agents of sedimentation grows in relevance and importance as the prospect of future changes in sea level increases due to global warming.

摘要

數十年來，無數地理學家、地質學家、林務人員、植物學家、生態學家以及農業專家均對紅樹林作為土地締造者的角色深感興趣。本文從現有的數據以及一些從香港及新西蘭搜集得來的資料，從全球觀點去回顧及評論紅樹林作為土地締造者的角色。此外，本文亦會從地貌學的觀點探討因全球變暖而引起水位上升時，紅樹林作為一個沉積促進媒介的相關性及重要性。

Introduction

Mangroves are intertidal coastal woodlands. Depending on their position in the zone between low and high tide, they can be covered or partly covered at each tidal cycle. They are widespread in tropical and subtropical regions, along coasts of low relief protected from high energy waves. They reach their best development in estuarine areas where sediment-laden rivers meet the sea. The extensive tidal mudflats of Mai Po at Deep Bay are Hong Kong's best known example of mangrove environments, but other sites occur in the numerous protected bays spread throughout the region. Those at Chek Keng and Sai Wan (Plates 1-3) in Sai Kung East Country Park are excellent examples of smaller mangrove sites that have been less influenced by human action than those found at Mai Po.

Over time, the build up of sediment in shallow coastal areas can rise above mean sea levels. The result is new land formation; a sort of natural reclamation process. This paper examines the role of mangroves in the accumulation of coastal deposits.

Firstly, the term sediment is defined, this is then followed by a description of how mangrove trees and shrubs can contribute to sedimentation and land building. The paper then examines the methods used to study sedimentation. Finally, the evidence for mangroves as land builders is critically examined using both local (Hong Kong) and global case studies.



Plate 1 - A typical seasonal sand bar plugs the mouth of the Sai wan estuarine habitat during winter.



Plate 2 - The Sai Wan mangrove-fringed inlet: a saline waterlogged winter situation alternates with a brackish tidal summer condition. This creates unusual sedimentation patterns at this remote coastal habitat.

Sediment and sedimentation

Surprisingly perhaps, the word sediment is not easy to define in a way that pleases everyone. Geographers, geomorphologists, geologists, ecologists and engineers do not define sediment in exactly the same way. Scientific opinion and philosophy can differ, especially in environmental studies where people from many different disciplines gather.

In essence, the term sediment refers to solid fragments of rock, such as particles or grains that have been transported and deposited. At one time, earth scientists defined sediment as the solid material that settled after being suspended in a liquid such as a stream, river or seawater. Today however, the term is used to include all fine, loose material transported and deposited by the agents of water (fluvial, estuarine, marine, and glaciers) and wind (Larson *et al.*, 1997; Whittow, 1984).

Sedimentation is the process of sediment build up over time. The sediment itself is a product of weathering of rock. It is useful to distinguish three types of sedimentation. Mixed types (Fig. 1) are typical of Hong Kong. But the pattern can and does change



Plate 3 - The lagoonal phase with mangroves adjoining disused paddy habitats.

over time. It may even vary with position within a coastal swamp or estuarine environment. At the mouth of a river or estuary, where it meets the coast, "out of house" (allochthonous) sedimentation may be more important. This happens in Hong Kong at Sai Wan for example (Fig. 1). Inside an estuary or lagoon type environment, "in house" (autochthonous) sedimentation may dominate, at least for a time.

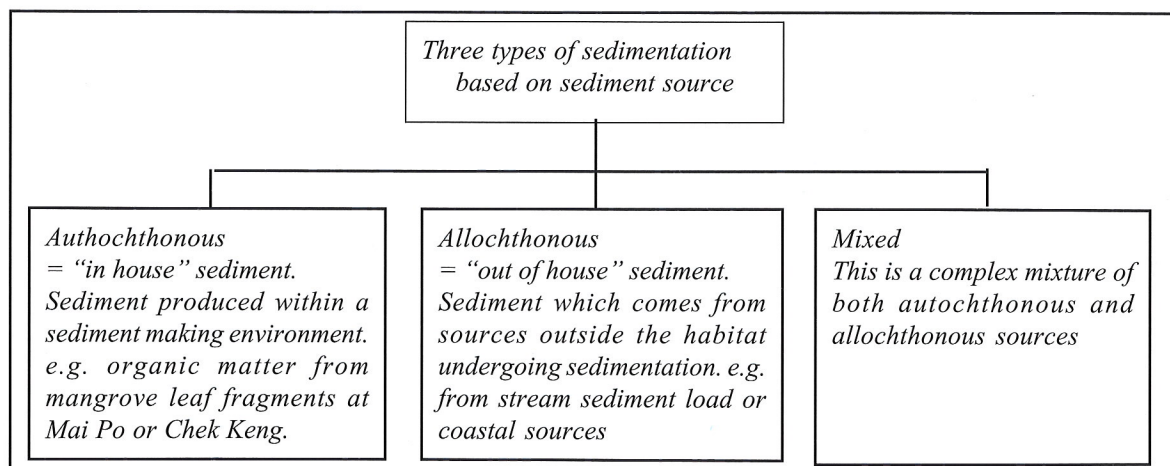


Fig 1 - Major types of sedimentation

Mangroves and sediment trapping

Long Harbour (Tai Tan Hoi) in Sai Kung East Country Park (Fig. 2) provides good example of a deeply indented Hong Kong coastline. Located between the disused paddy at the seaward end of the Chek Keng valley plain and the eastern arm of Long Harbour (Fig. 2), the Chek Keng mangroves include all the important mangrove species typical of Hong Kong. Unlike those of Mai Po in the North West New Territories, those of Chek Keng have developed on a relatively firm substratum of small stones and rock fragments, with the finer sediments of mud, silt and sand captured in the spaces between the numerous rocks.

Morphological features of mangrove trees and shrubs that tend to promote sedimentation include:

(a) Stems with broad, triangular basal outgrowths called buttresses that support the trees in an unstable substratum and protect against tidal movement (see *Kandelia candel*, Fig. 3)

(b) Special aerial roots that protrude like fingers from beneath extensive below-ground cable roots (seen in *Avicennia marina*, Fig. 3). These aerial roots or pneumatophores are adaptations related to airless muddy sediments and help gaseous exchange in anaerobic mud.

(c) Prop roots that arise from the downward growth of special structures arising between the stem and root (seen in *Kandelia candel* in Hong Kong, but can be more massive in tropical mangroves such as *Rhizophora* species) (Fig. 3).

These features of stem and root are structural adaptations that help to support mangrove growth in an unstable environment with a moving substratum and tidal flow. In addition, these structures tend to assist in the slow build up of fine sediments. Such sediment will be mixed, containing both autochthonous and allochthonous material. Mangrove stems, aerial and prop roots can help to trap sediments which are deposited beside the mangroves. The same kind of process occurs when sand or silt is deposited beside a solid object on a beach such as a stone, piece of drift wood or discarded bottle.

In a recent detailed study of the mechanisms of how mangrove trees function in the sedimentation process, Furukawa and Wolanski (1996) showed that mangroves trap suspended sediment in tidal water by causing micro-turbulence around their roots and stems as the tide invades. This keeps the sediment in suspension and it forms flocs (clumps together). These flocs settle in the mangrove forest at slack high tide. As the tide ebbs, the water currents are too small to take this sediment out again, and it

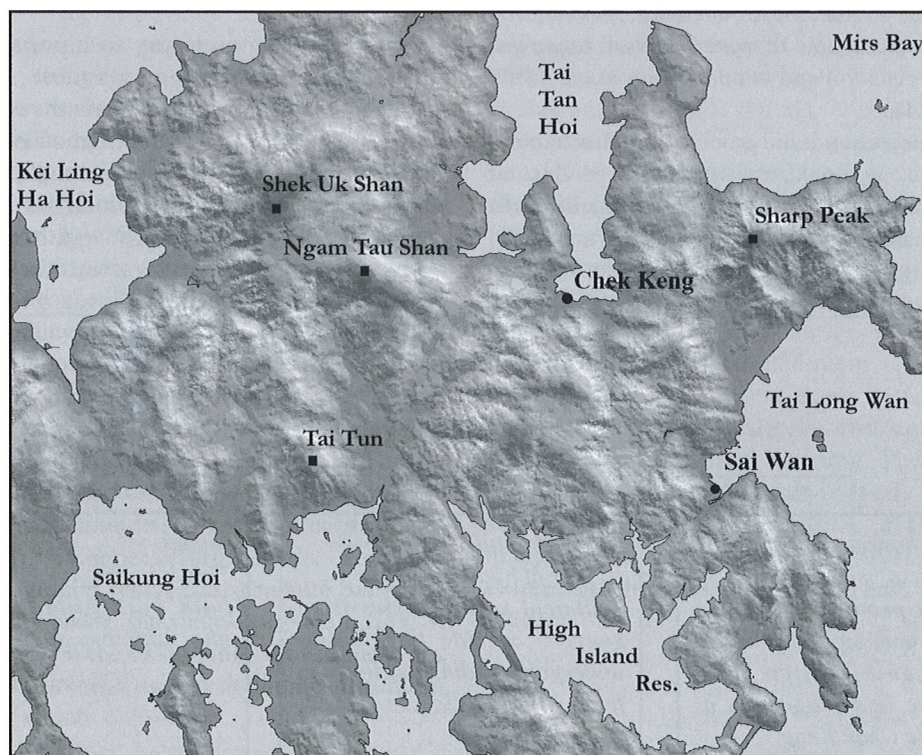


Fig 2 - Location map for Sai Kung County Park

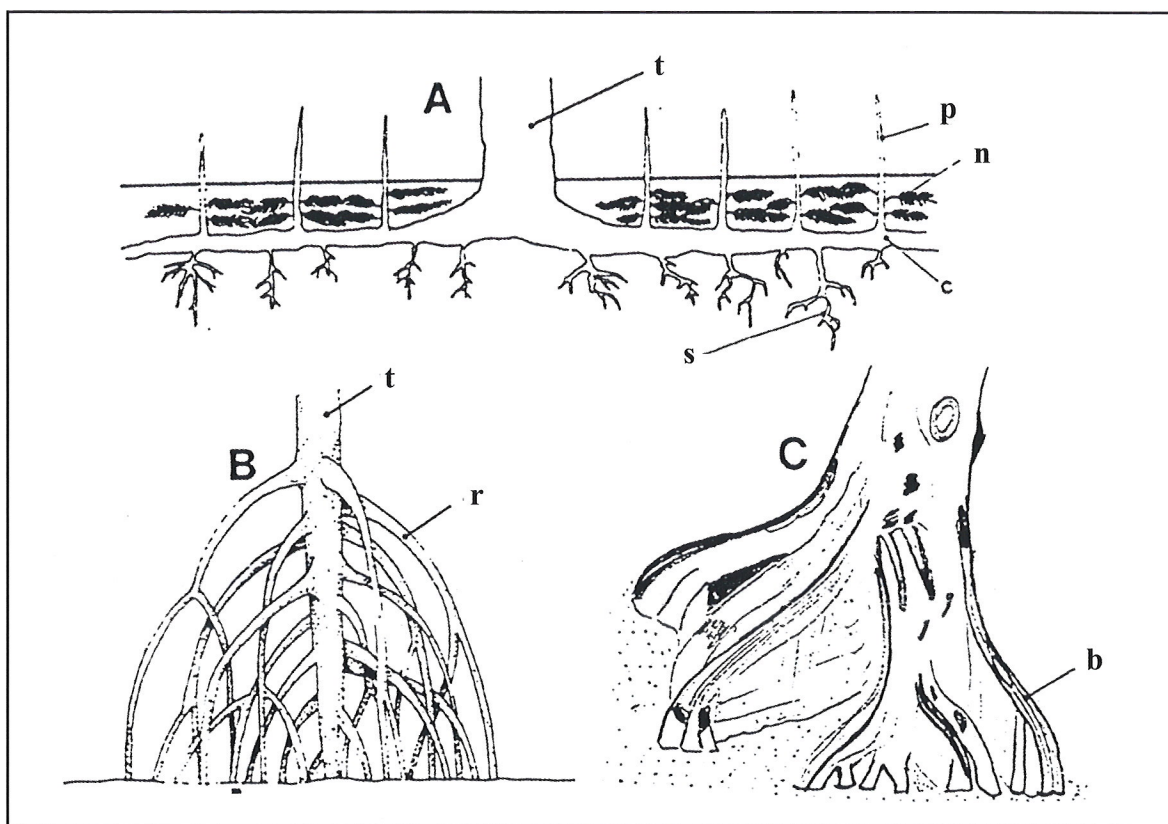


Figure 3 - Mangrove morphological features that assist in the sedimentation process. (Drawings A and B taken from Hodgkiss, 1986; C by Gordon Maxwell). A - *Avicennia*, B - *Kandelia candel*, C - buttress structure in *K. candel*; t - trunk, b - buttress; c - cable root; n - nutritive roots; p - pneumatophore; s - support or anchoring root; r - prop root.

becomes trapped and builds up within the mangrove habitat. The process represents interaction between hydrodynamics (water physics) and plant shape (phytomorphology).

In some mangrove habitats, the mangrove mud can become very dense and anaerobic (lacking oxygen). At times, it becomes black and smelly due to the activity of bacteria converting sulphate ions to hydrogen sulphide (H_2S) gas, releasing a smell of rotten eggs. In response to these harsh living conditions, mangroves such as *Avicennia* may increase the number of aerial roots or pneumatophores, which can reach densities of about 400 per m^2 . These numerous finger-like projections protrude above the mud surface like a forest of pencils. Although small, these living aerial roots can accelerate sediment build up.

Unlike inanimate physical objects such as stones or plastic bottles, the aerial roots continue to grow as the sediment level increases. Living in such difficult conditions is not easy. For some mangroves the demands of producing more pneumatophores may help survival but come at a cost. The investment of biological resources into numerous aerial roots may mean that there are fewer

resources available for reproduction. Though important, this topic is beyond the scope of the present discussion. Studies by Maxwell (1971, 1984) and Young and Harvey (1996) in New Zealand, Spenceley (1977) in Australia, Saifullah and Elahi (1992) in Karachi, and Panapitukkul *et al.* (1998) in Thailand, have all reported on the positive roles of mangrove aerial roots in the sedimentation process.

These morphological adaptations of mangroves do not create allochthonous sediment, which comes from the processes of weathering and erosion on land and is transported by water to the coastal zone. Once in the marine environment, the sediment can be transported further away and/or be deposited as marine sediment. Only some of the sediment may remain in the mangrove habitat. Mangroves also contribute their own biological material to sediment. This is autochthonous sedimentation (mentioned above). Leaves, twigs and dead trees contribute to this organic material. Mangroves thus assist in the process of coastal sedimentation in two ways: by capturing allochthonous sediment and by making autochthonous material. As such, mangroves may function as biogeomorphological agents.

These sedimentary processes can only happen in what geomorphologists call low-energy coastal situations, i.e. in the quiet waters of protected bays and inlets suitable for deposition to take place. The total overall process of sedimentation, as will be shown below, is dynamic. Periods of deposition typically alternate with periods of erosion. Even mangrove areas, which are usually low energy settings, are subject to some violent attacks by tropical storms and typhoons - a feature of Hong Kong's climate. In studies of mangroves as land builders a long term viewpoint must be adopted. Even net gains in coastal sediment build-up over say 30 years can be lost through erosion during one violent storm. Means and averages can give a very unrealistic picture of reality, which is especially true in coastal geomorphology (Fritter *et al.*, 1995).

Methods for studying mangrove sedimentation

As indicated in Table 1 there are two main approaches to estimating coastal sedimentation: sediment deposition (accretion) as the rate of vertical increase in sediment depth over time, and sediment expansion horizontally outward from the coastline. In Table 1, accretion was measured as an increase in depth over time, and usually expressed in centimetre units, while land building horizontally was expressed as metre (or greater) advancing per year.

Many methods have been devised to determine accretion and include:

(i) marker stakes, poles, posts and even perspex placed into the existing sediment against which sediment build up is measured with a ruler, tape or micrometer gauge.

(ii) brick-dust or feldspar marker horizons are placed onto sediments and the rate at which new natural (darker) sediment is deposited on top of the marker is measured at set time periods.

(iii) radioisotopes of lead (^{210}Pb), Caesium (^{137}Cs), or radiocarbon, are used to mark sediment layers and newly deposited material can be distinguished from the radioisotope marker elements.

Rates of land building (expansion) or land removal (retreat) have been estimated in a variety of ways including: aerial photography, historical maps, poles or wharf locations. In more recent times, remote sensing and geophysical technology data-bases have also been applied. Despite the high technology of remote sensing

and geographic information systems (GIS) there is still a vital need to collect, examine, touch and smell sediments (Larson *et al.*, 1997).

Mangroves as land-builders, the evidence

A debate about mangroves as land-builders has been going on for at least 60 years. When Davis (1940) presented a case for the role of mangroves as geologic agents in Florida, USA, he did not imagine that this issue would still be debated in the year 2000. The debate is not so much about whether mangroves can or cannot help build land. It is rather, about their relative importance as agents of coastal sedimentation when compared to other geomorphological factors such as winds, tidal action, storms and sea level changes.

An inspection of Table 1 shows that mangroves are indeed biogeomorphic agents, but they are not essential for the process of coastal sedimentation. The evidence indicates that they accelerate a process that is going on anyway. This is shown by comparing non-mangrove locations (at places outside the tropics where it is too cold for mangrove survival), with mangrove locations. An excellent example of a non-mangrove location is the mouth of China's massive Yellow River where it flows into the Bohai Sea. The only river system approaching the Yellow River in size is the Amazon in South America. Unlike the Yellow River the Amazon's massive estuarine system includes mangrove vegetation and sediment is deposited at a rate of 2.4 cm per year.

The data in Table 1 reveals that wide variations occur in sedimentation rates around the world. Many sites show steady gains, e.g. the Cairn's coast in Queensland Australia, Kosrae island in Micronesia, Deep Bay in Hong Kong and the Piako River in New Zealand. Those showing gains are mangrove areas, but in most cases the gains in sediment are small to modest, e.g. 0.8 cm per year at Cairns in Queensland, just 0.1 to 0.2 cm per year at Kosrae island, 0.64 cm per year in New Zealand and 1.1 cm per year at Mai Po - one of the highest listed.

Significantly, a number of sites display episodic patterns of cyclic gains and losses. This is the case at Magnetic Island near Townsville, Queensland, where gains of 0.46 cm per year were offset by losses of 0.81 cm per year. Malaysia's dynamic coastline is interesting and instructive too, with some sites along Peninsular Malaysia advancing (depositional coastlines) and others retreating (eroding) (Table 1). While Mai Po and Deep Bay mangrove mudflats are gaining sediment

Place	Type of environment	Increase in sediment depth	Sediment mass rates (weight)	Land building	Authority (data source)
Amazon River mouth	Massive estuarine system with mangrove (<i>Avicennia</i>)	2.4 cm yr ⁻¹	10 ⁶ -10 ⁷ tons yr ⁻¹	nsd, but dynamic sediment budget	Allison <i>et al.</i> , 1996
Northern England, Wansbeck R.	Small estuarine man-made semi-lagoon (estuary with barrage) (no mangroves)	<4 cm yr ⁻¹	~127g per m ² per tidal cycle	infilling of lagoon	Worrall and McIntyre, 1998
npp	Estuaries in general	~0.2 cm yr ⁻¹	-	-	Barnes, 1984
Cairns coast N. Queensland, Australia	Depositional coastal plain near delta of Barron R. with extensive mangrove (<i>Avicennia marina</i>)	0.8 cm yr ⁻¹	-	episodic, but has reached about 60 m in 30 years	Bird, 1972
Kosrae Island, Micronesia	Mangrove peat on coral reef coasts (<i>Rizophora</i> spp.)	0.1-0.2 cm yr ⁻¹	-	a steady rate over the past 2000 yrs.	Fujimoto <i>et al.</i> , 1996
Cairns, and Queensland	Mangrove coast with extensive mangrove (both <i>Rhizophora</i> & <i>Avicennia</i>)	up to 270g /m ² /tide (depends on mangrove & position)	-	strong evidence on a daily tidal basis	Furukawa Wolanski, 1996
Thailand (S.E.)	Expanding coastal mangrove	nsd	-	38.6m per year over a 28 year period (1966-94)	Pananitukkul <i>et al.</i> , 1998
Magnetic Island near Townsville, Queensland	Mangrove forest (<i>Avicennia</i> at sea front, <i>Rhizophora</i> behind)	0.46-0.81 cm yr ⁻¹	-	cyclic gains (deposition) & losses (erosion)	Spendely, 1982
Malaysia	Peninsula Malaysia (general survey). Gains where mangroves can still grow	nsd	-	Cyclic: those advancing do so at >15 m/yr., others eroding at about 8m/yr.	Teh and Lim, 1993
Malaysia	Kemaman mangrove forest	1.46cm yr ⁻¹	-	-	Saad <i>et al.</i> , 1999
China, Yellow R.	Huge river delta into Bohei Sea (no mangroves)	nsd	0.8-1 billion tons per year	20-40 km ² /yr.	Wang <i>et al.</i> , 1998
South Africa, Kosi wetland	Estuarine, lagoon and lake system (<i>Avicennia</i> present)	0.08cm yr ⁻¹ (maximum)	-	very slow and erratic	Wright <i>et al.</i> , 1997
New Zealand i) Hauraki Plains, Piako River ii) Waiheke Isl., Auckland	mangrove estuary (<i>Avicennia</i> & <i>Kandelia</i>) Tidal creek (<i>Avicennia</i>)	0.64cm yr ⁻¹ 0.31cm yr ⁻¹	- -	~200m in 50 years -	Young & Harvey, 1996 Maxwell, 1984
Hong Kong i) Deep Bay ii) Sai Wan, Sai Kung East	Mangrove mudflat (<i>Avicennia</i> & <i>Kandelia</i>) Mangrove estuary/ lagoon (<i>Aegiceras</i> , <i>Kandelia</i> , <i>Excoecaria</i>)	1.1cm yr ⁻¹ 0.23 cm yr ⁻¹ data from 1980-2000	- -	7.6 cm yr ⁻¹ episodic & limited to small island and bank building	Duke and Khan, 1999 Maxwell, 1981, 1997, & present study

Table 1 - Mangroves and coastal sedimentation rates around the world. Two non-mangrove areas are also included for comparison: the huge Yellow River and a small estuary in England. npp: no particular place; nsd = no specific data available; - = no information.

at 1.1 cm per year in depth and growing in a seaward direction at 7.6 m per year (Table 1), this is not always the case in Hong Kong mangrove habitats. At Sai Wan, in Sai Kung East Country Park, studies for 20 years have shown an episodic pattern. This cyclic pattern and process of gains and losses over a long period of time (e.g. 200 years) may be the norm.

An episodic model of alternating periods of sedimentation and erosion, (deposition and erosion) may be useful. The steady accumulation of mangrove mud at a rate of 1-2 mm per year for the past 200 years, which has kept pace with sea level rise as reported by the Fujimoto team (Table 1) in Micronesia, may be an exception to the episodic model. However, 200 years may not be long enough. In terms of Earth history, episodes can be measured on many time frames from historic intervals of decades and centuries to geologic time covering millions of years. Short term thinking and over-reliance on statistical tests and computer models is most unwise in geomorphology, especially coastal geomorphology. The net result over a long period of time is more meaningful than average rates. Attention must be given to local variation rather than regional, country, or even district by district situations. Thus means and averages can give us a comparison and perspective, but should be used with great caution in prediction.

Summary and Conclusions

There is strong evidence from Hong Kong and other locations where mangrove ecosystems occur and develop that mangrove trees and shrubs can act as biogeomorphological agents. While the rates of accretion or sediment build-up varies from site to site and from region to region, an average figure of 0.8 cm per year is typical of mangrove environments. A figure of 0.2 cm per year is cited as typical of estuaries globally, with or without mangrove vegetation (Barnes, 1984, Table 1). From this it is possible to conclude that mangroves accelerate the general process of sedimentation that occurs in estuarine environments.

In Hong Kong, at Mai Po, mangroves may be advancing onto the mudflats at 7.6 m yr⁻¹, as the mud level increases at about 1.1 cm yr⁻¹. At this rate all of Deep Bay should cease to be a bay and become a mud flat by the year 2080 ± 10. However, this estimate may not reflect the episodic nature of such environments and may be an overestimate. The pattern and process

described at Sai Wan in Sai Kung (Fig. 2) may be more representative of global trends. Clearly however, mangrove ecosystems do act as sediment traps and mangroves could be described as land builders.

However, it may be misleading to say that they can create their own habitats. As pointed out by Furukawa and Wolanski (1996) some writers prefer to describe them as opportunists; colonising mud made by other geomorphological processes. However, this viewpoint tends to ignore the biological inputs of mangrove material e.g. leaf, twig and root biomass into the ecosystem. Some of this material decomposes and contributes to organic build up in the sediments. Thus mangroves play a role as both sediment trap and source. While they may not be able to create their own habitat (muddy shore) they can certainly assist in its maintenance and continued development. This is why they have been used in Vietnam to protect sea dykes and coastal rice paddy areas (Hong, 1993) and in New Zealand (Maxwell, 1971) to protect coastal dairy farms from marine or estuarine tidal invasions.

An important question is what would happen to these coastal rice growing areas in Vietnam or dairy farms in New Zealand, if the mangroves were destroyed. To some this is a terrifying thought! In both countries, a dollar value has been placed on the mangroves as economic assets in the fight against coastal erosion (Maxwell, 1976; Hong, 1993). In some cases mangroves can be so successful in accelerating sediment build-up that the sediment eventually rises above mean sea level. When this happens, a plant succession occurs and the intertidal mangrove community is replaced by land plants.

The role of mangroves in coastal succession has attracted the interest of ecologists for a long time (e.g. Davis, 1940; Chapman, 1944, 1976; McNae, 1968; Maxwell, 1971, 1976; Hutchings & Saenger, 1987; Field, 1995). The exact role of mangroves in succession is still debated. More field work is required. However, few would doubt their role in coastal protection (erosion control) and sedimentation. Mangroves have earned the titles of land-builders and biogeomorphological agents.

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Dedication

The author would like to dedicate this paper to the memory of Professor V. J. Chapman, one time Professor of Botany at the University of Auckland, New Zealand, for his life time work in mangrove science. His book *Mangrove Vegetation* published in 1976 remains a mine of mangrove information and a much needed reminder that extensive studies of all literature, both past and present, is an important hallmark of genuine scholarship.

Sadly, as the age of Information Technology gains in momentum, it continues to seduce busy believers in quick technology fixes, to feel that the only information needed today is IT based. This seductive force and fashion has a power of its own. Deep scholarship takes time, careful reading and much thought. I therefore dedicate this paper to Professor Chapman's catholic appetite for broad-based literature surveys and the importance of seeking connections between diverse subject areas. There are no short cuts to scholarship. Information Technology with its search engines and other computer based timesaving devices is but one tool in the whole tool box needed in the pursuit of academic excellence.

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Modification of regional groundwater regimes by land reclamation

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Abstract

Land reclamation has played a significant role in the urban development process in many coastal areas in the world. While reclamation provides valuable land, it also creates various coastal engineering, environmental and marine ecological problems. These problems directly caused by reclamation have been well recognized and widely studied. However, it has not been recognized yet that reclamation will almost certainly change the regional groundwater regime, in turn causing similar problems. This paper represents the first attempt to address the impact of reclamation on groundwater regimes. It will be demonstrated that large-scale of reclamation will increase groundwater level, modify the groundwater divide, and alter submarine groundwater discharge to the coast. The change of groundwater conditions will cause engineering and environmental problems by modifying the infiltration capacity, flooding pattern, stability of slopes and foundations, interface between sea water and groundwater, and the coastal marine environment. This paper suggests that, for a major reclamation project, the change of the hydrogeological system in response to reclamation should be evaluated so that the disturbance to groundwater regimes and the damage to environment might be minimised.

摘要

填海可為世界上不少濱海地區提供寶貴的土地，但同時也引起不少濱海工程、環境及海洋生態問題。這些由填海直接產生的問題大多為人們所了解，並廣泛為人們所研究。但填海會改變濱海地下水狀況，從而可能間接引起上述問題這一現象卻很少為人所了解。本文首次試圖探討填海對地下水狀況之影響。文章表明，大面積填海會抬高區域性地下水位、移動地下分水嶺、減少地下水向濱海的排泄。這些變化將通過改變土體中雨水入滲、增加水浸的可能性、降低地基與斜坡的穩定性、改變鹽淡水界面、改變濱海海水化學成分而引起環境與工程問題。因此，本文建議，就大型填海工程而言，一定要對填海所造成的水文地質條件的改變進行研究，並設法減少填海對地下水狀況的改變，從而減少因此而產生的工程與環境問題。

Introduction

Reclamation of land from the sea has played an important role in the development of coastal areas in many parts of the world, including China, Britain, Japan, Korea, the Netherlands and the United States (Chen & Wang, 1999; Lee, 1998; Bouchard *et al.*, 1998; Schofield *et al.*, 1992). While reclamation provides valuable land, it also creates various engineering, environmental and ecological problems. These problems are widely investigated. For example, there are studies about the impacts of reclamation on coastal wetlands (Lee, 1998),

coastal ecology (Yip, 1978) and marine environment (Poon, 1997). However, it has not been recognised yet that reclamation will almost certainly have an impact on the regional groundwater regime, in turn causing coastal engineering and environmental problems. Since the response of groundwater regime to reclamation may be slow and not so obvious, the study from this perspective has been largely ignored. Mahmood & Twigg (1995) appear to have been the first to notice that groundwater conditions may be altered by

reclamation. They report that the water table rises in, or immediately adjacent to, an area of reclaimed land in Bahrain Island of Saudi Arabia. Apart from that, there has been little study to address the impact of reclamation on regional groundwater regimes.

A research project has been initiated in the University of Hong Kong to understand the modification of the natural groundwater regime caused by large-scale reclamation in coastal areas. In this short research communication, the background of land reclamation in Hong Kong will be briefly introduced. Then, the ways in which reclamation may influence groundwater regimes, including the water level, groundwater divide and submarine groundwater discharge (SGWD), will be discussed. Attempts will be made to link the modification of groundwater conditions to slope stability, flooding and other possible coastal environmental and engineering problems.

Brief background on land reclamation in Hong Kong

Hong Kong is mountainous territory with little natural level ground other than mud-flats, mangrove swamps and marshes. Since 1841 to the present, there has been a continuous gain of developable land through reclamation and levelling of hills. Over 10% of the Hong Kong developed land area is reclaimed from the sea.

Before the mid-1950s, reclamation was essentially strip development along the coast near urban areas, straightening out the coast line by constructing substantial sea-walls and filling in the enclosed lagoons by public dumping, together with draining and filling in of some inland marsh land (Lumb, 1976, 1980). Some pre-war reclamation areas were nothing more than public rubbish dumps.

By 1955, a rapid increase in population and a heavy demand for factory space led to a new reclamation policy – filling of shallow bays and coves remote from the traditional centres – to create large industrial areas and associated housing estates. Large borrow areas had to be laid out in the nearby hills to provide fill. By terracing or platforming these borrow areas, substantial amounts of levelled land could be formed at the same time that the reclamation was being won. The fill is generally the easily excavated decomposed granite residual soil mantle, which is essentially silty coarse sand.

Since 1973, the Hong Kong Government has introduced the New Town Programme, the main objective of which is to provide land in the New Territories in Hong Kong for public housing development. Six new towns have been created and

three are in the active construction stage. Much larger bays and coves are reclaimed for the creation of these towns. With full development of these towns there would be a population capacity of about 3.5 million. The fill materials are mainly marine sand extracted from the seabed.

The quality and nature of fill can be extremely variable, and there is nearly always a layer of soft marine mud on the seabed beneath reclamation sites. An attempt is usually made to displace or dredge out the mud before reclamation, but very often a layer of mud with thickness ranging from 5 to 10 m remains in place (Lumb, 1980). At some reclamation sites, such as the Tuen Mun new town site, the mud was intentionally not displaced. At another site in Sha Tin, the mud was supposed to be progressively pushed off from the site, but in actuality, the mud was reworked and very little was removed. This layer of mud is troublesome. It gradually becomes less and less permeable and leads to differential ground settlement as consolidation continues.

Submarine groundwater discharge

Coastal areas are usually the ultimate discharge zones of groundwater. The dynamic connection of the coastal groundwater and sea water has been studied by groundwater hydrologists since the 1950's (Jacob, 1950; Erskine, 1991; Jiao & Tang, 1999). Traditionally it was estimated that the amount of SGWD ranged from 0.01% to 10% of surface-water runoff. Recently, Moore (1996) has discovered that SGWD could amount to as much as 40% of the total river flow into the ocean, a surprisingly large percentage compared with the previous estimation. This finding has the potential to radically alter our understanding of oceanic chemical mass balance and suggests that groundwater input may play a very significant role in the marine environment.

SGWD can occur anywhere along the coastline or through the seabed in the form of distributed flow, but it may also concentrate locally in the form of submarine springs through fracture or fault zones or other special geological structures, just like springs formed on hill slopes on the land. A recent study, based on diving research (Marui and Hayashi, 2000), off a volcanic island in northern Japan indicates that some SGWD points occur 9 to 27 m below sea level. More comprehensive studies have been conducted on SGWD on an island in Hawaii. Light stable isotope and carbon-14 data for the deepest fresh aquifer showed that its recharge originated at an average elevation of about 2,000 m and that it had resided in the formation for about 1,800 years. Submersible surveys conducted offshore of the island also showed that the

flow through this aquifer was discharged at about 300 m below sea level (Thomas, 2000). Although there has not been any similar study in Hong Kong to date, this kind of SGWD surely exists in Hong Kong considering its large coastal areas with diverse geological conditions. If reclamation happens to block a major submarine discharge zone, such as a large groundwater-conductive fault zone, the impact on regional groundwater regimes can be profound and lasting.

Modification of groundwater regimes by reclamation

Figure 1 shows an unconfined coastal groundwater system before and after reclamation. Reclamation increases the groundwater flow path (or travel time) to the sea and reduces the groundwater discharge toward the coast. This will cause groundwater pressure buildup behind the original coastline. Groundwater may be forced to outcrop in

the form of springs in the slope at the contact between the original coastline and the reclaimed land. The pressure build-up can be great if the slope is covered by chunam or shotcrete. How significant the modification due to reclamation will be depends on the permeability of the fill materials and the distance between the old and the new coastlines (or the scale of the reclamation).

An important feature of the modification is that it is slow and becomes more significant as time goes by. This is because the permeability decreases progressively with time due to gradual consolidation of fill materials and marine mud. Eventually the mud at the seabed may be so well consolidated that in places it may essentially cut off the hydraulic connection between the seawater and the groundwater behind the reclamation site. Another reason for the time-variant feature is due to gradual urbanisation over the site. More and more buildings and engineering structures will be constructed at the site. Deep foundations of

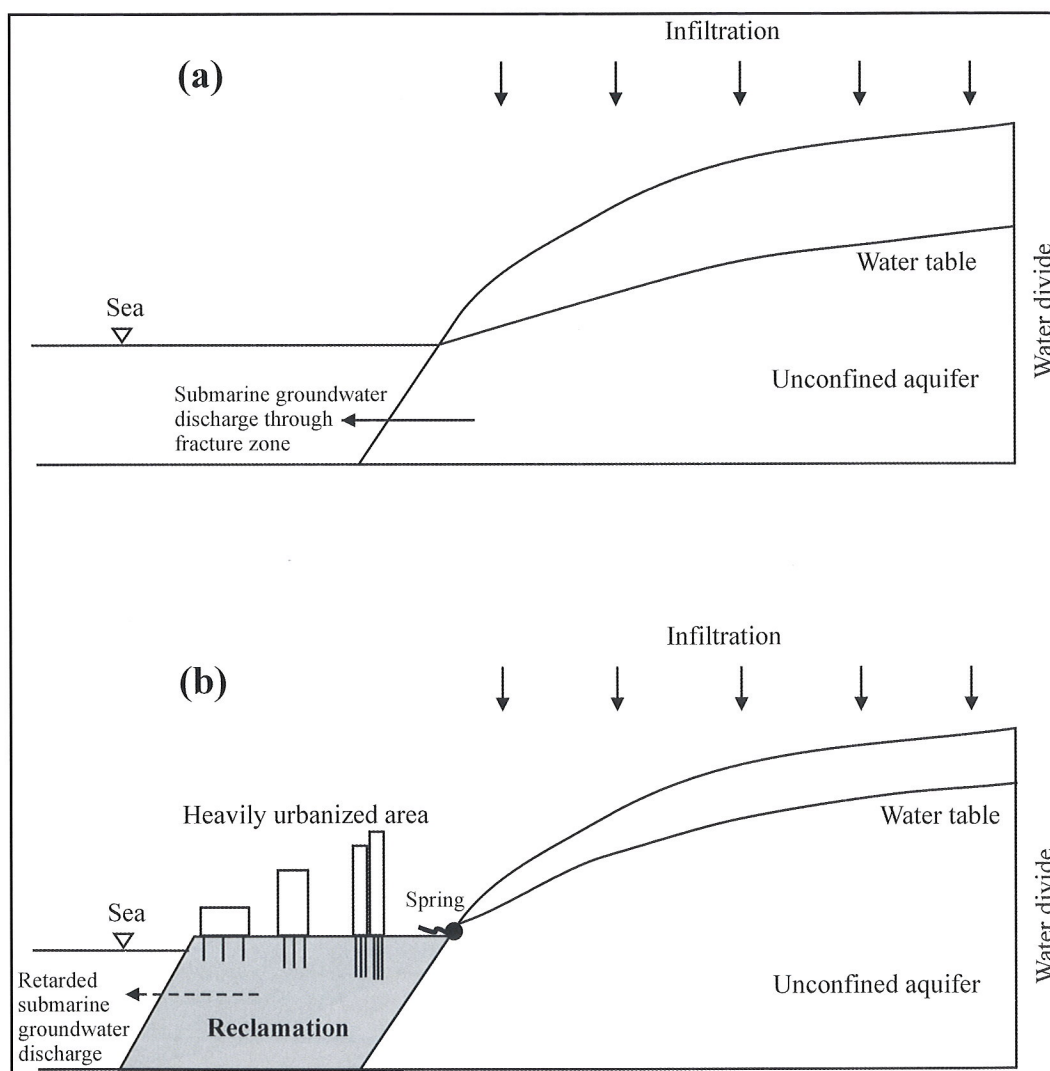


Fig. 1 - An unconfined aquifer system in a hillside near the coast (a) before and (b) after reclamation.

the structures will reduce significantly the horizontal permeability. The buildings, roads and pavements, and the shotcrete over the slopes near the reclamation site will reduce the over vertical permeability.

Figure 1 assumes that the groundwater divide is so far from the coast that the water divide remains unchanged after reclamation. The reclamation has an impact only on the groundwater regime of one side of the hill. When the scale of the reclamation is comparable or greater than the size of the original groundwater catchment, as often occurs in Hong Kong, the modification can be more significant. As shown in Figure 2, since the SGWD to the left after reclamation is obstructed by the fill materials, more infiltrated water will flow to the right-hand side of the hill. In this situation, the reclamation on one side of the hill may cause displacement of the groundwater divide and eventually change the groundwater conditions on the other side of the hill. The process of modification may occur over years. One day it may be found,

unexpectedly, that more groundwater exists on the right-hand side of the island and that there is more SGWD to the coast on the right.

For the simple unconfined aquifer systems in Figures 1 and 2, the pore pressure build-up behind the slope may not be very significant if extra groundwater can discharge as springs at the surface. For a coastal slope consisting of weathered igneous rock in HK, the flow system can be much more complicated. Conventionally, it is believed that the permeability decreases progressively as the depth increases or as the rock becomes less decomposed (GEO, 1996). Groundwater modeling studies in Hong Kong therefore assumed that superficial soil is an unconfined aquifer and that rockhead is an impermeable boundary (Lerner, 1986; GEO, 1996). Recently it has been demonstrated, however, that the permeability distribution in a weathered profile may include a relatively high permeability zone associated with the jointed rock mass near rockhead (Jiao & Malone, 2000) and that in some

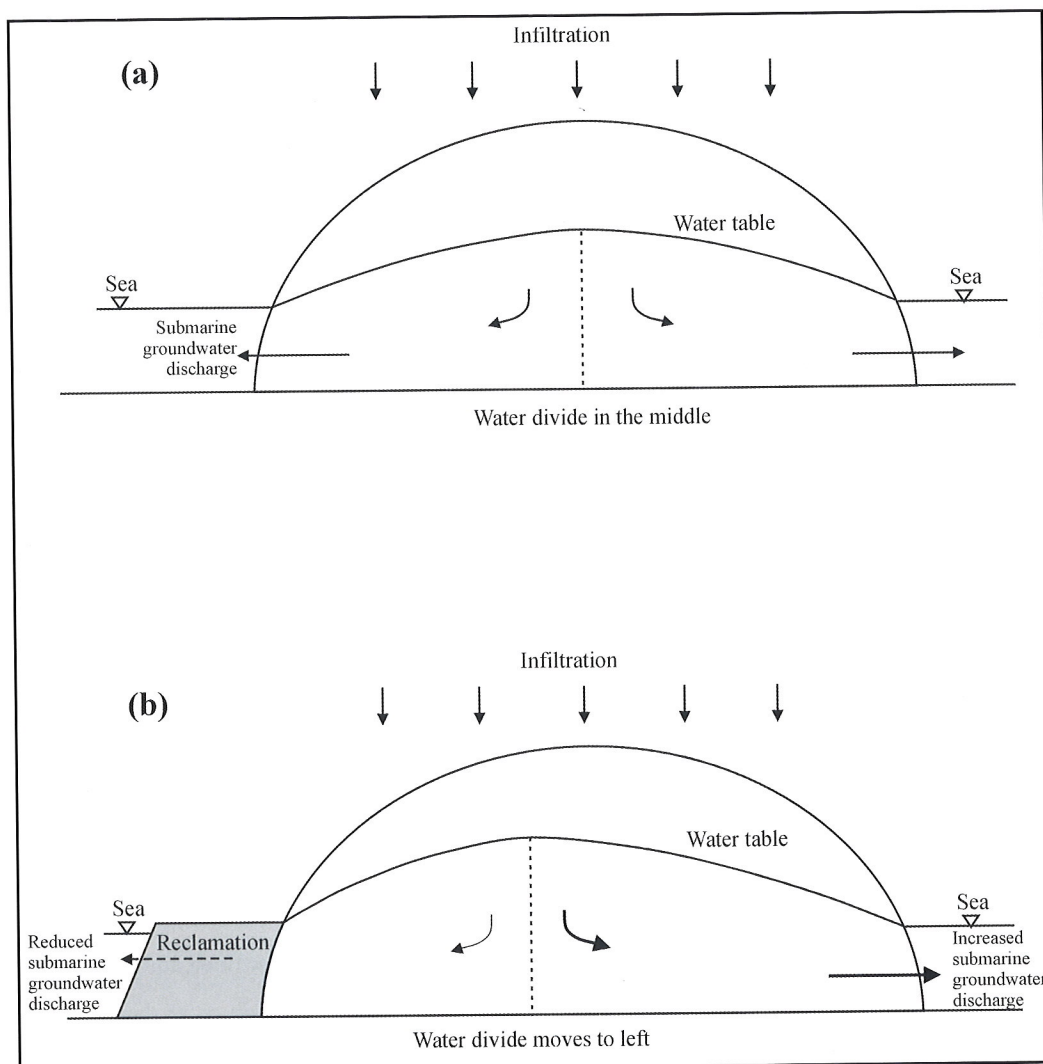


Figure 2 An unconfined aquifer system in an island (a) before and (b) after reclamation.

places the rockhead is chair-shaped (Jiao, 2000), as shown in Figure 3(a). If the toe of such a fracture zone is exposed at the ground surface, or is in good hydraulic communication with seawater in the form of submarine discharge, then the pore pressure may dissipate fairly quickly and there will be no significantly pressure build up even during heavy rainfall. If the discharge at the toe is significantly obstructed by reclamation, as shown in Figure 3(b), then the groundwater in such a permeable zone may be well confined, resulting in high pore pressures during exceptionally heavy rainfall periods.

Impact of modification of groundwater regimes on coastal engineering and environment

Reclamation and slope stability

If reclamation is believed to have an impact on the regional groundwater level, it is natural to speculate that it may have an adverse effect on slope stability. Rainfall is the apparent cause of most landslides in

Hong Kong. Some slides are rather shallow and show an immediate response to rainfall. This is probably caused by quick and local saturation of the superficial soil in response to heavy rainfall. To understand these types of shallow landslides requires study of the movement of infiltrated water in unsaturated zones (Anderson, 1983). Some landslides in Hong Kong, however, exhibit movements well after the peak of the storm, and many are delayed by a few days. The risk levels associated with such delayed failures are high because delayed failures are unexpected. These kinds of landslide are usually deep-seated and of large scale. Most of the deep-seated landslides are, speculatively, associated with high pore pressure and complex hydrogeological conditions (GEO, 1993; Jiao *et al.*, 1999; Jiao & Malone, 2000). Malone (1999) identified ten deep-seated landslides and discussed several features of their slope movement.

A re-examination of the ten landslides compiled by Malone (1999) shows an interesting aspect: seven

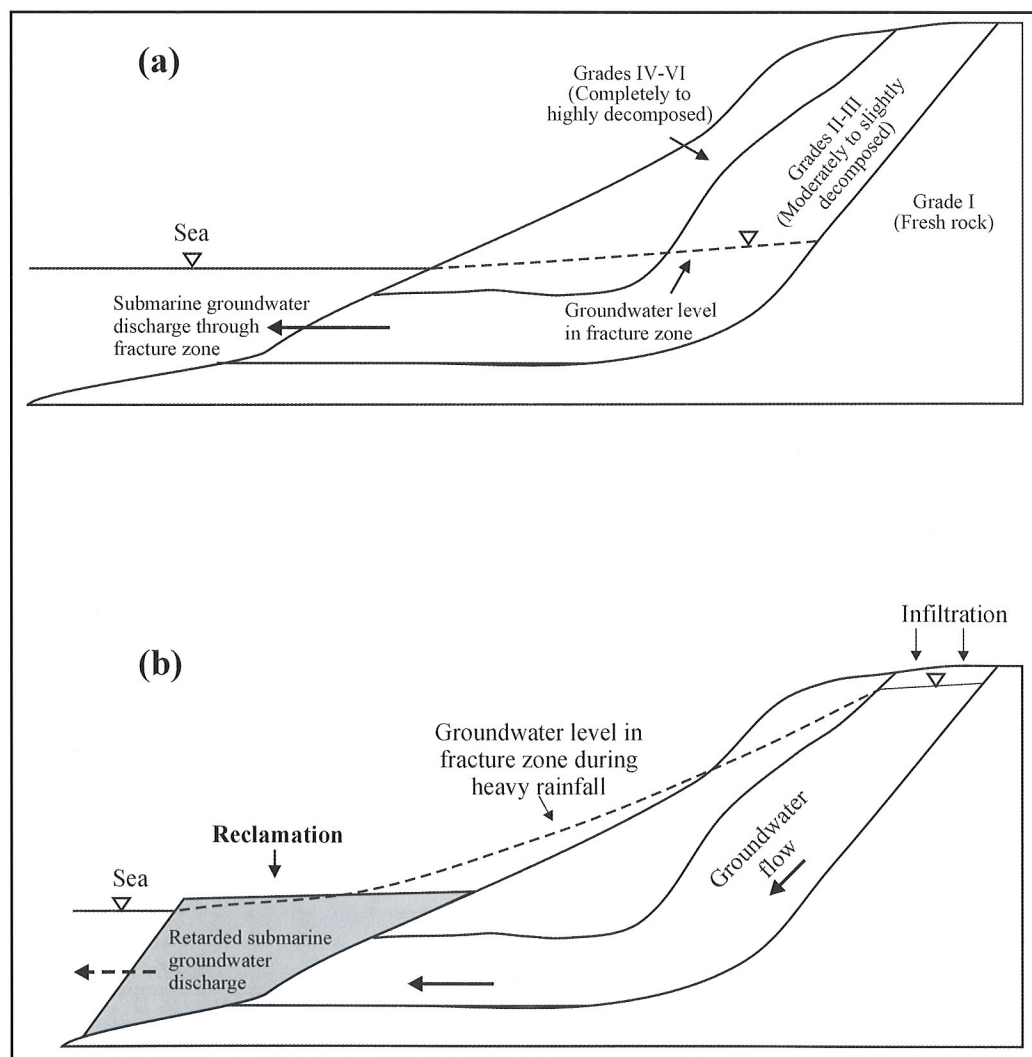


Fig. - 3 A hillside with a confined fracture aquifer zone in a slope of weathered igneous rock (a) before and (b) after reclamation.

of them are located in slopes immediately behind major reclamation sites. This suggests that there may be a connection between reclamation and deep-seated landslides. It appears that some of the failures can be explained by Figure 3. For the hydrogeological setting shown in Figure 3, reclamation can affect the groundwater level in slopes tens of meters above the sea level. This will generate hydraulic conditions detrimental to slope stability. This hypothesis, however, requires more detailed studies.

Reclamation and flooding

It is broadly accepted that reclamation increases the possibility of flooding by modifying the pattern of surface runoff, but it is not so well known that the alteration of groundwater conditions due to reclamation can also have the same effect. Reclamation obstructs groundwater flow to the sea and a part of the groundwater becomes surface water in the form of springs at the contact between the reclamation site and the original soil.

An aquifer behaves like an underground reservoir and can receive a certain amount of rainwater. After reclamation, the groundwater table is higher and consequently infiltration capacity may be significantly reduced. More rainwater may therefore runoff directly. Meanwhile, the reclamation area is usually heavily urbanized and the surface is covered by concrete materials such as buildings, roads and pavements. The land surface impermeability will lead to weak infiltration (Foster *et al.*, 1994) and a large portion of rainfall will become surface water directly.

Large-scale reclamations may increase the risk of flooding not only in the area around the reclaimed site, but also on the other side of a hill by elevating the water level over the entire island, as discussed earlier

Reclamation and other possible engineering and environment problems

Modification of groundwater regimes due to reclamation may cause other engineering and environmental problems. For example, the rise of water level will lead to reduction of bearing capacity of foundations. Groundwater may also penetrate the underground concrete and cause corrosion of the steel reinforcement. The increase of water level may cause damp surfaces and superficial damage to the floor of residential buildings (Mahmood & Twigg, 1995). A significant modification of SGWD will surely have an impact on coastal water quality and the marine environment since coastal water and some species may be sensitive to groundwater input. Although the coastal water quality depends on both the surface runoff and SGWD, so far the latter has been ignored in studies of coastal water quality in Hong Kong.

Evaluation should be made of these environmental and engineering impacts before a major reclamation project is carried out, especially when such a project is next to an environmentally sensitive area such as a wetland, or near landfills.

Figure 4 illustrates the possible engineering and environmental impacts of reclamation. After reclamation, the groundwater will be redistributed and the groundwater divide will move toward the reclaimed land. Special attention should be paid to the stability of slopes near area "A", since the build-up of the water level may be the most significant of all the slopes around the bay. After reclamation the coastline around the Dollar Bay is much shorter and there is only a very small amount of SGWD to the bay. However, the groundwater discharge to the coast near areas B and C will be increased. This will push the interface between sea water and groundwater towards the coast. The wetland on the east may become wetter since it has more groundwater input from its west bank due to

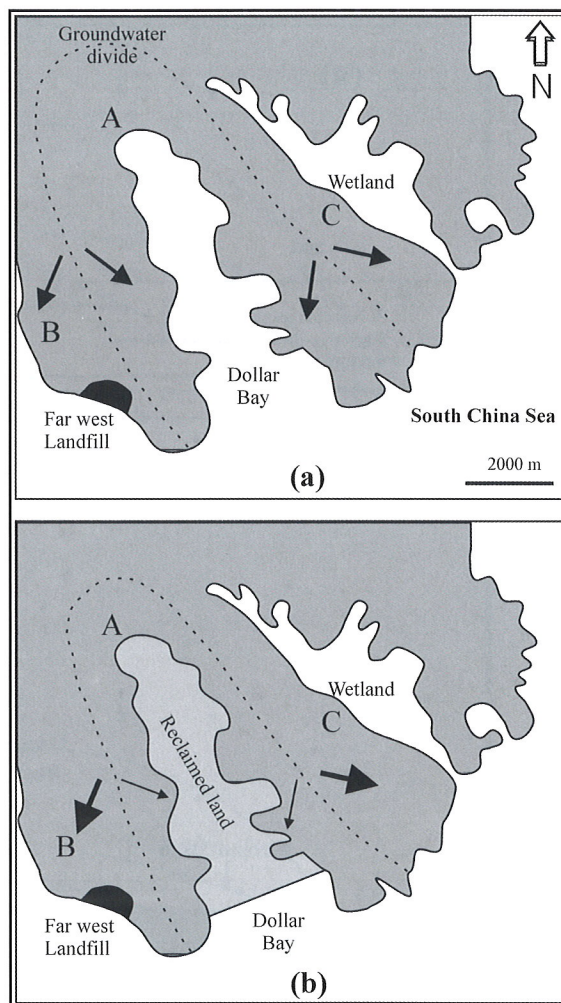


Fig. 4 - Reclamation near environmentally sensitive areas (a) before and (b) after reclamation (the size of arrows represents schematically the magnitude of groundwater flux).

reclamation in the Dollar bay. Whether the impact on the wetland is positive or negative depends on the groundwater quality. If the groundwater in this region is significantly contaminated, the extra groundwater input to the coastal water in areas B or C will surely damage the water quality or ecology of the wetland.

In Hong Kong there are many poorly-designed old landfills located near the coast. Some are now under restoration. If there is a landfill near area B, it may unexpectedly generate more leachate several years after reclamation of the Dollar Bay. It is easy to understand the direct impact of reclamation around the bay, but it may not be so easy to appreciate the impact in the neighborhood areas beyond the bay. It may take years for the modification in the neighborhood areas to become noticeable. How much time it will take depends on hydrogeological conditions, such as the permeability of the reclaimed site, the aquifer structures, and the process of consolidation of fill and mud. It is highly possible that by the time the impact of the reclamation becomes significant in areas beyond the bay, people will not link the effects to the reclamation, having forgotten about its construction.

Summary

This paper discusses the impact of land reclamation on coastal groundwater regimes, an issue largely ignored in the literature. It is believed that the degree of modification of groundwater conditions by reclamation depends on the scale of reclamation, the permeability of the fill materials, and the hydrogeological structures of the hill slope.

If reclamation is of a large scale and the permeability of the fill is low, reclamation will not only increase water level in the immediate area around a reclamation site. It will also move the groundwater divide and eventually modify the groundwater conditions through an entire island or area. Although the impact of reclamation on the groundwater regime near a reclamation site may be easily understood, the influence on coastal areas opposite reclamation sites may be ignored.

This paper also suggests that the change of groundwater conditions will in turn cause engineering and environmental problems by modifying the infiltration capacity, the flooding pattern, the stability of slopes and foundations, the interface between sea water and groundwater, and the SGWD. It is also pointed out that the modification of groundwater regimes due to reclamation is a slow process and may occur over years due to the time-dependent soil consolidation. It is suggested that for a large reclamation site, the response of groundwater regime to reclamation should be studied in detail to evaluate

its environmental and engineering impacts. The concepts and speculations discussed in this paper form the basis for ongoing research carried out in the University of Hong Kong.

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Hong Kong's Classic Geology, No. 2

Ping Chau - a saline lake basin

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Geology

Lacustrine sediments of early Tertiary age crop out on the island of Ping Chau (Fig. 1) in Mirs Bay (NE Hong Kong) (Lai, 1991; Lai *et al.*, 1996; Lee *et al.*, 1991a & b; Nau *et al.*, 1990). The precise dating is controversial (Heanley, 1923; Williams, 1943; Davis, 1953; Ruxton, 1960; Allen & Stephens, 1971; Peng, 1971; Lee, 1985, 1987). The Ping Chau Basin is one of several in Guangdong and Hong Kong (Lai & James, 2000). It consists of an asymmetric half-graben that contains two major sedimentary units (Lai, 1985). The Ping Chau Formation lies at the basin centre (Fig. 1) and is characterised by parallel finely laminated (<0.5 mm) sediments (Plates 1-3), with local cross-lamination (ripples), tabular cross-bedding, slumps and mudcracks. There is little or no bioturbation and laminae can be traced for many tens of metres. The rocks consist of mudstone, siltstone and marlstone, although Taylor *et al.* (1990) note that calcite and dolomite



Plate 1 - Highly laminated sediments are characteristic of Ping Chau and are best exposed on the southwest coast



Plate 2 - Dips are gentle and towards the northwest. These control the overall cuesta shape of the island forming a steep southwesterly cliff that is backed by a gentle dip slope.



Plate 3 - Wave action has produced a prominent wave-cut platform that is well-exposed at low tide.

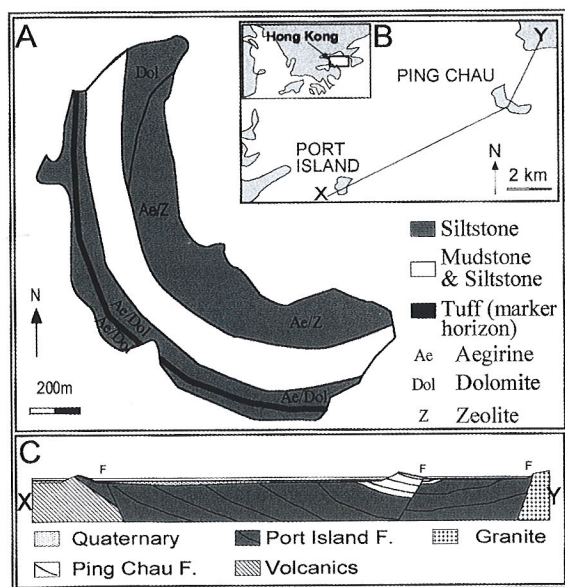


Fig. 1 - Geology of Ping Chau Island. A - Distribution of major facies and authigenic minerals (modified from Nau, 1979; Lee *et al.*, 1991b; Lai, 1991). B - Location of Ping Chau and cross section. C - Simplified cross section (after Lai, 1991), inferred from seismic data and outcrops on islands.

predominate locally. They comment that there are very few terrigenous particles and that the rocks should be referred to as limestone and dolostone.

The lower and upper Ping Chau Formation are largely concealed below sea level. The middle Ping Chau Formation is well exposed and was further subdivided by Lai (1991) into three parts, based on rock type and authigenic mineralisation, which was first mapped (Fig. 1) and recognised by Nau (1979).

The lower part (62 m thick), as recognised by Lai, is dominated by laminated, aegirine-bearing (<1 mm radial clusters) and dolomitic siltstone (10-45% dolomite), with mudstone and marlstone. A distinctive cherty tuff (Wu & Nau, 1989) forms a prominent marker horizon (Fig. 1). These rocks give way to a middle part (46 m thick) that is dominated by laminated and thinly bedded dolomitic siltstone, siltstone and mudstone, all of which contain abundant pyrite. The upper part (92 m thick) of the sequence includes thinly bedded, laminated, zeolitic (natrolite and analcime) siltstone with local pyrite and dolomitic and calcareous siltstone. Locally, laminae drape over zeolite nodules (up to 5 cm diameter). The zeolites and aegirine occur as syngenetic crystals parallel to lamination (Peng, 1971; Taylor *et al.*, 1990), as replacements of gypsum (Wu & Nau, 1989) and as epigenetic veins and lenses that cut across laminae (Taylor *et al.*, 1990). Taylor *et al.* also note the presence of felsic volcanics and their possible relationship to the growth of zeolites and aegirine.

Fig. 2 shows a composite section for a 114 m portion of the Middle Ping Chau Formation (part of the base and several tens of metres of the uppermost zeolitic sequence are not recorded). Distinctive features visible in the field include aegirine and pyrite nodules towards the base and the presence of wispy calcite laminae, and carbonate infilled pseudomorphs (after evaporites?) at two distinct levels (14-22 m & 70-74 m above the base of the composite section). Zeolites are present at about 80 - 82 m. Massive mudstone layers, generally <5 cm thick, are common below the tuff horizon at 40m.

The occurrence of calcite (and dolomite) suggest a saline-alkaline setting rich in Ca and Mg, whereas the zeolites and aegirine (as well as albite) are indicative of a Na-rich environment (Taylor *et al.*, 1990). The occurrence of pyrite implies reducing conditions together with forms suggestive of the Tertiary.

According to Nau *et al.* (1990) the palynological flora is dominated by

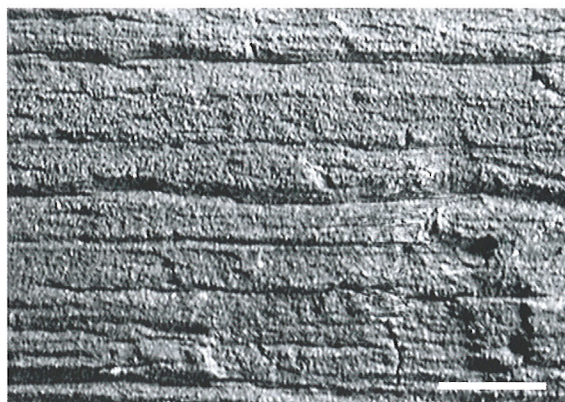


Plate 4 - Typical finely laminated calcareous mudstone of the Ping Chau Formation. Scale bar = 5 mm.

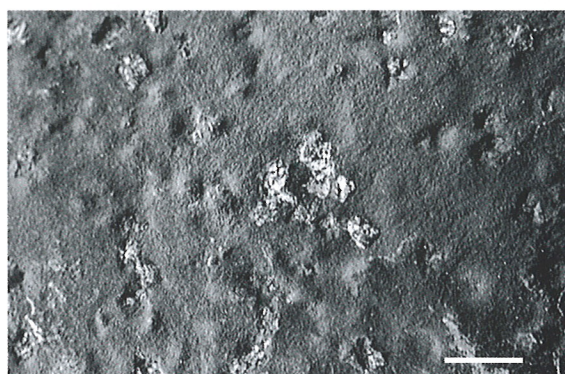


Plate 5 - zeolite crystals on a weathered bedding plane (basal section 2C in Fig. 2). Scale bar = 5 mm.

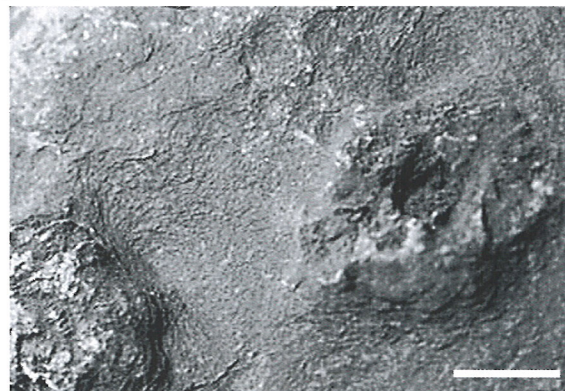


Plate 6 - Weathered radial crystals of authigenic aegirine (basal section 2C in Fig. 2). Scale bar = 5 mm.

pteridophytes and to a lesser extent by gymnosperms. Lee *et al.* (1991a) report 17 genera of spore-pollen, of which five species are restricted to the Tertiary or early Tertiary.

Palaeogeography

The late Cretaceous-early Tertiary rocks of southern China and Hong Kong suggest a period of continental deposition. Wang *et al.* (1985) note that the Upper Cretaceous red beds of Guangdong and Hong Kong formed in an arid zone that extended across much of southern and

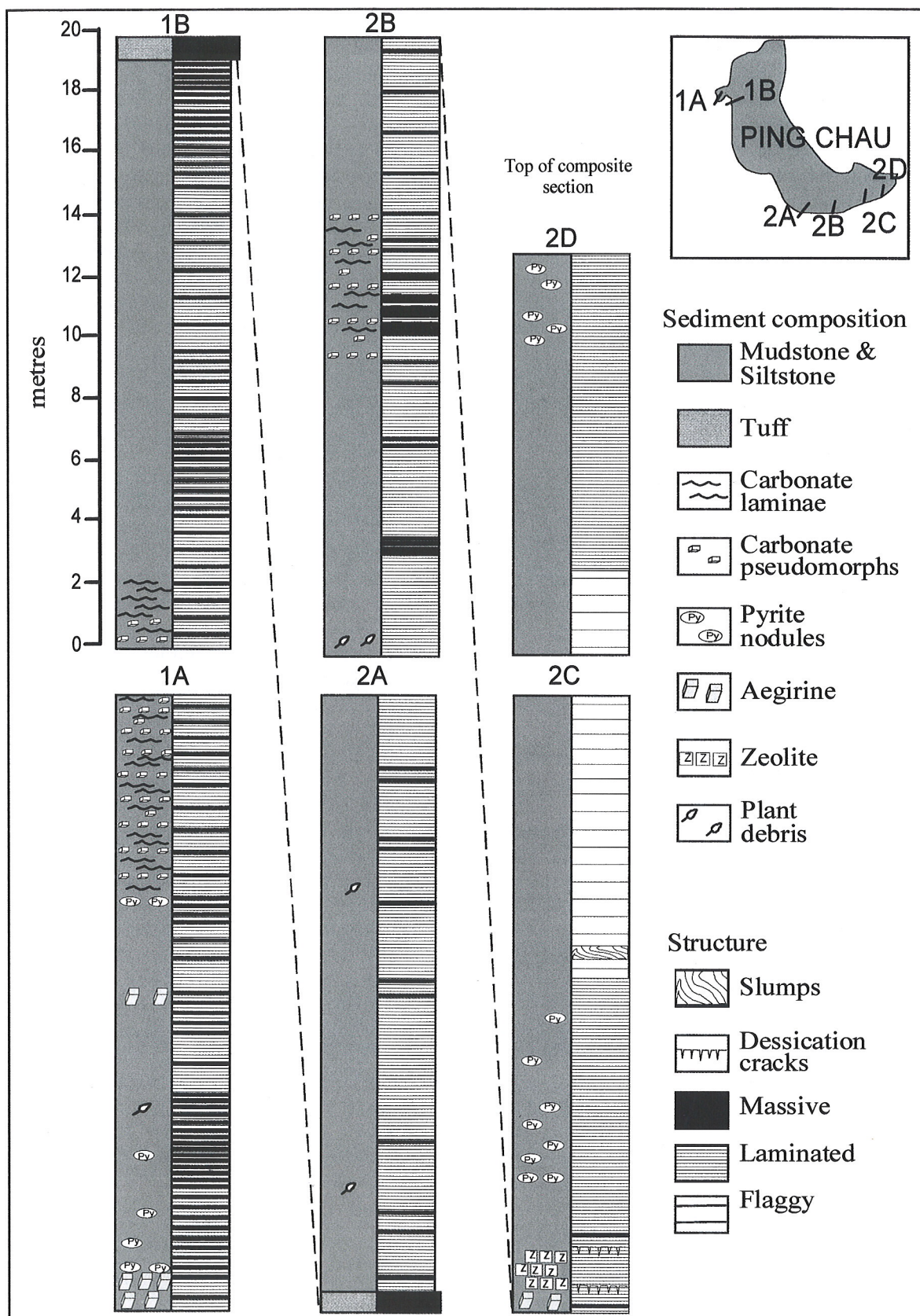


Fig. 2 - Composite section showing the exposed part of the middle Ping Chau Formation. The massive beds are mostly mudstones.

central China. Wang *et al.* also indicate that climate changed and produced a humid subtropical to tropical conditions across southern China during the early Tertiary, which Gu & Renaut (1994) suggest occurred by the early Late Eocene and signified the onset of the Asian monsoon. This humid belt gave way northwards to arid environments in central and northern China.

Lee *et al.* (1991b) suggest that the Eocene Ping Chau Formation developed close to the boundary between these arid and humid climatic zones in a saline lake environment. Wang *et al.* (1985) add that there were in fact several such lake basins present during this period in southern China.

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