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Characteristics of Formation and Development of Hidden Karst at the Pingshi Power Plant (Station B), Guangdong Province, China

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Abstract

The relationship between the formation, development and geologic environment at the site of the Pingshi Power Plant (Station B) is discussed in this paper. The characteristics of this site are concluded as follows:

(1) Karst is mainly developed in thick-bedded dolomitic limestone of the Hutian Group (middle-upper Carboniferous Series).

(2) Karst caves are intensely developed along fractures, especially along the F_1 fractures and the intersection of fractures F_1 and F_4 .

(3) The degree and type of karst varies in different geomorphic units. On terraces, karstification is not a serious problem and is characterised by the development of small caves. On slopes, karstification takes place to a medium degree and is characterised by the development of karrens at the top and caves on the footslopes. In valleys, karstification is intense and characterised by the existence of many large caves.

(4) Karstification is vertically layered and is controlled by the ancient and present base level of erosion.

摘要

本文論述坪石發電站（B 站）地基結構、發展和地質環境的關係，本場址特徵可歸納如下：

- (1) 發育中上石炭統壺天群厚層狀白雲質石灰岩為主；
- (2) 卡斯特溶洞順裂隙強烈發育，特別是沿 F_1 號斷裂以及 F_1 號斷裂和 F_2 號斷裂之間的交切點；
- (3) 岩溶作用的程度和形式是隨不同的地貌單位而變化。在台地上，岩溶作用問題不嚴重而以發育小型溶洞為特色。斜坡上，岩溶作用呈中等程度發育，和以頂部發育溶溝而坡下發育溶洞為特色。在峽谷地區，岩溶作用強烈並以存在許多巨大溶洞為特色。
- (4) 岩溶作用呈垂直層狀並受由古而今的侵蝕基準面所控制。

Introduction

The Pingshi Power Plant (Station B) is located on the second terrace (30-40m above water level) on the right bank of the Wushui River, 5 km south east from Pingshi Town in Guangdong Province. The plant is a middle-sized power station.

The area is underlain with karst (hidden karst), an understanding of which is crucial to the further development of the site. The purpose of this paper

therefore is to examine the formation and development of such hidden karst.

Geologic Setting

1. Strata

At the site of the plant, the strata includes the lower Carboniferous Shidengzi and Zimenqiao Formations, the Hutian Group (middle-upper Carboniferous), the Siaoping Formation (upper Triassic), and

upper Cretaceous-Eogene red beds. The Hutian Group is the most widespread and accounts for 60% of the total area of the plant site (Figure 1). The details are given below:

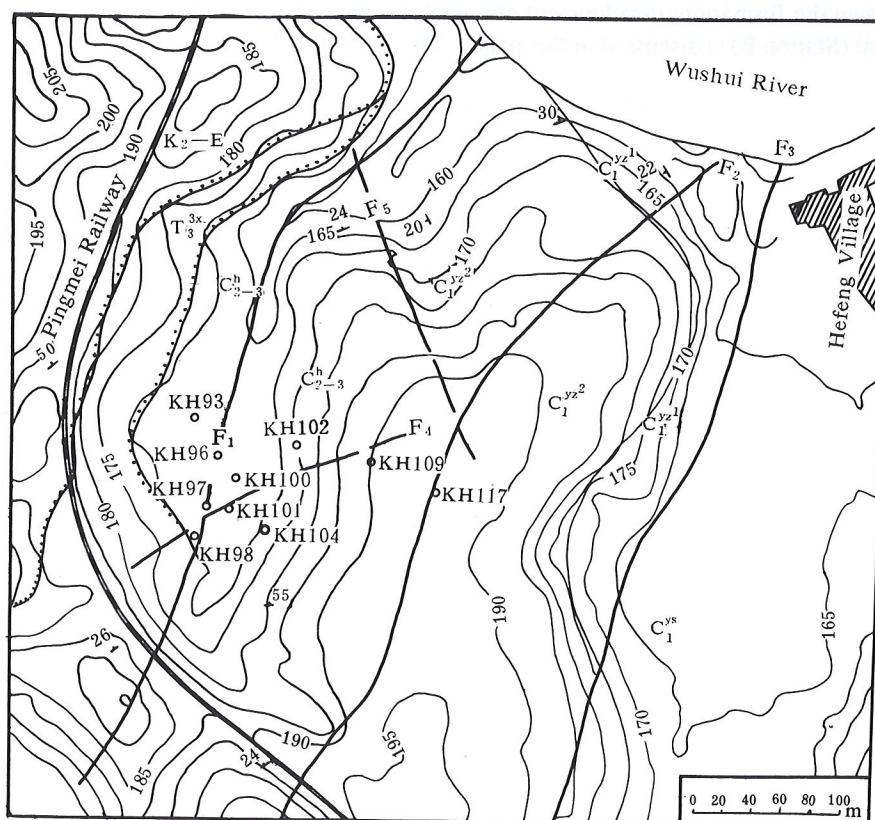
(1) The Shidengzi Formation of the lower Carboniferous (C^{ys}) is distributed to the east of the plant site and consists of thick-bedded light grey and grey-white limestone with a thickness of more than 300m and contacting the overlying Zimenqiao Formation with a fault.

(2) The Zimenqiao Formation of the lower Carboniferous (C^z) is also distributed to the east of the plant site. Two members can be recognised: the lower

member is composed of light grey-coloured, thick-bedded, dolomitic limestone containing chert clumps and stripes, with a thickness of 80-100m; the upper member is composed of fine-grained quartz sandstone interlayered with shale and is 50-80m thick.

(3) The Hutian Group of the middle-upper Carboniferous ($C_{2,3}$) is distributed to the west of the plant and is mainly composed of 150m of thick-bedded dolomitic limestone and dolomitite, and is in fault contact with underlying strata.

(4) The Xiaoping Formation of the upper Triassic (T_3) occurs to the east and the south west of the Pingshi Meitian railway and is composed of fine-



- K₂-E Upper Cretaceous-Eogene System
- T₃ Xiaoping Formation (Upper Triassic)
- C₂₋₃ Hutian Group (Middle-Upper Carboniferous)
- C₁₋₂ Zimenqiao Formation(1) (Lower Carboniferous)
- C₁₋₂ Zimenqiao Formation(2)
- C_{ys} Shidengzi Formation (Lower Carboniferous)
- 170 Stratigraphic boundary
- 20 Unconformity
- 20 Attitude of strata (number showing angle of dip)
- F₁ Faults and their number
- KH93 Boreholes and their number

Figure 1 - Geological map of the Pingshi power plant (Station B) area.

grained feldspar quartz sandstone and coal beds. The formation thickness varies from several metres to tens of metres, contacting the underlying Hutian Group with faults or unconformities (Photo 1).

(5) The upper Cretaceous-Eogene red beds (k2-E) occur in a zone from the west of the Ping-Meitan railway to Pingshi Town and are composed of brown-coloured sandy conglomerates and silty shales, with a thickness greater than 500 m and rests unconformably on the Xiaoping Formation.

2. Geologic Structures

The main geologic structures at the plant site are fractures which can be divided into NE and NW trending sets. The NE trending set includes the fractures referred to as F_1 , F_2 , F_3 , and F_4 , and the NW trending set contains only F_5 fractures. These fractures were mainly formed in the Yanshan period and have been activated repeatedly, reflecting compressive stress (compressive-shear) at the earlier stages and tensile or tensile-shear stress at the later stages. Consequently, not only are compressive lenses, densely-developed joints and cleavages observed, but tensile structural breccia is commonly found along fractures.

For convenience, the location, length, width, attitude, manifestation and other characteristics of each fracture at the plant site are listed in Table 1.

Characteristics of the Formation and Development of Hidden Karst

The formation and development of karst is influenced by lithologic character, geologic structures, erosion base-levels and landforms. There are three landform units at the plant site: terrace (platform) areas, valley areas, and slope (terrace bank between terrace and valley) areas. The geomorphic units are clearly reflected in the contour map of the bedrock surface (Figure 2). The contours of the former two units are sparse, but those of the latter unit are dense. Karst caves are mostly concentrated in the valley, secondarily developed in the upper part and at the foot of the slope, but are rare in the terrace area. Types and scale of karst vary between different geomorphic units.

1. Relationship between Karst and Limestone of the Hutian Group

The rocks of the Hutian Group at the plant site are mainly dolomitic limestones, which are pure and thick-bedded. They have been crushed to breccia and recrystallised due to fracturing (Photo 2). The rocks abound with underground water, the condition being favourable to the development of karst. So the ratio of caves found in boreholes reaches up to 66.7%. Karst in the terrace area, is characterised by small caves occurring along bedding places. Slope areas are characterised by development of karrens in the upper part



Photo 1 - Limestone of the Hutian Group is thrust over the Xiaoping Formation by Fault F1 in the head of the valley

Table 1 - General characteristics of the faults at the site of the Pingshi Power Plant

No. of faults	Location	Length (km)	Width (m)	Attitude of faults			Main manifestations of faults	Mechanical nature	Influence on plant site
				Strike	Dip	Angle of dip			
F ₁	Extends northeast from borehole KH42, through Pingshi-Meitian railway and along the valley in the west side of the plant site to the Wushui River	1	100-150	NE20° ~45°	SE	65° ~80°	Hutian Group was thrust over the Xiaoping Formation, Rock intensely shattered. Limestone recrystallized. Hidden Karst developed. A valley in landform	Compressoshear at the earlier stages, tensile or tensoshear at the later stages	The originally planned chimney and boiler room, parts of the main factory buildings
F ₂	Extends from the Pingshi-Meitian railway by the east of the main factory buildings to the Wushui River	0.8	Several metres to tens metres	NE35° ~45°	SE or NW	75°	Zimenqiao Formation was thrust over the Hutian Group, Rocks on both side of it shattered. Strata steepened. Compressive lens. joints, schistositities developed	"	Influence to some extent on parts of heavy loading buildings in the northeast of the plant
F ₃	Lies in the east valley of the plant, extends northwards to Hefeng Village, crossing the Wushui River	1.5 ~ 2.0	150-200	NE40°	SE or NW	50° ~70°	The limestone along the fault is intensely shattered and silicified. Attitude of rock beds on the both sides changes greatly. Cracks, fractures developed. A valley and Karst formed	"	Little influence on the plant
F ₄	Extends northeast in the southwest of the plant site	about 0.1	Several metres to tens metres	NE55° ~60°	SE	70°	Sandstone of Xiaoping Formation intensely shattered. Many joints and networks of calcite veins developed. Limestone fractured and recrystallized. Karst caves formed	"	Influence to some extent on the originally planned boiler room and chimney
F ₅	Extends from the mouth of the north valley to the turning of highway of the plant site	0.15 ~ 0.20	5 ~ 15	NW25°	SW or NE	45°	Limestone of Hutian Group contacts the sandstone and shale of Zimenqiao Formation with a fault. Polished surfaces and schistositities developed. Attitude of rock beds on the both sides different sharply	"	Little influence on the plant

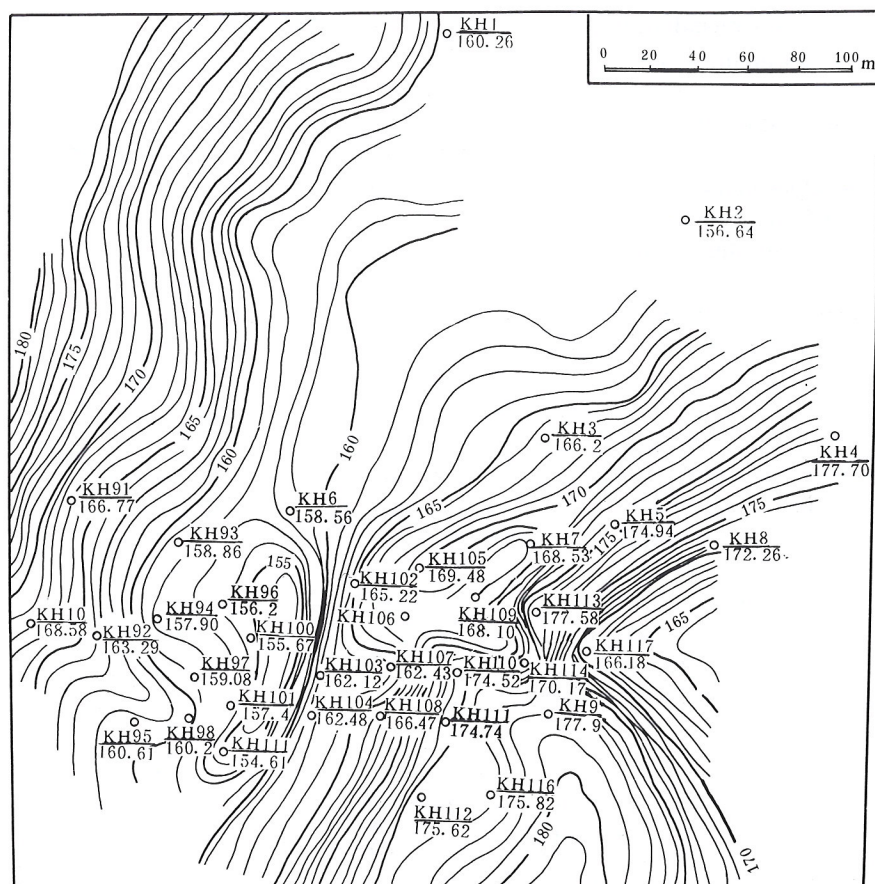


Figure 2 - Contours of the bedrock surface at the site of the Pingshi power plant (Station B)



Photo 2 - Fault breccia at a depth of 9.9-11.0 m in borehole KH 104 affected by Fault F1 in the valley area

and caves in the foot region. On the other hand, caverns and small caves are associated with the valleys.

2. Geologic Structures, Landforms and Karst Development

At the plant site karst develops mainly along fractures and their shatter zones, intersections and cracks. Karst caves are linearly distributed like a string of beads.

(1) A wide erosion valley is formed along the NNE trending fracture F_1 to the west of the plant site. Karst caves develop intensely along the shatter zone of the fracture F_1 in the valley. All boreholes in the shatter zone (100m or more wide) have revealed structural limestone breccias. Caves were identified within all eight boreholes (such as Borehole KH 98 and others) in the valley. As for the vertical linear ratio of karstification (the ratio of the accumulative height of caves to the length of drilling footage through the limestone in which caves exist), the maximum is 71.56% (Borehole KH 98), the minimum 20.21% (KH 96), and the average 44.35%. Therefore, the valley be-

longs to an intensely developed karst area at the plant site (Figure 3). The ratio of karst in boreholes within the valley area is shown in Table 2.

According to the geophysical surveying, each cave found in borehole KH 98 is funnel-shaped, with its plane diameter being 16m, the biggest one with a height of 21.2m.

(2) The NE trending fracture F_4 , which extends along the line between boreholes of KH 98, 101, 102 and 109, obliquely cuts the slope area where the main factory buildings are built. A shatter zone of the fracture is of a width about 40m according to drilling data and geophysical surveying. Karst caves occur mainly along the shatter zone and on both sides of it. 66.67% of boreholes on the slopes on both sides of the valley area have caves. The vertical linear ratio of karstification reaches a maximum of 59.70% (KH 109) on the east slope, and 61.16% (KH 92) on the west slope. The minimum is zero on both slopes, and the average is 22.1%. So the slope area belongs to a medium-developed karst area of the plant site. Karst caves exist mainly in the foot (KH 102, 103, 104) and

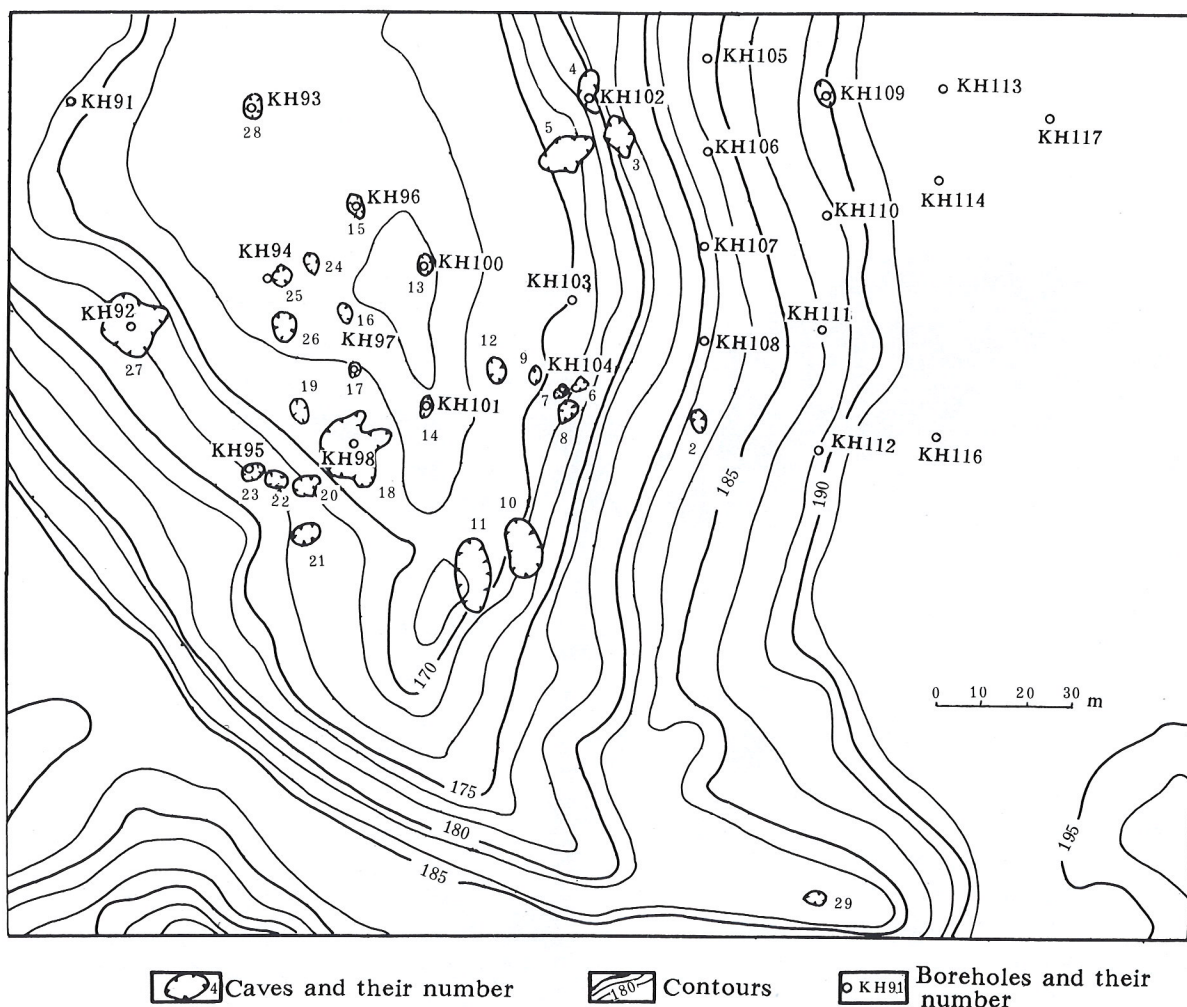


Figure 3 - Distribution of the hidden karst caves at the site of the Pingshi power plant (Station B) (obtained from drilling and geophysical exploration data)

Table 2 - General characteristics of the hidden karst caves in the valley area

Borehole No.	Top altitude of cave Section (m)	Bottom altitude of cave section (m)	Numbers of caves [height of each cave (m)]	Accumulative height of caves (m)	Drilling footage in limestone (m)	Linear ratio of Karst (%)
KH93	157.96	150.36	4 (0.8, 3.60, 0.40, 3.20)	5.60	9.60	58.33
KH94	157.40	147.40	5 (0.75, 0.40, 0.30, 0.40, 3.20)	5.05	10.50	48.10
KH95	159.91	153.66	3 (1.30, 0.40, 0.90)	2.60	7.15	36.36
KH96	155.72	147.62	3 (1.00, 0.50, 0.40)	1.90	9.40	20.21
KH97	156.18	150.63	2 (0.65, 1.85)	2.50	9.65	25.82
KH98	158.40	138.05	3 [(0.80, 2.70, 12.35 (not through))]	15.85	22.15	71.56
KH100	155.27	148.67	5 (1.75, 1.80, 0.85, 0.30, 0.30)	5.00	7.70	64.92
KH101	155.10	152.20	1 (2.90)	2.90	9.85	29.44

Table 3 - General characteristics of the hidden karst caves in the slope area

Characteristics		Borehole No.	Top altitude of cave section (m)	Bottom altitude of cave section (m)	Numbers of caves (height of each cave: m)	Accumulative height of caves (m)	Drilling footage in limestone (m)	Linear ratio of Karst (%)
Location								
Slope area	West	KH91			0	0	5.60	0
	East	KH92	163.19	154.69	2(0.50,6.90)	7.4	12.10	61.16
		KH102	164.12	156.27	2(5.0,0.70)	5.70	9.95	57.29
		KH103			0	0	10.20	0
		KH104	161.88	155.38	6(0.30,0.40,0.70 0.20,0.40,0.30)	2.30	7.70	29.87
		KH105			0	0	4.70	0
		KH106			0	0	8.60	0
		KH107	154.93	154.21	1(0.70)	0.70	8.10	8.60
		KH108			0	0	5.00	0
		KH109	167.25	162.95	2(1.10,2.90)	4.00	6.70	59.70
		KH110	173.62	170.92	3(0.20,0.30,0.40)	0.90	5.70	15.80
		KH111	174.04	171.54	4(0.30,0.30,0.40, 0.30)	1.30	5.70	22.81
		KH112	175.12	171.42	4(0.30,0.30,1.30, 0.30)	2.20	5.30	41.51
		KH2	155.04	151.64	3(0.60,0.20,0.10)	2.90	8.30	10.84
		KH3	160.29	153.29	8(0.30,0.30,0.80, 0.20,0.20,0.20, 0.80,0.80)	3.60	15.40	23.38

top (KH 109, 110, 111, 112) parts of the slopes; but in the middle slope (KH 105, 106, 107, 108) karstification is not so serious. The biggest height of a single cave is 6.9m in the west slope (KH 92) and 5.0m in the east slope (KH 102). The vertical linear ratio of karst in the slope area is given in Table 3.

(3) In the terrace (platform) area of the plant site, rocks are composed of dolomitic limestones which contain many chert lumps and stripes. The influence

of fracturing is not strong, so karstification is weak. Statistics of drilling data for 9 boreholes shows that there are only 3 that penetrate caves. The ratio of karst met in boreholes is therefore 33.33%. The vertical linear ratio of karstification reaches a maximum of 65.75% (Borehole KH 12); the minimum is zero and the average is 8.51%. The terrace area belongs to a weakly-developed karst area in which caves are few: only karrens and small caves are developed. The

ratio of karst found in boreholes in the terrace area is as shown in Table 4.

To sum up, the karstification of the valley, slope and terrace areas are to be classified as strong, medium and weak respectively. The size of the karst caves varies, the biggest being 21.20m high (according to the data of geophysical surveying KH 98), but they are generally smaller than 5m, and mostly smaller than a metre. 20 caves, among the 64 caves in total, are filled with clay and collapsed rocks, amounting to 31.25% and there are 40 caves that are empty (68.75%). The bigger the cave, the higher the ratio of fillings, and vice versa. This is because in large-sized caves the cross section of underground streams enlarges and the current velocity lessens; as a result finer sediment may settle out. Columnar correlation of karst caves revealed by boreholes in the different landform units is shown in Figure 4.

3. Vertical Layering in Karst and its Relation to Terrace Altitude and Erosion Base-Level.

The karst caves at the plant site can be divided into upper and lower layers.

(1) The upper layer occurs in the limestone section at an altitude of 178.26~170.92m, with the altitude of cave bottom being the same as that of the first level of terraces in this region. Caves of the upper layer are seen in the terrace area (boreholes KH 19, 12, 112, and 113) and are the result of uplifting of the ancient erosion base-level in the Quaternary. One of these caves (borehole KH 12) reaches a height of 4.80m, whilst the rest are less than a metre and most less than half a metre high.

(2) The lower layer of caves occur in limestone at an altitude of 163~147m and most are distributed in the valleys and the footslopes. The altitude for caves to develop is controlled by the Wushui River, the lowest erosion base-level in the region. The water level of the Wushui River changes from 147.28m at the lowest water level to 161.41m at the highest water level in a flood season. The altitude for caves

to develop corresponds to the fluctuations of water levels in the Wushui River. In the valley area and on the footslopes caves develop at greater depth to the influence of fractures F_1 and F_4 , especially at the intersection of fractures. For example, at borehole KH 98, the cave bottoms develop at an altitude of 129.20m (revealed by electrical sounding). This altitude is 18m lower than the lowest water level of the Wushui River. Caves can be formed at these depths because of their location at the intersection of fractures F_1 and F_4 where the rocks are intensely shattered. This condition is favourable for underground water to move downwards through vein pipes and causes karstification to develop.

The caves of the upper layer are weakly-developed and of small-size. The main cause is that there was no long-term stable erosion base level during the late Pleistocene due to frequent block-faulting. This meant that underground water could not fully exert karstification step by step and form large-sized caves. The lower layer of caves are well-developed and of large-size, because the valley areas belong to a confluent zone where the surface and subsurface water converges, and because of Holocene crustal instability at the time of valley cave development.

Discussion

Three subzones can be recognised within the plant site:

(1) the terrace (platform) area in which the karst is weakly-developed and only the upper layer of caves are present; the ratio of karst in boreholes is 33.33% and the vertical linear ratio of karstification averages 8.5%. It is characterised by development of small-sized caves and karrens (most with a height smaller than one metre) along bedding planes and joints.

(2) the terrace bank (slope) area in which karst is moderately well developed, the ratio of karst in boreholes is 66.67% and the vertical linear ratio of karstification averages 22.1%. Karst occurs mainly at the top and the foot of the slope area and is characterised by de-

Table 4 - General characteristics of the hidden karst caves in the platform area

Borehole No.	Top altitude of cave section (m)	Bottom altitude of cave section (m)	Numbers of caves (height of each cave: m)	Accumulative height of caves (m)	Drilling footage in limestone (m)	Linear ratio of Karst (%)
KH113	177.33	177.03	1(0.30)	0.30	5.50	5.45
KH114			0	0	6.17	0
KH116			0	0	5.00	0
KH117			0	0	5.00	0
KH7			0	0	2.20	0
KH9	176.11	175.61	1(0.50)	0.50	9.30	5.38
KH12	178.20	173.40	1(4.80)	4.80	7.30	65.75
KH5			0	0	10.30	0
KH8			0	0	5.80	0

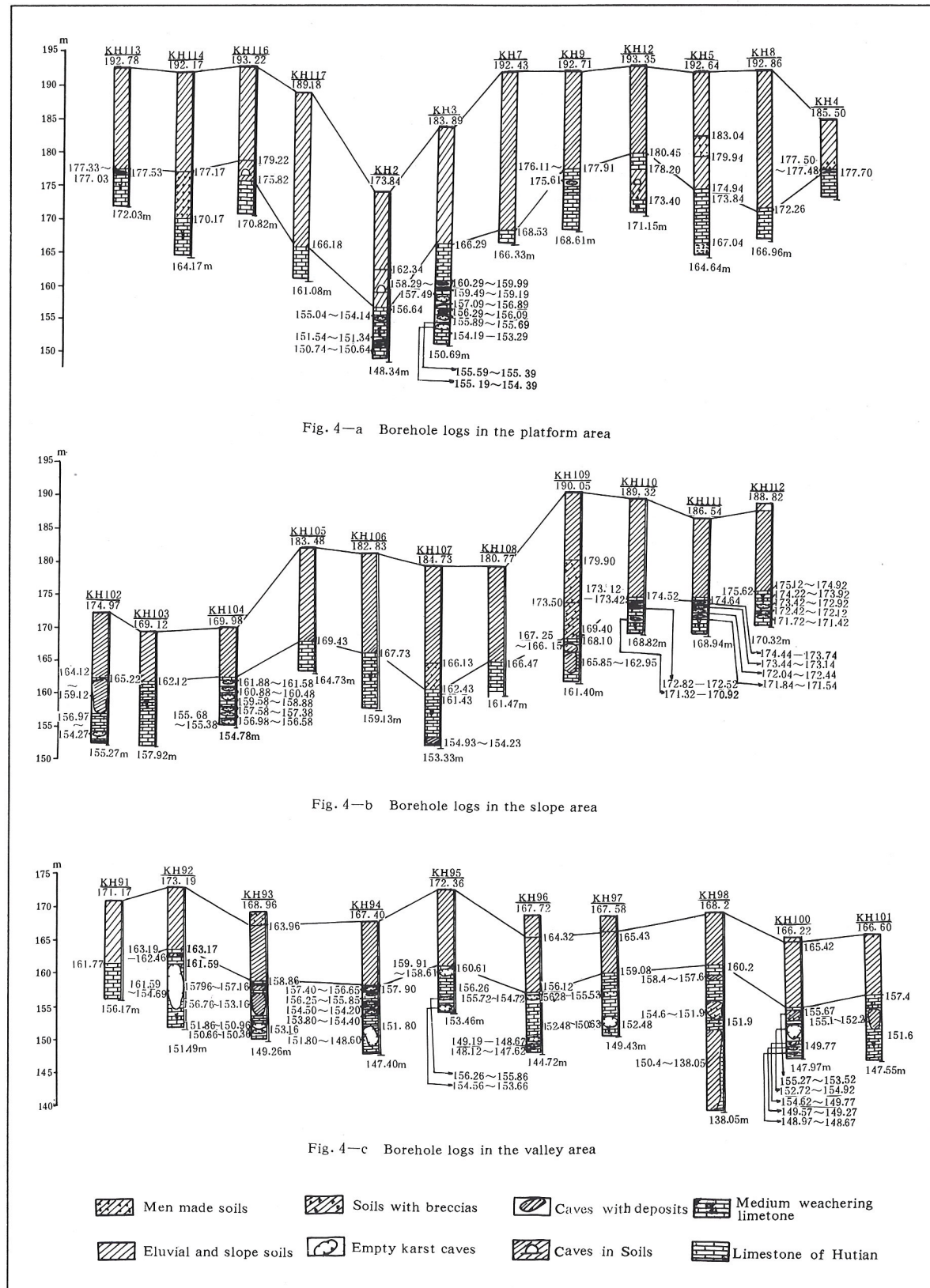


Figure 4 - Correlogram of boreholes showing the hidden karst caves at the site of the Pingshi power plant (Station B)

velopment of karrens at the former and of caves at the later.

(3) the valley area in which karst is intensely-developed. It is characterised by development of large and small caves. The ratio of karst in boreholes reaches 100% and the vertical linear ratio of karstification averages 44.35%. Therefore, when designing buildings the geological structure and karstification need to be considered.

The terrace area and the middle-upper parts of the slopes, in which caves are poorly developed and the rock body is relatively intact, can be taken as the main place to locate various engineering buildings since there are good geologic conditions. On the other hand, the valley area and the foot of the slope area, in which the rock is shattered and karstification is intense, are quite unfavourable to ground stability, and not suitable for heavy-loading and important buildings such as chimneys and boiler rooms. If there is a need to arrange heavy-loading

buildings in the valley, foundations need to be at least 40-50m deep (altitude of 127~117m) where more continuous bedrock occurs.

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Frequency and Time Series Analysis of Recent Earthquakes in the Vicinity of Hong Kong

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Abstract

We have examined the spatial and temporal patterns of 9876 $M_L \geq 1.0$ earthquakes that occurred within the region bounded by longitudes 111° E and 117° E, and latitudes 19.5° N and 25.5° N during 1973-1995. The seismic energy density map of the region reveals distinct zones of seismic activity that coincide approximately with presumably active faults. The statistical parameters of the magnitude-frequency relation have been computed for $M_L \geq 2.0$ earthquakes using both the least-square regression and the maximum likelihood estimator methods. Frequencies of $M_L \geq 6.0$ and $M_L \geq 7.0$ earthquakes computed using the maximum likelihood estimator method agree well with observed frequencies from historical data. A Fourier analysis of the earthquake data does not reveal any short-term cycles in the seismic record.

摘要

國家地震局在 1973 年至 1995 年間，一共紀錄了 9876 次在華南 111° E - 117° E, 19.5° N - 25.5° N 界定範圍內發生的一級以上地震。用該地震目錄計算的地震能量空間分佈，顯示地震活躍地區和第四紀斷層大致吻合。我們利用回歸分析和最大似然分析兩種方法，計算出區內地震發生頻率和震級的關係參數。再用最大似然分析的結果，去估計區內 6 級和 7 級地震的或然率。計算結果和區內近 400 年紀載的 6 級及 7 級地震頻率吻合。最後，利用傅里葉法，我們分析區內地震的功率譜。結果顯示區內的地震序列，並不存在短於 6 年的周期性。

Introduction

Hong Kong and its adjacent areas are located in a seismic zone known as the Southeast Coastal Seismic Belt. Although the area is not subject to a high seismic risk, several destructive earthquakes have occurred in the area during historical time. Recently, there has been some interest in the seismicity of the Hong Kong region (e.g. GCO, 1991; GSHK, 1996). Most of the published reviews on this subject have focused on relatively large earthquake events of magnitude ≥ 4 . Because of the short history of detailed instrumental measurement of earthquakes in the area, it has been difficult to assess the recurring intervals of major earthquakes in the region based on earthquake information. In this study, we have examined several aspects of the seismicity of the area adjacent to Hong Kong. First, we have summarized the available data of magnitude ≥ 1.0 for the last 25 years for Guangdong Province. Based on the record, the seismic

energy density is computed using the conventional energy-magnitude relation to show the distribution of seismic activity. Secondly, the seismicity of the Shenzhen area immediately north of Hong Kong is examined in greater detail. Thirdly, we have determined the frequency-magnitude relation using both the least-square regression method and the maximum likelihood estimator method. The computed frequencies of earthquakes from the two methods are compared with observed ones. Lastly, the power spectrum of the earthquake events has been analysed to detect if any short-term cycles exist in the earthquake record. The results are useful for the earthquake risk assessment of the region and evaluation of engineering requirements of buildings in Hong Kong.

Seismicity of the Region

The most comprehensive review of the earthquakes in the Hong Kong region is given by GCO

(1991). The region covered by the review is bounded by longitudes 111° E and 117° E, and latitudes 19.5° N and 25.5° N. Earthquakes that occur outside this area are considered less critical as they would not produce strong earthquake intensity in Hong Kong. In this study, we have adopted the same boundaries, giving a rectangular region of about 500 km across with Hong Kong located approximately at the centre of the region.

Two seismographic networks are operated independently in the region, one by the Royal Observatory of Hong Kong and the other by the Seismological Bureau of Guangdong Province, a subsidiary of the State Seismological Bureau of China. In the former network, three Teledyne Geotech vertical component short period seismometers ($T_0=1$ sec) are used to monitor local and micro-earthquakes (Tse et al., 1993). The latter network comprises 17 seismographic stations and two local observation stations distributed over the entire province of Guangdong.

We have acquired the earthquake record of Guangdong Province for the duration 1.1.1970 - 30.6.1995 from the State Seismological Bureau of China. The record contains information of epicentral location, focal depth, origin time, magnitude, and precision estimates for earthquakes of local magnitude 1.0 that occurred during the period. The data for the interval 1970 -1972, however, are incomplete and were therefore excluded from the analysis described in this paper. This is probably the most complete seismic record available for Guangdong for the time interval. We sorted out from the record a list of 9876 ML 1.0 earthquakes which occurred within the region between 1973 and 1995 (Table 1). The locations of the epicenters are shown in Figure 1. Most of these earthquakes were aftershocks from several major earthquakes, notably the Heyuan earthquake swarm in 1981, which was probably induced by water loading in a nearby reservoir. In this study, we have not attempted to exclude any induced earthquakes from the analysis.

The distribution of seismic energy density can show the intensity of the earthquake activity of the region. A map of seismic energy flux density has been presented by Lin and Xie (1996) for the coastal area of South China. The seismic energy flux density considered all historical earthquakes of relatively large magnitudes. In the present study, we are interested in determining the seismic energy dissipated by earthquakes in the region during the time interval. The computed seismic energy will also be used as the basis for the detection of seismic activity cycles. The conventional energy-magnitude relation is used to determine the energy of the earthquake, which is given by:

$$\log E = 11.8 + 1.5 M_s$$

where E is energy in ergs and M_s the surface wave

magnitude scale. For small and shallow-focus earthquakes, it is sufficient to take M_s and M_L the same (Bullen and Bolt, 1985). It should be noted that there are other methods to estimate seismic energy, that also take into account other seismic parameters such as focal depth. For the purpose of this study, this equation is sufficient since most of the earthquakes in the region were small and shallow.

The region in consideration is divided into a 30x30 grid of divisions, each approximately 460 km² in area. The total seismic energy of each division was calculated using the energy-magnitude equation above. The results were plotted and contoured using an AXUM 2D contouring software and smoothing grid ratios equal to 5. The seismic energy density map shows a broad belt of high energy along the coast of Guangdong (Figure 2). Within the belt, there are several zones of relatively greater seismic activity. In eastern Guangdong, the areas of seismic energy concentration form N to NW trending zones that are coincident approximately with the NW-SE striking faults. Two other centres of seismic energy concentration are located around Yangjiang area in western Guangdong and Heyuan. The low seismic energy zone over the offshore area is due to the small number of relatively large earthquakes in the offshore area. The Pearl River Delta area is located in a pocket a low seismic activity between the two relatively more active zones. The northwestern part of the region also shows relatively low seismic activity.

Earthquakes of the Shenzhen Area

A detailed analysis of the seismicity of the Shenzhen area immediately north of Hong Kong is important since a small earthquake occurring in the area can potentially produce substantial ground motion in Hong Kong. The microseismicity and earthquakes that occurred within the territory of Hong Kong have been reviewed by Yim (1991) and Tse, et al. (1993), while comprehensive reviews of the fault systems in the Shenzhen area are given by Lai (1993) and Song, et al. (1994). Geologically, the area is dissected into rectangular blocks by three sets of faults. The most prominent set, known as the Shenzhen Fault Belt, runs in a NE-SW direction. Lai (1993) identified five major NE-SW striking faults in this fault zone, namely, the Nigang, Henggang, Tiankuoleng, Yantian, and Jingxinbei faults. These faults are cut by less-prominent, NW-SE striking faults. In the Shenzhen area, the most important NW-striking faults are the Shuibei, Buxin, and Pankushi faults (Figure 3). Several E-W striking faults, which are probably older than the NE or NW striking faults, extend across the entire region.

At least twenty $M_L \geq 1.0$ seismic events have been recorded in the Shenzhen area (Figure 3). A cluster of epicenters is located near where the Buxin and Pankushi faults intersect the Tianluokeng fault south of the Shenzhen Reservoir. The magnitudes of

Table 1 - Number of seismic recorded events between 1.1.1973 and 30.6.1995

Magnitude	Number	Magnitude	Number
1.0-1.4	4643	1.5-1.9	2094
2.0-2.4	1856	2.5-2.9	831
3.0-3.4	320	3.5-3.9	88
4.0-4.4	26	4.5-4.9	9
5.0-5.4	8	5.5-5.9	1

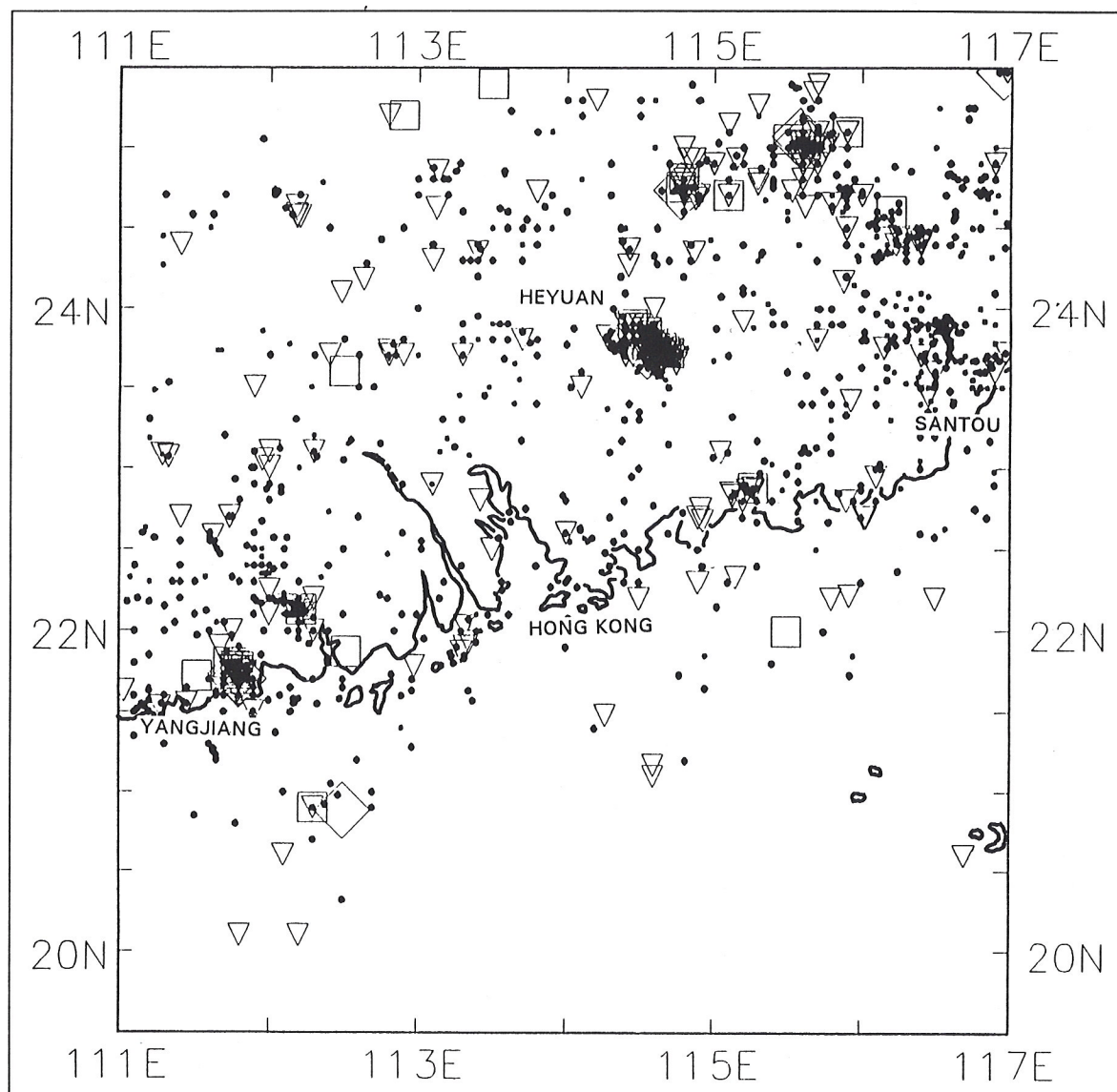


Figure 1 - Seismic events during 1.1.1973-30.6.1995 recorded by the State Seismological Bureau of China. The magnitudes are represented by smaller dots ($M=1.0-1.9$), larger dots ($M=2.0-2.9$), inverted triangles ($M=3.0-3.9$), squares ($M=4.0-4.9$) and diamonds ($M \geq 5.0$)

these earthquakes range from 1.1 to 2.8. A $M_L = 2.3$ earthquake occurred in 1988 near the intersection of the Tianluokeng and Pankushi faults. No earthquake of $M_L \geq 3.0$ has been recorded during the last 25 years in this area. Most of the earthquakes that occurred

on the NW-striking faults had very shallow focal depths. The nature of these small earthquakes is enigmatic; they may be due to minor adjustments of the faults or to water loading in nearby reservoirs.

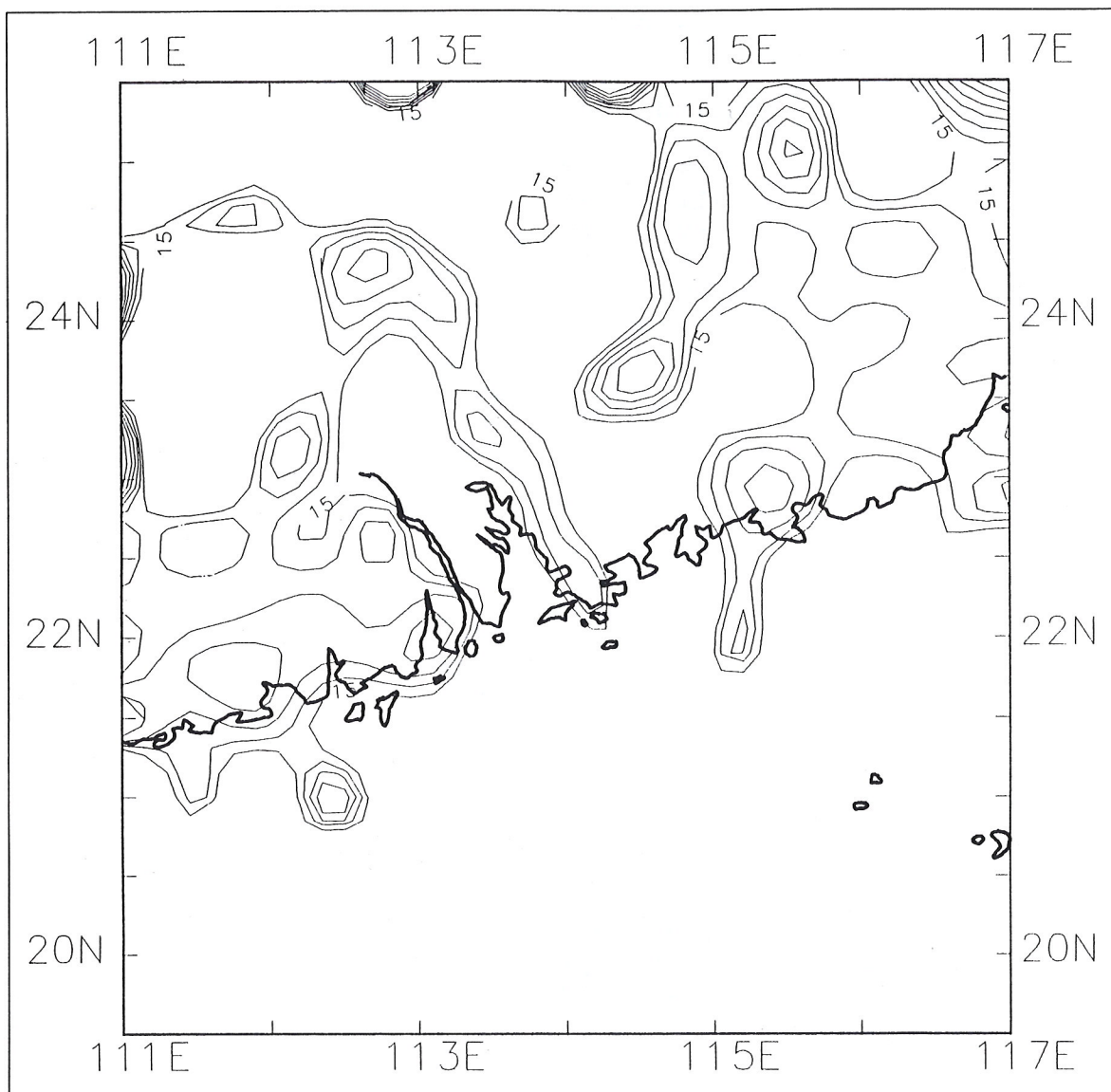


Figure 2 - Seismic energy density of Southern Guangdong region, plotted at contour intervals of 10^{15} , 10^{18} , 10^{21} ... ergs.

Relation Between Magnitude and Frequency of Occurrence

The magnitude-frequency relation for a region is useful for the determination of the recurring interval of earthquakes, which is often used in evaluation of long-term earthquake probability. While there have been many reports and discussions on the seismicity of the region, the authors are not aware of any published analysis of the frequency-magnitude relation for this particular region. In the present study, we have endeavoured to determine the statistical parameters in the magnitude-frequency of occurrence relation using two different statistical methods. Since the record for earthquakes of $ML < 2.0$ is incomplete, this statistical analysis has included only earthquakes of magnitude ≥ 2.0 .

It is customary to use the logarithmic value of the cumulative frequency in the equation describing

the magnitude-frequency relation. The general form of the cumulative frequency equation is given by:

$$\log N_c = a - b ML$$

where ML is local magnitude scale, N_c the cumulative frequency, given by the total number of earthquakes of or greater than a particular magnitude, and a and b statistical constants determined empirically. The inverse relation between the earthquake magnitude and its cumulative frequency of occurrence is represented by b , the slope of the cumulative frequency equation, which has value close to unity. An area with little seismicity generally has a small a value, the intercept of the cumulative frequency curve on the Y-axis. For the whole world, the values of a and b are 7.5 and 0.95 respectively for earthquakes of magnitude < 6.0 . The recurring interval, defined by the average return period of earthquakes greater than a particular magnitude, can be readily determined from

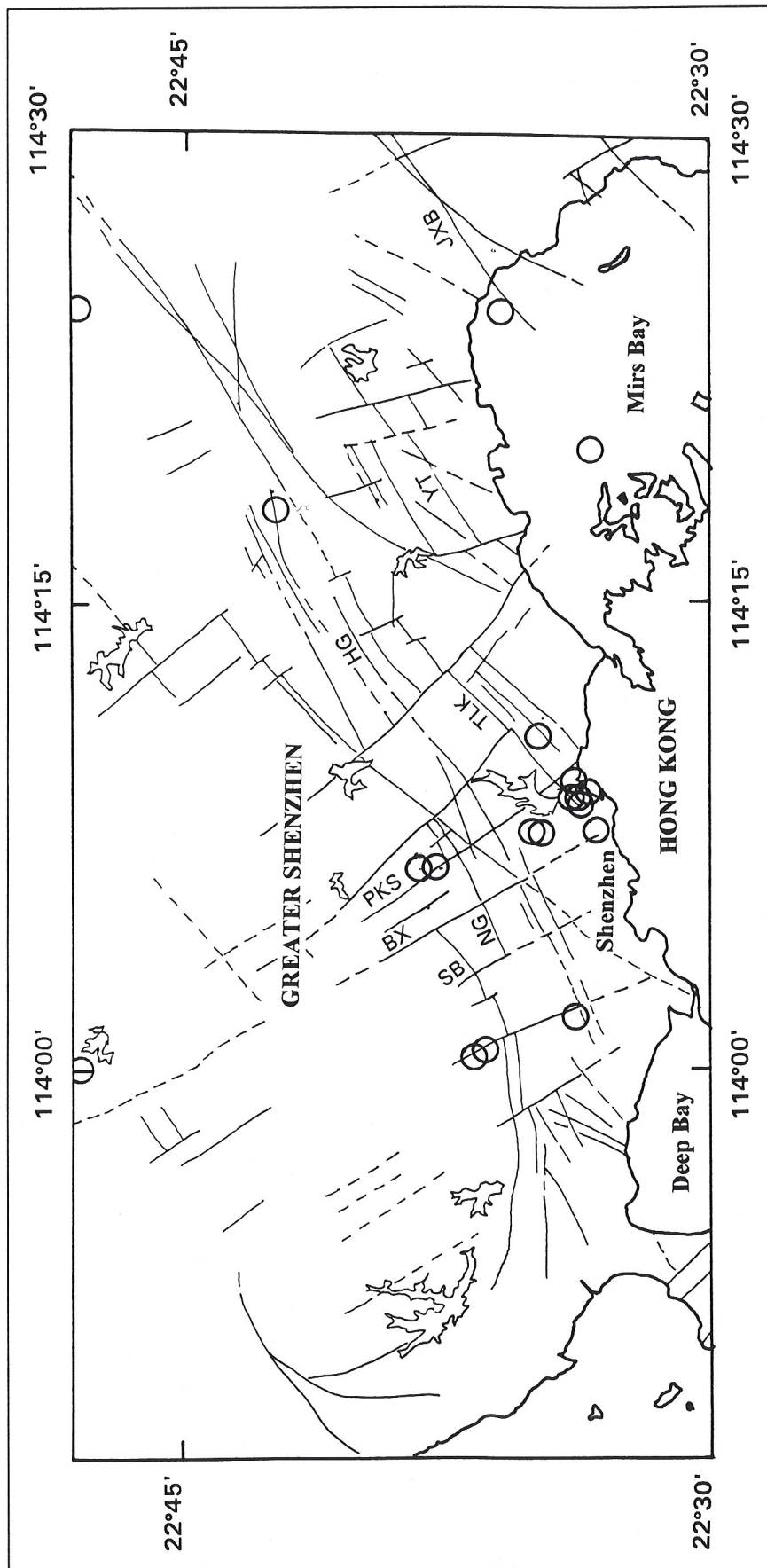


Figure 3 - Seismicity of Shenzhen. The symbols for the faults are JXB: Jianxinbei, YT: Yantian, TLK: Tianluokeng, HK: Henggang, NG: Nigang, PKS: Pankushi, BX: Buxin and SB: Shuibei.

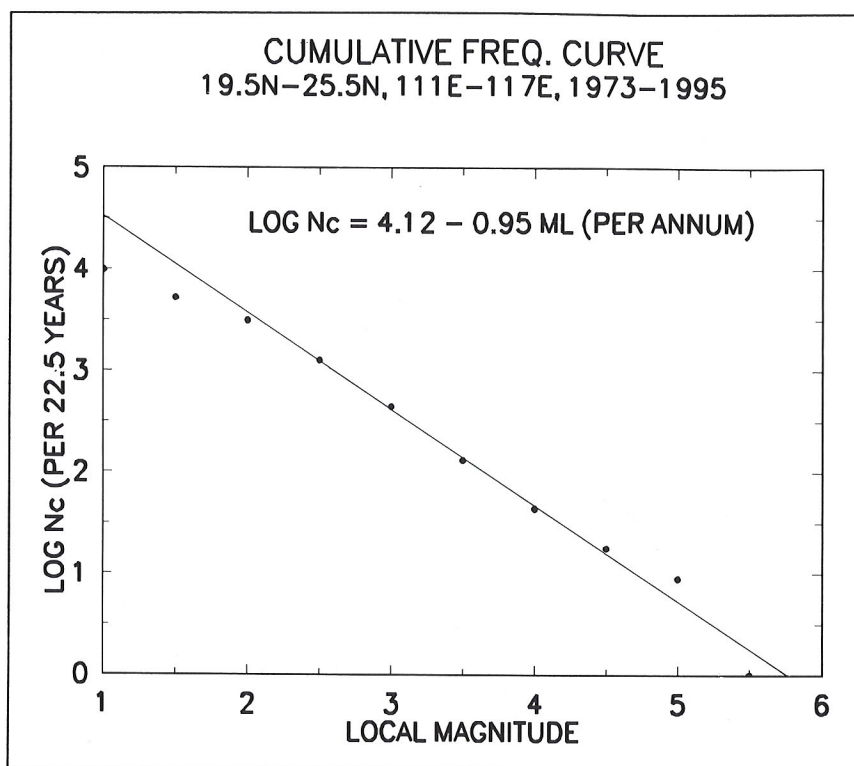


Figure 4 - Magnitude-cumulative frequency curve based on least square regression analysis.

the inverse of the cumulative frequency.

As shown in Figure 4, the cumulative frequency of earthquakes is plotted against the earthquake magnitude at 0.5 increments. A least-square regression analysis was conducted using data points of $ML \geq 2.0$. Most of the data points fall very close to the regression line except for $ML = 1.0, 1.5$, and 5.5 . The depletion in the $ML < 2.0$ earthquakes is due to the lack of earthquake records in the offshore area. The small number of $ML \geq 5.5$ events is partly because of the short duration of the recording period which does not reflect accurately the long-term earthquake frequency. The cumulative frequency equation obtained using the least square regression method is:

$$\text{Log } N_c = 4.12 - 0.95 \text{ ML}$$

with coefficient of correlation, $R=0.9857$.

The least square regression method has a major disadvantage since the presence of even a few large earthquakes can influence the b value significantly. The method of maximum likelihood estimator is often regarded as an alternative method to estimate the probability distribution function. Detailed description of the method can be found in statistical textbooks such as Larson and Marx (1981). The method has been applied by Shi and Bolt (1982) to estimate the value and standard error of the b value in the magnitude-frequency of occurrence relation. In this study, we have used the maximum likelihood estimator method to determine the predicted frequency of earth-

quakes of different magnitude ranges for the region. The probability function for earthquakes of a particular magnitude range is assumed to follow the geometric distribution, i.e.

$$P(k) = (1-p) \exp(k-1) \cdot p \quad k=1, 2, \dots$$

in which p is the maximum likelihood estimator and k the group number of the magnitude range. The maximum likelihood indicator is given by:

$$p = 1/M$$

where M is the density function given by:

$$M = \sum kN/\sum N$$

The predicted frequency of occurrence of a particular magnitude range is given by:

$$N_{k, \text{predicted}} = \sum N \cdot (1 - 1/M)^{(k-1)} \cdot 1/M$$

From the equation, the probability, $P(k)$, and the predicted frequency of occurrence, N , of each earthquake magnitude have been determined as shown in Table 2.

The cumulative frequencies were then determined and converted to annual cumulative frequencies. A simple curve-fitting was done to obtain the statistical parameters in the magnitude-frequency relation, which is given by:

Table 2 - Determination of Predicted Frequency of Occurrence by Maximum Likelihood Estimator Method for a 22.5 Years.

Magnitude	k	N(observed)	k.(N)	P(k)	N(predicted)
2.0	1	1856	1856	0.6191	1943.5
2.5	2	831	1662	0.2358	740.2
3.0	3	320	960	0.0898	281.9
3.5	4	88	352	0.0342	107.4
4.0	5	26	130	0.0130	40.9
4.5	6	9	54	0.0050	15.6
5.0	7	8	56	0.0019	5.9
5.5	8	1	8	0.0007	2.3
$\Sigma N=3139$, $M=1.6152$, $p=0.6191$					

$$\log N_c = 3.95 - 0.88 M_L$$

A method of assessing the standard error of the b value is presented by Shi and Bolt (1982). However, in the present study, we have not attempted to evaluate the standard errors of the statistical parameters in the magnitude-frequency relation because of the preliminary nature of the analysis.

Comparison between Observed and Predicted Frequencies

The observed and predicted frequencies of M_L 2.0-7.0 earthquakes, based on the cumulative frequency relations obtained by the least-squares regression and the maximum likelihood methods, are shown in Table 3. For $M_L \leq 5.0$ earthquakes, the cumulative frequencies are *per annum* as determined from the 1973-1995 record. The observed cumulative frequencies for $M_L = 6.0$ and $M_L = 7.0$ earthquakes are based on the seismic catalogue of the last 100 and 400 years respectively (GCO, 1991). There were 6 $M_L \geq 6.0$ events during the last 100 years and 2 $M_L \geq 7.0$ events during the last 400 years in the region. As shown in Table 3, the predicted cumulative frequencies from the two methods agree well with the observed cumulative frequencies. In general, the least-square regression method tends to overestimate the frequency of relatively smaller earthquakes and underestimate the

frequency of the relatively larger ones. The maximum likelihood estimator method, on the other hand, yields predicted frequencies that compare better with the observed ones for all magnitude ranges except for $M_L = 4.0$.

Even though no large earthquakes occurred in the region during the 22.5 year time period covered by this study, the recurring interval of large earthquakes can still be inferred from the magnitude-frequency relation. As shown in Table 3, the predicted recurring intervals for magnitude ≥ 6.0 and 7.0 earthquakes are, respectively, 22 years and 166 years.

Time-series analysis of earthquake events in the region

Lin and Xie (1996) analysed the historical record of large earthquakes with the maximum entropy method to determine the time distribution of the earthquake events. They pointed out that the record of large earthquakes in the coastal area of South China exhibits a 310 years period. We are interested in knowing if the earthquake events also exhibit short-term cycles. A Fourier analysis of the seismic data was conducted to obtain the power spectrum of the earthquake data. For rule-of-thumb, at least three cycles are needed in a time-series to establish the cyclicity. The current data set spans an interval of 22.5 years and thus allows for detection of periodicity

Table 3 - Comparison of observed and predicted frequency of occurrence

M_L	N_c (observed)	N_c , pred. (LSR)	N_c , pred. (MLE)	Recurring Interval
2.0	139.5	164.3	152.4	2.4 days
3.0	20.0	18.4	20.0	18 days
4.0	2.0	2.1	2.6	4.6 months
5.0	0.4	0.23	0.34	2.5 years
6.0	6/100yr	2.6/100yr	4.5/100yr	22 years
7.0	2/400yr	1.2/400yr	2.4/400yr	166 years

on the order of 7 years or less.

Instead of using the number of earthquake events of particular magnitude range, we used the total seismic energy flux dissipated in the entire region per quarter as the input variable. The total energy flux per quarter was computed and the results were submitted to a fast Fourier transform using the MATLAB software. The power spectrum obtained is plotted alongside the time series in Figure 5. The power spectrum of the seismic energy flux reveals no

discernable peaks, suggesting that the seismicity of the area does not exhibit any short-term cycles of 7 years or less. However, the result does not argue against the presence of longer cycles.

Conclusions

In this study, we have analysed several aspects of the seismicity of the area in the vicinity of Hong Kong. The magnitude-frequency of occurrence relation based on the available seismic record for 1973-

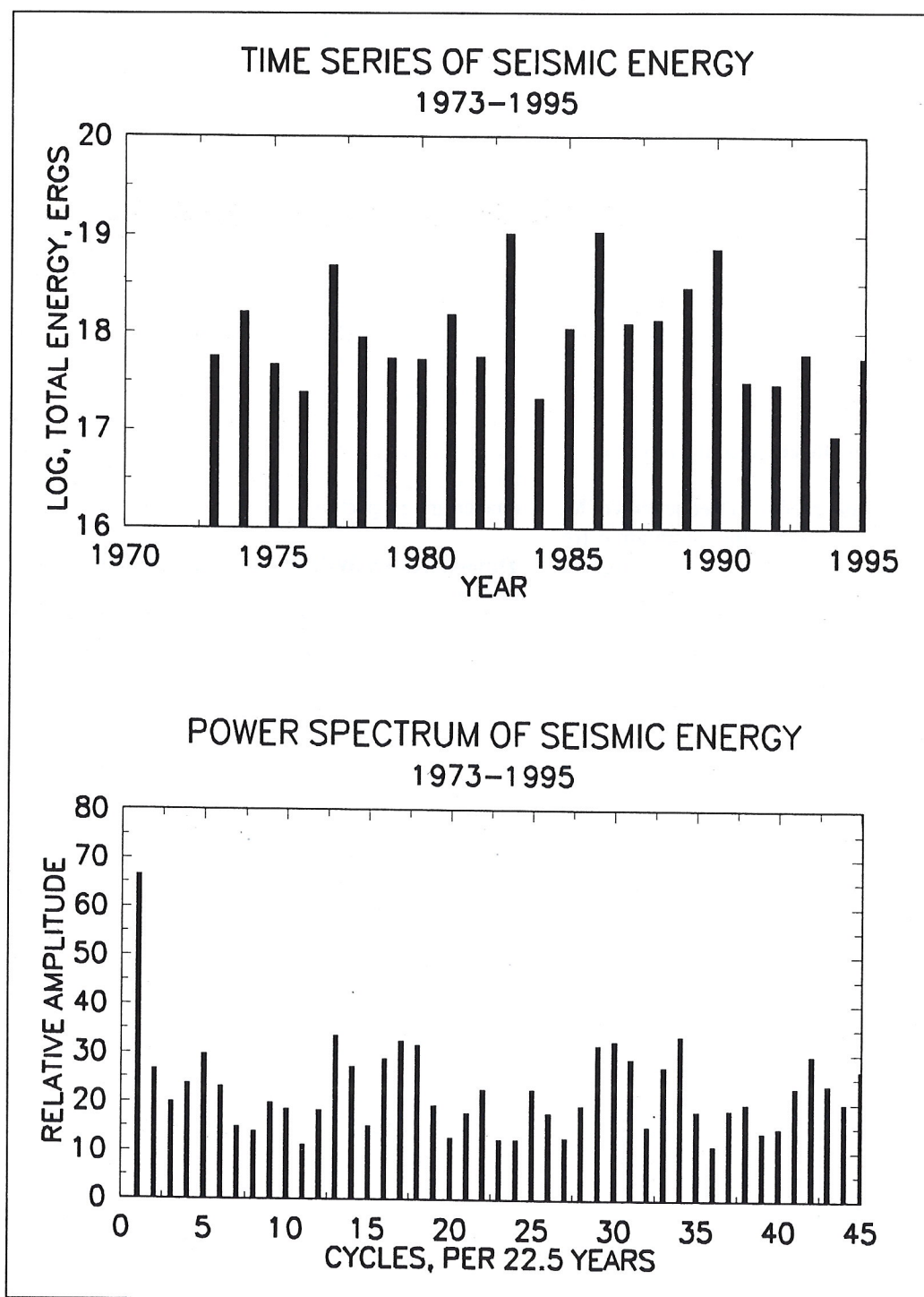


Figure 5 - Time and frequency domains of total seismic energy for the region

1995 has been established. The method of maximum likelihood estimator yields a maximum-frequency of occurrence relation for the region that can potentially be used to predict the recurring intervals of larger earthquakes. The predicted recurring intervals for $M_L \geq 6$ and 7 earthquakes are 22 and 166 years respectively. The magnitude-frequency of occurrence relation and the recurring intervals obtained in this study are provisional; in nature because of the short recording duration and the absence of strong earthquakes in the region during the time period. However, the long-term frequencies extrapolated from the relation for $M_L \geq 6$ and 7 earthquakes are in good agreement with the observed frequencies for the last 100 or 400 years. The spatial pattern of seismic energy density shows distinct areas of relatively higher seismic activity. Some of the high seismic energy zones are coincident with presumably active faults of the region, suggesting that at least some of the seismic activity was generated by movement on these faults. The power spectrum does not reveal any pronounced short-term cycles in the earthquake occurrence. The presence of long-term cycles, however, cannot be ruled out by the current analysis.

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THE DISCOVERY OF LATE PERMIAN FOSSIL PLANTS AND ITS STRATA IN HONG KONG

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Abstract

Several specimens of fossil plants have been collected for the first time in Hong Kong, on the northeastern shore of Centre Island, Tolo Harbour, in the New Territories of Hong Kong. The specimens were found in black carbonaceous shale, silty shale, siltstone and sandstone, which Allen and Stephen (1971) considered to be the beds of the Tolo Harbour Formation and possibly of Permian Age (Addison et al., 1986), although at the time they had no palaeontological evidence for this supposition. They therefore considered that this bed might also be the same as the beds of the Ma Shi Chau Island Formation.

The specimens have been carefully identified to genus and species as follows:

Pecopteris (Asterotheca) cf. norinii Halle;

Pecopteris sp. (cf. *P. lativenosa* Halle);

Compsopteris cf. contracta Gu et Zhi;

Cordaitea cf. shenkii Halle;

Gigantopteris (cf. *Gigantopteris* sp.).

They belong to the early upper Permian (P_2^1) "Gigantopteris flora" commonly seen in the Longtan Formation (formally known as the Longtan Coal Series) on Guangdong Province, China (Hou, et al. 1979). Since the stratum yielding the above-mentioned fossil plants is significantly different from the Tolo Harbour Formation in lithology, fossil content and hence in age, the author recommends that it be renamed the "Centre Island Formation".

摘要

一九八一年二月，筆者在香港新界大埔海丫洲島東北海岸出露的黑色炭質頁岩、粉砂質頁岩、粉砂岩及砂岩中，首次發現了一些植物化石，這些岩層以前未見化石情況下，Allen 和 Stephen (1971) 認為屬於大埔海組，其時代可能為二疊紀 (Addison 等，1986)，與馬屎洲島的地層組合相同。

這些化石經詳細鑑定有以下屬種：

變葉櫛羊齒 (變葉星囊蕨) 比較種

厚脉櫛羊齒比較種

基縮蕉羊齒比較種

大羽羊齒類 (大羽羊齒未比較種)

它們屬中國華南常見的早期晚二疊世龍潭組 (前稱龍潭煤系) 大羽羊齒植物群 (侯等，1979)。

鑒於丫洲島上述地質發現了大羽羊齒植物群，意味着該岩層與馬屎洲島具海相化石的大埔海組有所區別，應另命名，為此，筆者建議起名為丫洲組。

Introduction

On Centre Island of Tai Po Hoi (Tolo Harbour) about 6 kms east of Tai Po Market in the northeastern part of Hong Kong (Figure 1), a banded series of slightly metamorphosed black carbonaceous shale intercalated with siltstone and sandstone is exposed. It forms a banded series of metamorphosed silty mudstones, black shales and metamorphosed quartritic siltstones. Allen and Stephens (1971) believe that lithologically this stratum is similar to the sandstone and shale of the Tolo Harbour Formation occurring on Ma Shi Chau Island about 1 km northeast of Centre Island. The Tolo Harbour Formation, consisting of grey and black shales and banded siltstones in which brachiopods, crinoidal stems, coral, plants and bryozooid had been discovered (Nau, 1980; Lam, 1973, Addison, 1986), was once believed to be marine beds of Carboniferous-Permian or possibly Permian age. Detail study in more recent years has revealed many fossils including the following index fossils: *Tenmichontes tenuilirata* (Chao), *Neoplicafifera huagngi* (Ustriski), *Paradoxipecten jiaheensis* Zhang, *Enchondria jiaheensis* Fang, *Enchondrioides zhuzhouensis* Fang, *Paracelites* sp.). However, the fossils mentioned above are Early Permian in age (Lee, et al., 1985; 1990).

In February 1981, when carrying out a brief geological survey of Centre Island (Plate I), the author collected from greyish black carbonaceous shale in the northeast tip of the island (Plate 2) a group of fossil plants which were later identified to be the *Gigantopteris* flora including: *Pecopteris* (*Asterotheca*) cf. *norinii* Hall, *Pecopteris* sp. (cf *P. lativenosa* Halle), *Compsopteris* cf. *contracta* Gu et Zhi; *Cordaites* and *Gigantopteris* sp. They are common in Late Permian

strata, specifically in the Longtan Formation in Guangdong Province and elsewhere in southern China. Therefore the discovery of these fossil plants (which have in part been identified down to genus and species) for the first time in Hong Kong has proven the existence of Early Late Permian stratum in Centre Island. It should be distinguished from, and is younger than, the Early Permian Tolo Harbour Formation in Ma Shi Chau Island. Since this stratum in Centre Island, with its fossil content, is entirely correlatable with the Late Permian Longtan Formation in southeastern China, the author recommends that it be named the Centre Island Formation.

Stratum

With is spindle outline the NNE-elongated Centre Island is situated in the Tai Po Hoi Sea (Tolo Harbour) to the northeast of Hong Kong. It is about 400 m long about 100-150 m wide, with hills about 26.8 m in height above mean sea level. The stratum exposed throughout the Island consists largely of greyish black to black shale, carbonaceous shale and pelitic shale intercalated with silty shale and grey, medium fine quartz sandstone and feldspathic quartz sandstone, with an exposed thickness of about 40 m. The shales are thin-bedded while the sandstones are largely thick-bedded in structure, dipping generally toward SN at angles varying from about 40° to 70°. In the southwest part of the Island, granite porphyry veins are recognisable, penetrating the black shale, causing the stratum in the island to be slightly metamorphosed. This weak metamorphism is demonstrated mainly by cordierite crystallites occurring as spots in the shales. The fossil plants are locate in a fossiliferous bed 30 cm in thickness amongst the black

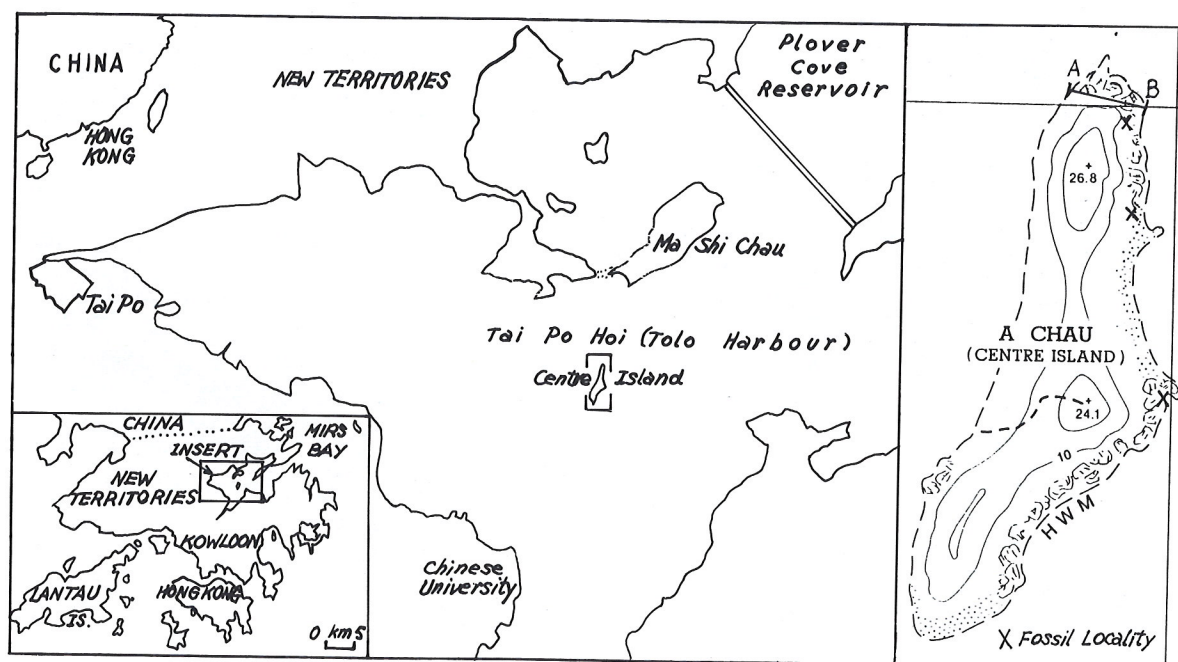


Figure 1 - Location map of fossil plant-bearing beds in Hong Kong



Plate 1 - Centre island with Ma Shi Chau in the background. Exposed here are banded shale and sandstone.



Plate 2 - Location of the fossil plants amongst black shale on the northeast corner of Centre Island. The exposed fossil bearing strata dip to NE 80°

carbonaceous shale of the sea cliffs on the northeast corner and east coast of Centre Island.

The geology of the surrounding area is more complex: there are Devonian sandstones, siltstones and conglomerates exposed at the Plover Cove Reservoir to the east; limestone in the sea area between Ma Shi Chau and Plover Cove Reservoir; limestone of possibly Devonian-Early Carboniferous age, granite, late Jurassic volcanic rocks, and metamorphosed sandstone and shale of possibly Permian age between Tai Po market and The Chinese University of Hong Kong.

A stratigraphical sequence is obtained along a line A-B (Figure 2). The line A-B is approximately perpendicular to the strike line of the beds and extends in a direction of azimuth 100° (southeast). The total thickness is about 40 m. It is recognised to be basically continuous from lower to upper. The lithological division and description in ascending order is as follows:

- | | |
|--|---------|
| 10. Grey and greyish purple mudstone | > 2.4 m |
| 9. Grey and greyish purple argillaceous siltstone | 2.4 m |
| 8. Grey fine-grained sandstone | 3.2 m |
| 7. Greyish black mudstone, yielding abundant plant fossils | 1.7 m |
| 6. Greyish yellow, grey, greyish purple and variegated argillaceous siltstone and fine-grained sandstone | 6.7 m |
| 5. Greyish purple banded shale | 2.2 m |
| 4. Greyish mudstone and carbonaceous shale | 1.5 m |
| 3. Greyish-white siltstone | 0.9 m |
| 2. Black mudstone | 8.2 m |
| 1. Black grey fine-grained sandstone and grey middle-grained sandstone | >1.0 m |

Fossil Plants

The fossil plants were discovered in black pelitic shale and are rich and densely distributed. Those collected to date are mainly Pecopterides, Gigantopterides, Cordaites and Stigmaria:

(a) *Pecopteris (Asterotheca) cf. norinii* Halle (Plate 3, Figures 1, 2 and 3)

There are altogether three well-preserved specimens showing penultimate pinnae about 10 cm broad. The ultimate pinna is linear, reaching lengths up to 3 cm and breadths of about 8 mm. Pinnules are tiny, closely set, regularly and nearly vertically attaching to the rachis on both sides, oblong or rectangular in geometry, 3.5-4 mm long and 1.5-1.6 mm broad with a length : breadth ratio of about 2.1-2.5, showing obtusely rounded apex and distinct margins. The midrib is distinct and thick, depressed but not decurrent. The lateral veins are fairly strong. Fertile pinnae are *Asterotheca*-type synangia on both sides of the midrib (Plate III, Figure 2).

(b) *Pecopteris* sp. (cf. *P. lativenosa* Halle) (Plate 3, Figure 4).

There are three specimens which show penultimate pinnae about 10 cm in length. The ultimate pinna is linear, reaching lengths up to 1-1.5 cm and breadths of about 3-5 mm. The width of the pinna decreases gradually towards the tip of the pinna, showing an obtusely rounded apex. The pinnules are closely set, and measure roughly seventy degrees from the rachis on both sides. The end portion of each pinna curves slightly towards the tip, and forms a sickle shape. At the base of the pinna, the upper portion forms a ear-shaped curve, and the lower portion forms a smooth curve extending downwards and approaching the rachis.

(c) *Compsopteris* cf. *contracta* Gu et Zhi (Plate 3, Figures 5, 6, 7, 8, 9, 10 and 11).

In the specimens collected, the pinnule is attached to the rachis by a point at the centre of the base, marking a 60° angle with it, alternate, about 60 mm long and 10 mm broad, obtusely rounded at apex, contracted at the lower base into an obtusely rounded ear-shaped outline. Midrib is distinct, reaching the apex. Lateral veins are thin and densely distributed,

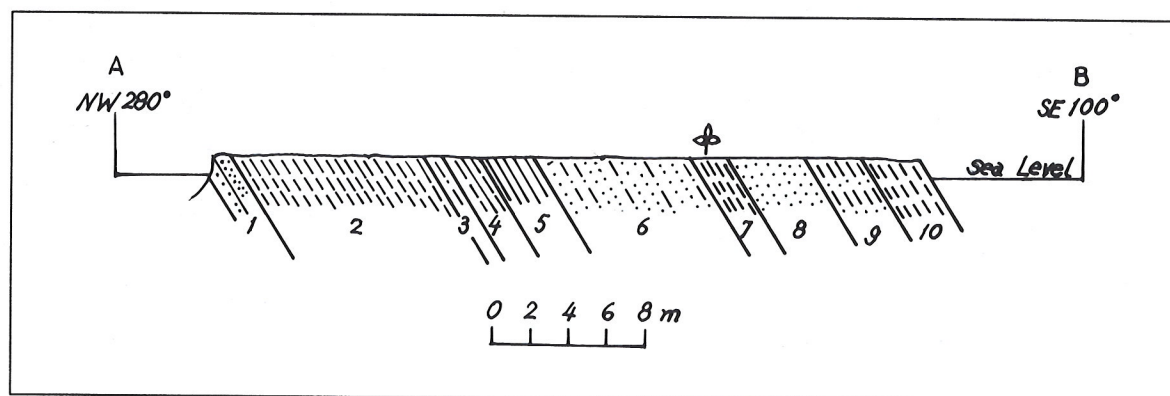


Figure 2 - Stratigraphical section across the Centre Island formation at Northern Centre Island. The location of section A-B is shown in Figure 1.

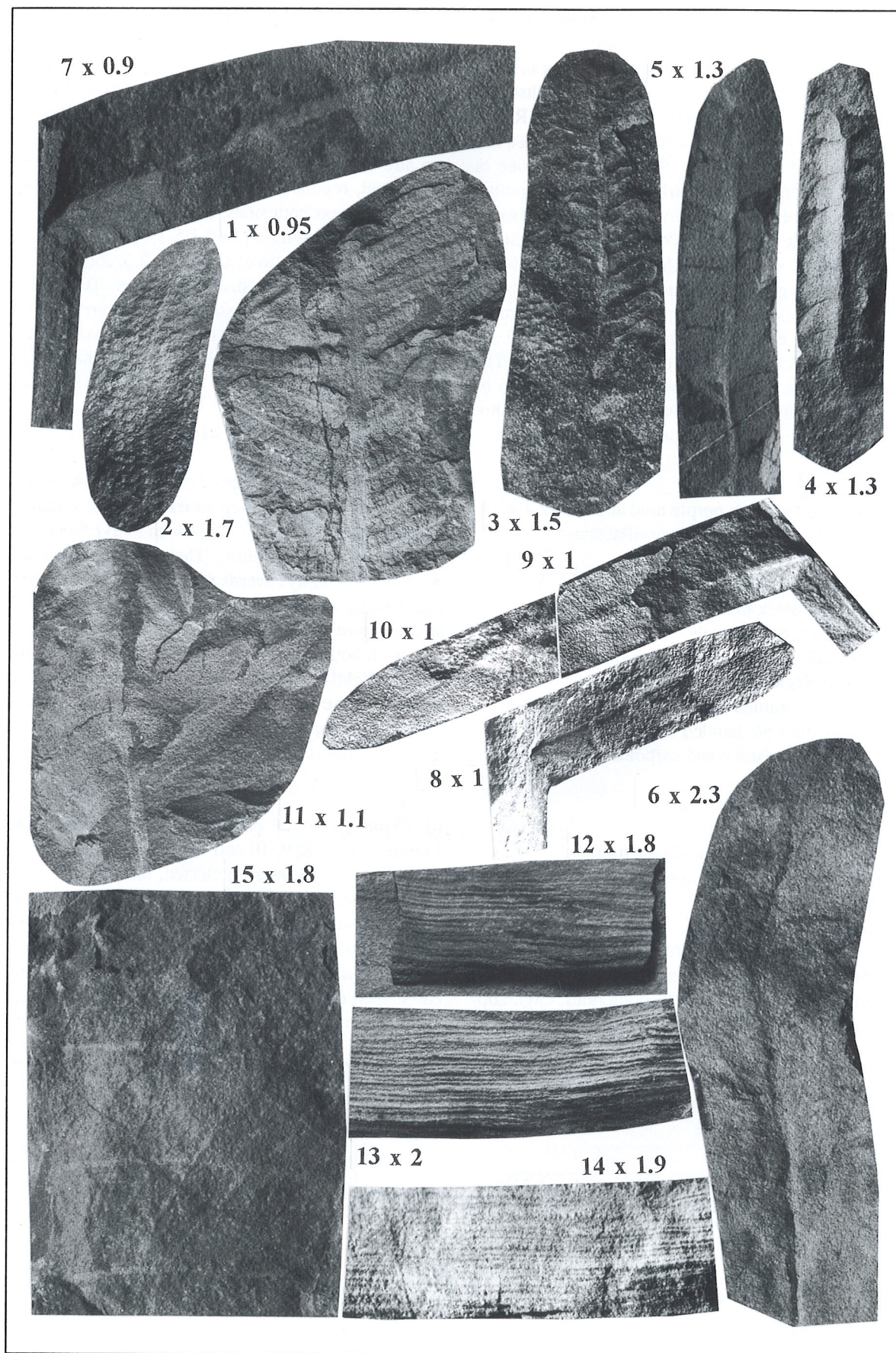


Plate 3 - Specimens of fossil plants collected from Centre Island (the first number, from 1-15, refers to the specimen number, the second number refers to the magnification)

arching outward while bifurcating. Pinnas are entire.

(d) *Cordaitea* cf. *schenkii* Halle (Plate 3, Figures 12, 13 and 14)

Only fragments of leaves are preserved in the specimens. The largest leaf fragment is more than 10 cm long and 3 cm broad, relatively smooth at the surface, with about 12-14 parallel veins per centimetre. In part of the specimens, the skin at the surface of the leaf is lacking, and the veins are distinct and are bulging slightly above the leaf surface. One to five longitudinal striations are recognisable, sparsely spaced, often thinner than, or as thin as the leaf vein.

(e) *Gigantopterides* (cf. *Gigantopteris* sp.) (Plate 3, Figure 15).

Only a fragment of this leaf is preserved. It is a large-scaled part of a pinnule or simple leaf with midrib (primary vein) thick and distinct. At least second lateral vein, veinlet anastomoses again and again, order by order, with the spacing of the first pinnate lateral vein measuring about 1 cm. This pinnate vein branches out nearly vertically from the midrib. The pinnule or leaf is very large, but the outline is unknown. The fossil is poorly preserved.

In specimens collected from Centre Island the leaf veins are not entirely equally spaced and often bulge above the leaf surface. This fossil plant is similar to the *Cordaitea schenkii* Halle from Gedingzhai, Renhua County of Guangdong Province, as reported by Hou, et al. (1979).

Discussion

Since there have previously been no fossil records relating to Centre Island in Tai Po Hoi (Tolo Harbour), the stratum in this Island was often correlated with the Tolo Harbour Formation of Ma Shi Chau Island and was considered to be of the same age (Allen and Stephens, 1971). Indeed, even though the author advised Dr Addison of the discovery of fossil plants on Centre Island, he continued to adopt the old stratigraphic classification in his Geological Survey report (Addison et al., 1986).

The discovery of fossil plants on Centre Island is unprecedented in Hong Kong. These fossil plants have been identified to be Late Permian in age. It should be pointed out that the fossil plant-bearing stratum of Centre Island is significantly different from the Early Permian marine facies fossiliferous Tolo Harbour Formation in Ma Shi Chau, not only in their fossil content but also in their lithologic features. Lithologically the stratum of Centre Island consists largely of greyish black pelitic shale, black carbonaceous shale, banded sandstone and shale, siltstone and quartz sandstone with part of the black carbonaceous pelitic siltstone showing banding and cross-bedding, from which the fossils collected are wholly fossil

plants. In contrast, the Tolo Harbour Formation in Ma Shi Chau consists largely of greyish white, greyish purple, dark grey pelitic shale and pelitic siltstone often bearing pyrite crystals, and calcareous siltstone with occasional sandstone. Relatively abundant fossils have been collected from this Formation (Lam, 1972; Nau, 1980; 1981, Lee, 1987) include brachiopods, lamellibranchia, ammonitida, crinoidia, bryozooids and corals, all of which are typical of Early Permian marine facies (Table 1) (Lee et al., 1990).

Therefore, on the basis of palaeontological and stratigraphic correlation, the Centre Island stratum cannot be equivalent to, and must be distinguished from, the early Permian Tolo Harbour Formation. The former should be assigned to Late Permian or possibly early Late Permian. Hence, the author recommends that it be identified as the Centre Island Formation. Because these two formations are found to be isolated on two separate islands, the contact relation between them remains unknown.

When correlating with the strata in southern China, and in particular in Guangdong Province, the fossil plants from the Centre Island Formation are similar to the Late Permian plants commonly seen in the Longtan Formation, which is a very important coal association known as the Longtan Coal Series in South China. It is likely that the Centre Island Formation in Hong Kong is equivalent to the Longtan Coal Series. This deserves further attention (Table 1).

Acknowledgements

The author thanks Mr Zhang Huanxin, a palaeontologist in Botany with the Institute of Geological Sciences of Guangdong Province, who has helped greatly with the identification of the fossils, Miss Wu Shunqing of the Nanjing Institute of Geology and Palaeontology for comments offered by her, and Professor Xu Run of the Institute of Botany of Academia Sinica who enthusiastically reviewed a draft of this paper and made helpful comments prior to his death, for which the author wishes to express his mourning. The author also wishes to thank Professor Yang Guansiu of the China University of Geosciences (Beijing), who also enthusiastically reviewed the final draft of this paper and offered helpful comments.

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Table 1 - Correlation of the Late Permian between Hong Kong and Guangdong Province

Northern Guangdong Province			Central-Southern Guangdong Province		Northeastern Guangdong Province		Hong Kong		
Lower Permian P ₁	Qixia Formation	P ₁					Marine Facies Limestone		
	Maokou or Gufeng Formation	P ₁ ²					Marine Facies		
Upper Permian P ₂	Longtan Formation (Coal Series)	P ₂ ¹					Coal Series	Centre Island Formation	<i>Pecopteris (Asterotheca) cf. norinii</i> <i>Pecopteris</i> sp. (cf. <i>P. Lativenosa</i>) <i>Compsopteris</i> cf. <i>contracta</i> <i>Cordaite</i> cf. <i>schenkii</i> <i>Gigantopteris</i> (cf. <i>Gigantopteris</i> sp.) <i>Tenuichontes tenuilirata</i> (Chao) <i>Neoplicatifer huangi</i> (Ustriski) <i>Paradoxipecten jiaheensis</i> Zhang <i>Enchondria jiaheensis</i> Fang <i>Enchondroides zhuzhouensis</i> Fang <i>Paracelites</i> sp.
	Sui Chu Tang Formation	P ₂ ²					Marine - Continental Facies		
	Wong Pan Li Formation	P ₂ ³							
	Chang Xin Formation	P ₂ ⁴					Marine Facies		

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Editors note: As this issue went to press Lee Cho Min and co-workers provided the editor with a list of newly discovered fossils from Lantau Island. This list was published in *Geosphere* (the Geology Society's Newsletter) February 13.

Exploration for Offshore Sand in Hong Kong: Detailed Surveys, Dredging and Environmental Assessments

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Abstract

Hong Kong used about 250Mm³ of marine dredged sand from 1991 to 1995 to form land for the new airport and port facilities, roads and various new town developments for housing and industry. The main sand reserves are Pleistocene fluvial deposits, the upper portions of which were largely reworked and laterally transported by early Holocene tidal currents. Economic sand reserves mostly occur where later Holocene mud deposition has been restricted by high tidal flows. Sand dredging proposals have been subject to the environmental impact assessment process and in some instances the decision was taken not to extract certain sand deposits for environmental, ecological and socio-economic reasons. Detailed dredging assessments have been undertaken to quantify economic reserves. Of key importance are the overburden ratio and a means to economically dispose of the overburden. Increasing use has been made of the empty sand borrow pits to provide sites for cost effective mud disposal while at the same time reinstating the seabed. The marine exploration programme has extended into Chinese waters where large deposits of sand have been identified. Despite the relatively greater distance of these reserves, their lower overburden ratio coupled with reduced environmental impacts mean that these will likely serve Hong Kong's future needs for reclamation fill well into the next century.

摘要

香港自 1991 年至 1995 年約用了 2 億 5 千萬立方米的海砂去開拓土地，用以建設新機場，海港設施，道路及新市鎮住宅和工業方面的發展。其中主要的砂源是來自更新世的河流沉積砂，早全新世的潮流使大部份砂層上部側移和再沉積。具經濟價值的砂源通常出露在沒有晚全新世淤泥覆蓋的急湍潮流水道中。

採砂建議是需要先通過環境影響評估的步驟，其中亦有因環保生態及社會經濟的原因，而決定取消去開挖某些海砂。並需用詳細評估採砂的方法去評定砂源的經濟儲量，而泥層與砂層的厚度比及是否有經濟的方法去卸置覆蓋的淤泥層是其中最重要的因素。現漸廣泛使用空置的採砂坑去卸置淤泥，這種安排既合乎經濟原則，同時亦可回復海床的原狀。砂源勘探的範圍現已延伸至中國水域，並已測定到豐富的砂源。雖然這些砂源距離較遠，由於淤泥層較薄，及對環境影響較輕微，因此這些砂源將可為香港下世紀的填海工程提供充足的填料來源。

Introduction

The background to Hong Kong's ever increasing demand for new land and the initiation, in 1987, of exploration for offshore sand for use

as reclamation fill has been covered in the companion paper (Shaw & Cheung, 1995). Other background information on the offshore fill resources can be found in Brand & Whiteside, 1990, Brand et al., 1994,

Whiteside, 1991 and Ooms et al., 1994. Shaw & Cheung (1995) covered the first stage of work from 1987 to 1991, called the SEAMAT study (Cheung & Shaw, 1993), which examined a series of fourteen potential sand resources.

Following on from the SEAMAT study, the fourteen resources were then further studied to determine the economic reserves. These further studies fall into three broad categories :-

- * detailed geological investigation of individual sand resources
- * dredging assessments, calculation of economic sand reserves, and preparation of borrow area development plans
- * environmental impact assessment of sand extraction and any associated mud disposal operations

The task of identifying economic reserves is to a degree an iterative process in which dredging and environmental constraints have to be balanced within the framework of the geology. The process is therefore not necessarily a sequential one - dredging designs often have to be revisited, geology permitting, as a result of predictions of environmental impacts. Further study of the fourteen resources showed that some have no economic reserves for geological, practical dredging or environmental reasons (e.g., Binnie, 1992). As a result, total proven reserves were insufficient to meet the anticipated long-term demand and so, using the same overall investigation approach (Whiteside & Massey, 1992) a further round of investigation was initiated - this time mostly in Chinese waters. This led to identification of further economic reserves which, in combination with known Hong Kong reserves, are now expected to provide sufficient sand for Hong Kong for the foreseeable future. Figure 1 shows the locations of the sand searches from 1991 to 1995.

In 1989, the Government set up the Fill Management Committee (FMC) which was charged with the responsibility of finding and managing suitable fill resources for developments in the Territory. The FMC comprises representatives of the government departments which plan and implement major developments and also those which have statutory regulatory roles. Establishing the FMC was a key step in achieving timely resolution of issues such as the competing demands for marine borrow areas, navigational safety, statutory and public consultative procedures, and environmental impacts.

The greatly increased need for data storage, manipulation and presentation which accompanied the post-SEAMAT work was met by setting up a powerful geographic information system (GIS) tailored to the

specific needs of geological, dredging and environmental data (Selwood & Whiteside, 1992).

Disposal of Dredged Mud

A closely related technical issue which is only touched on in this paper is that of disposal of uncontaminated dredged material. This subject, which is now arguably a more contentious and difficult issue than that of sand winning, is often an integral part of planning borrow area development, for two reasons. Firstly, most of Hong Kong's marine fill reserves are covered by Holocene mud. This has to be removed and disposed of before the sand can be dredged. Secondly, dredging is an extremely plant intensive operation with dredger utilisation the prime economic concern. Every effort is therefore made to avoid "wasteful trips" either by dredgers travelling great distances to mud disposal sites or returning empty from the reclamation site to the borrow area. If at all possible, borrow areas are worked in a series of pits to permit convenient local disposal of overburden from one pit into a previous, empty one. Also, when possible, combined cycling is incorporated into the operation - for instance, by taking mud from the reclamation site back for disposal in an empty portion of the borrow area. These considerations are important for FMC in preparing development plans for borrow areas and for contractors in planning and costing dredging operations. Geological factors often govern the most economic pit layout because, for instance, zones of interburden or poorer sand can be the best locations for the unworked bunds between pits.

Geological Setting of the Economic Sand Reserves

Shaw & Cheung discussed the geological setting of the offshore sand resources as revealed in the SEAMAT study, and the overall picture has not altered substantially since then. However, the additional investigations and dredging case histories have provided a fuller perspective which is summarized here together with some comments on the deposits in Chinese waters. Figure 2 shows the locations of the Hong Kong economic reserves which were extracted between 1991 and 1995.

The geological model of Hong Kong's offshore sand resources has developed from the original, simplified picture of Pleistocene fluvial deposits lying along palaeo-drainage lines to a more complex picture in which the main addition is the effect of early Holocene tidal reworking of the Pleistocene sands. The Holocene marine transgression added very little sand to the offshore area - deposition of such coarser material being mostly confined to near source, along the coastline where it is now evident as beaches and their nearshore extensions. The sands in the offshore area are therefore the Pleistocene alluvial sediments and their reworked derivatives. In some places, the upper surface of the alluvial sands was extensively

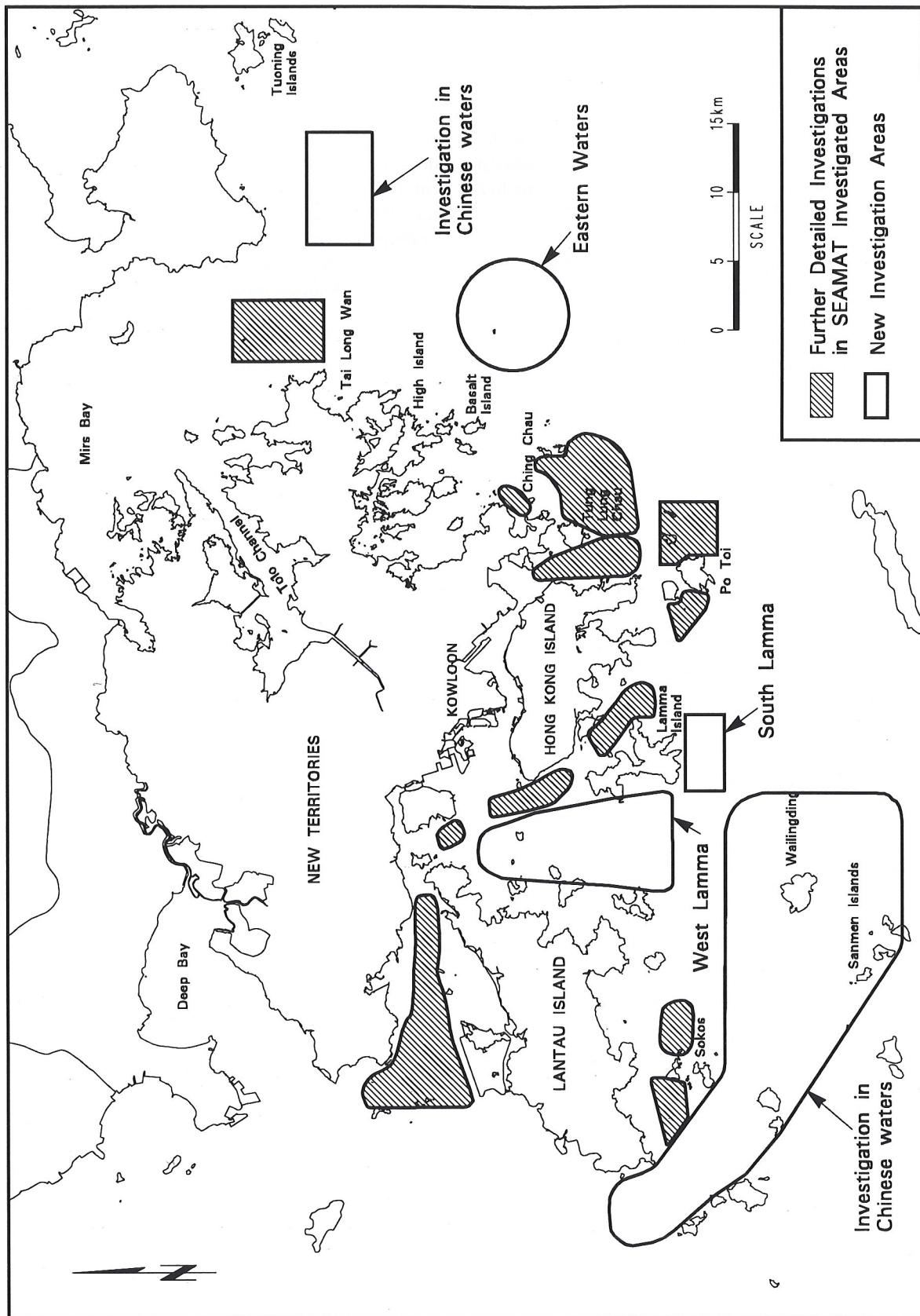


Figure 1 - Location of all sand search areas from 1991 to 1995

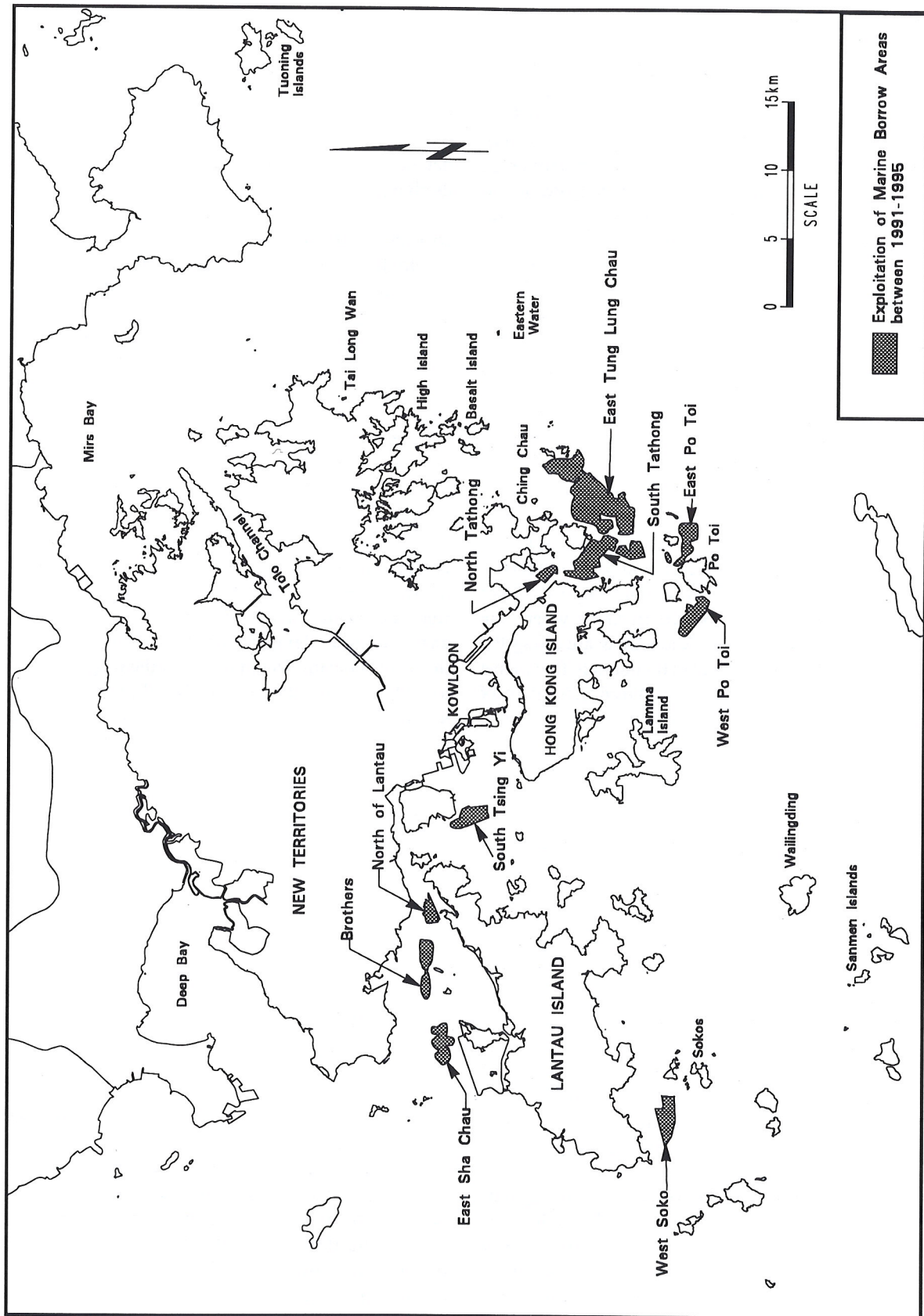


Figure 2 - Map showing the areas from which sand was extracted between 1991 and 1995

reworked in its original location with the result that the subangular immature quartz alluvial sands are now topped by layers composed of more rounded quartz with comminuted shell fragments. A good example is provided by the deposits south of Tsing Yi island (Whiteside, 1988). In other locations, tidal reworking also laterally transported the sands sometimes as migrating, low, asymmetric banks which later in the Holocene became moribund and were eventually buried beneath Holocene mud (Evans, 1988). In other areas, such as the Tathong Channel, where even today with about 20m of water the tidal flows are strong enough to produce migrating sand waves, early Holocene reworking has resulted in a more extensive redeposition which is now difficult to relate to pre-Holocene river channels.

Large deposits of sand are not necessarily economic if the overburden ratio is too high; that is, if the ratio of the volume of overburden requiring removal to the volume of dredgable sand is too high. Fairly extensive tracts of sand are thought to exist beneath the west Lamma Channel, for example, but the overburden thickness of about 20m renders it uneconomic. The economic sand deposits have therefore mostly been located in areas where the Holocene mud is thinner. Such areas are along the Holocene tidal channels where higher tidal flows have resulted in non-deposition or reduced deposition of mud (Arthurton, 1985). The intersection of these two patterns then, the Pleistocene river channels, where there is sand, and the Holocene tidal channels, where the overlying mud is thin, has provided many of the best resources.

The very extensive sand resources in Chinese waters, particularly those to the south of Hong Kong, appear also to consist primarily of clasts of pre-Holocene age with the addition of variable amounts of comminuted shells. However, this more seaward area of the continental shelf did not have the hills and valleys which were present in the area of the Hong Kong deposits. Alluvial sediments are more mature and finer grained, and although river channels are evident, swaths of reworked sediment are more the norm than in Hong Kong where they provide a capping to well-defined alluvial channel sands. The stratigraphy and history of erosion and deposition is still being unravelled.

No account of the sand dredging in Hong Kong would be complete without a mention also of the small but significant proportion of sand which has been dredged from the inner part of the Pearl River Estuary. Much of this has come from the area just south of the Boca Tigris narrows - a stretch of fast flow where the river bed has been scoured deeper. South of the narrows, the Estuary opens out into what is presumably a depositional area, and it is from here that a fleet of small bucket dredgers have loaded small river barges with sand.

Some Geological Aspects of Dredging Assessments

Although the geological characteristics of a sand deposit largely dictate the extent to which it can be economically dredged, the relative importance of the different factors can only be determined during a detailed dredging assessment. In economic terms, dredging is a plant-

intensive operation - that is, material and manpower costs are relatively insignificant whereas the cost of the dredger is high. The overall cycle time for each trip from borrow area to reclamation site and back plus "unproductive" time spent removing and disposing of overburden are the most important parameters in determining the economics of an operation. For this reason, although the overburden ratio is of prime importance, there is no fixed value above which a deposit becomes uneconomic because it has to be considered in conjunction with the distance to the reclamation site and the distance to the overburden disposal site.

The time taken to load a trailer hopper dredger is very dependent on the grain size of the sand and on the fines content. In the overflowing process, loss of fine sand is unavoidable although undesirable from an economic dredging perspective. The finer-grained the sand being dredged, in general the longer it takes to load, and hence the more costly is the sand delivered to site. Some sand deposits have a very high shell content and because the specific gravity of calcium carbonate is lower than that of quartz, comminuted shell sand is lost more readily than the same sized quartz sands. Most of the early Holocene reworked sands are relatively loose, but with increasing depth, the undisturbed Pleistocene alluvial sands become progressively denser and intercalated with silty clay and hence more difficult to dredge by suction dredger. While increasing grain size makes for easier loading of the hopper, increasing grain size in Hong Kong's granitic derived sand tends to mean decreasing maturity and hence increased angularity. This factor increases friction and wear in suction pipes and pumps. It can become a significant cost increase when, as for instance for the Tin Shui Wai project in the northwest New Territories, sand has to be rehandled and pumped long distances.

The cohesive strength of the overburden and the density of the sand deposits affects the slope angle necessary to maintain stability in the sides of dredged pits. The flatter the side slopes the higher the overburden ratio becomes. These constraints and any other navigational and environmental constraints have to be taken into account in calculating the volumes of economic sand reserves which can be extracted from a given geological resource. Figures 3 and 4 show some typical output from part of a dredging assessment (DEMAS, 1996).

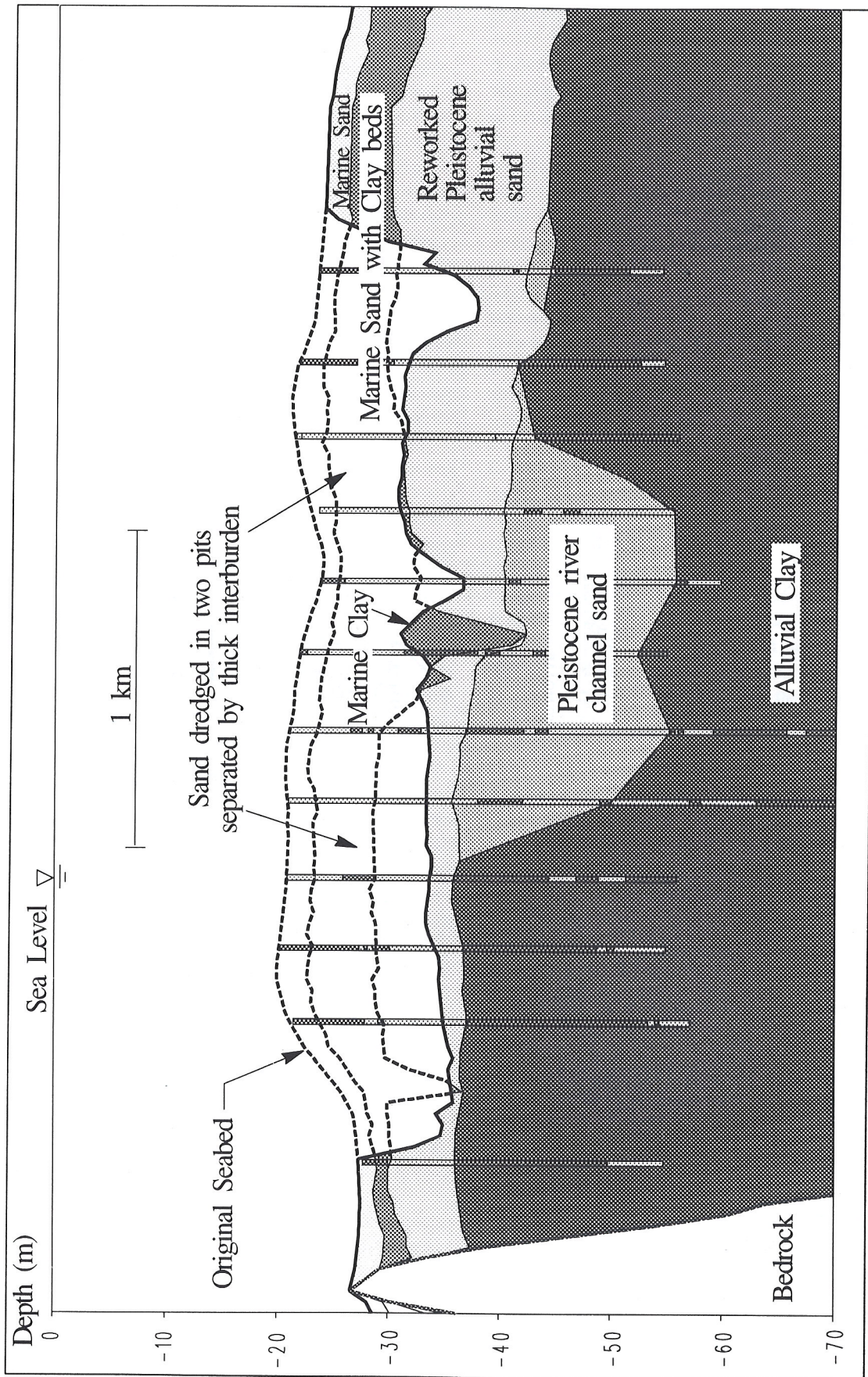


Figure 3 - Example of a detailed dredging assessment and borrow area development with the area of thicker interburden being used to locate the bund between two pits

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Some Geological Aspects of Environmental Impact Assessments

One result of the environmental impact assessments (EIAs) was that some otherwise economic sand reserves were abandoned because of the likely adverse impact on the marine ecosystem. This in turn prompted a renewed effort in the exploration programme which firstly re-examined some of the more marginal Hong Kong resources, and secondly and more importantly moved into Chinese waters.

The principal environmental concern has been the generation and dispersion of plumes of suspended sediment associated with sand dredging. The sand dredging in Hong Kong has almost exclusively been undertaken by trailer suction hopper dredgers. In a similar manner to the operation of a domestic vacuum cleaner, a sand and water mixture is sucked from the seabed and discharged into the dredger's hopper. If this operation were to stop when the hopper was full of the mixture, the load in the hopper would be mostly water. The mixture is therefore allowed to "overflow". This process retains most of the sand in the hopper while allowing the water and suspended fine particles, mostly silt and clay, to return to the sea. Considerable research has been undertaken in Hong Kong on the resulting plumes of suspended sediment. Use of computer modelling (Whiteside & Rodger, 1996), field measurements (Whiteside et al., 1995; Dredging Research Limited, 1996) and remote sensing has demonstrated that the influence of plumes is essentially restricted to the immediate vicinity of the dredging area. A key input into predictive modelling calculations is the amount of fines in the *in situ* sand deposit. Particle size distribution analyses of all borehole samples from the economic deposits are stored as part of the GIS database. In general, the alluvial sands have less than 15% fines, while in contrast, the "marine sands" produced by early Holocene reworking of the upper alluvial sands commonly have between 20% and 50% fines. Although the term "sand" is generally reserved for material with less than 30-35% fines, some early Holocene marine granular deposits with over 40% fines has been worked because sufficient fines were lost during the dredging process to result in a low-fines sand in the hopper (Wragge-Morley, 1988), without causing any adverse environmental impact (Holmes, 1988).

Part of the concern related to the possible effects which settling sediment might have on soft bottom benthic communities. One of the techniques used to study this has been the seabed camera, one version of which is the REMOTS system (Rhoads & Germano, 1982) which provides vertical profile photographs of the top 200mm or so of the seabed. These images have provided information on the benthic in-fauna and pollution (Valente et al., 1996) but also on the sedimentary features resulting from periods of storm-

related remobilisation and deposition (Selby & Evans, 1997). The intensive bioturbation of the upper layers of the present day seabed suggest that the same process was responsible for the generally unstructured nature of the Holocene mud in Hong Kong.

A concern in the early stages of the environmental studies was the lack of scientific data about the naturally dynamic nature of the local marine environment. Being at the mouth of China's third largest river and in an area regularly affected by severe tropical storms, Hong Kong waters experience very large natural variations in temperature, salinity and suspended sediment. Although considerable historical data existed, there were and to some extent still are, significant information gaps. In an attempt to provide an overall perspective of the natural suspended sediment regime, a programme of field measurements using satellite data, aerial photography, Acoustic Doppler Current Profilers and water sampling was undertaken territory-wide (Evans & Woods, 1994; Dredging Research Limited, 1994).

The Future

Prior to the dramatic increase in reclamation associated with the start of the new airport and other projects in 1991, Hong Kong had been using about 15Mm³ of fill material per year since the mid-1960s. In addition to the demand from the proposed new Lantau Port Development, a similar pre-1991 background demand still exists. Although most of Hong Kong's economic reserves have already been used, the very large economic reserves now proved in nearby Chinese waters will be more than sufficient to cope with Hong Kong's long-term fill requirements well into the next century.

Acknowledgement

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Hong Kong Landform Series, No. 3

Alluvial Floodplains And Upward-Fining Stratigraphic Sequences

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Approximately 5% of Hong Kong is covered by alluvial floodplains (GCO, 1989), principally to the north and northwest of the New Territories, though innumerable smaller units are found throughout the Territory. Floodplains are defined by geomorphologists as the relatively flat land adjacent to a river channel, comprising sediments deposited by that river channel, and which are periodically inundated. Terraces are abandoned floodplains, the essential difference between the two being the reduced frequency of inundation.

Formation of Floodplains

Floodplains are created by a complex pattern of in-channel and overbank depositional processes. Within a channel coarse transitory unstratified sediments are deposited, which are essentially bed load deposits temporarily at rest, as well as alluvial islands, which are coarse bed load deposits capped with finer sandy material. On the margins of a channel are point bar deposits, which on meandering channels are to be found principally on the convex bank and on straight channels on alternating sides. These are initially produced by bed load moved by traction and evolve upward as increasingly finer sediment is added, principally by within-channel flood events. This process of point bar deposition is particularly important on laterally migrating river channels wherein erosion of one bank is approximately equalized by deposition on and growth of the point bar on the opposite bank (Knighton, 1984).

Overbank flooding results in the deposition of a veneer of finer grained sediments (suspended sediments), which can take on many forms. Such deposits gradually cap point bar deposits (and occasionally alluvial islands) and in doing so reduce surface morphological irregularities. Sometimes overbank sediments are quite conspicuous, as when they take the form of natural levees or backswamp deposits. The combined effect of these processes is illustrated in Figure 1. A point bar is progressively constructed against one bank as the other bank is eroded.

There has been some debate in recent years over the relative importance of these two main processes. Early work in the United States concluded that 60-80% of the floodplain sediments associated with migrating channels were deposited by lateral accretion (Leopold, Wolman and Miller, 1964) and that

vertically accreted deposits were limited because overbank flows are often deficient in sediment and because of the uneven pattern of velocities across a floodplain. It is now realised, however, that significant variations in these processes occur even within a single valley and that vertical accretion can dominate in a wide range of environments, particularly in lower energy environments (lower slopes). This distinction in processes is quite important, with particular implications for channel engineering works, as floodplains developed adjacent to non-migrating channels dominated by vertical accretion lack underlying lag deposits. If channels are diverted away from their immediate gravel beds the protective armouring effect is lost and deep incision may result (Nanson and Young, 1981).

Floodplain Stratigraphy

Figure 1 illustrates another important characteristic of floodplains, their upward fining stratigraphy. The point bar is the key to this process. On the convex bank the water level decreases gradually landward, as do flow velocities, producing a sequence of well-defined sedimentary structures. Where the water shallows sufficiently to affect the streamflow current, sands and gravels are deposited in the form of the lag deposits previously mentioned. This deposition in turn diverts the currents from the bar thereby encouraging further accretion of lag deposits and the lateral growth of the point bar. These lag deposits are in turn buried by sandy dunes, exhibiting trough cross-beds, and then by sand ripples generated by low velocity flows. At this stage the point bar is no longer a part of the active channel, but has been integrated into the floodplain. Nevertheless it continues to develop in a vertical manner through the deposition of fine sands or silts and muds derived from overbank flows.

The end result of this depositional process is most visible in an eroding bank face, where a stream cuts into previously deposited sediments. The base of the exposure is usually composed of lag deposits, often exhibiting a sharp boundary with the overlying sands and silts which in turn may exhibit trough cross-bedding, ripple cross-laminae, clay plugs (oxbow lake infill) and so on.

This depositional sequence is time-transgressive. It is incorrect to consider the horizontal bounda-

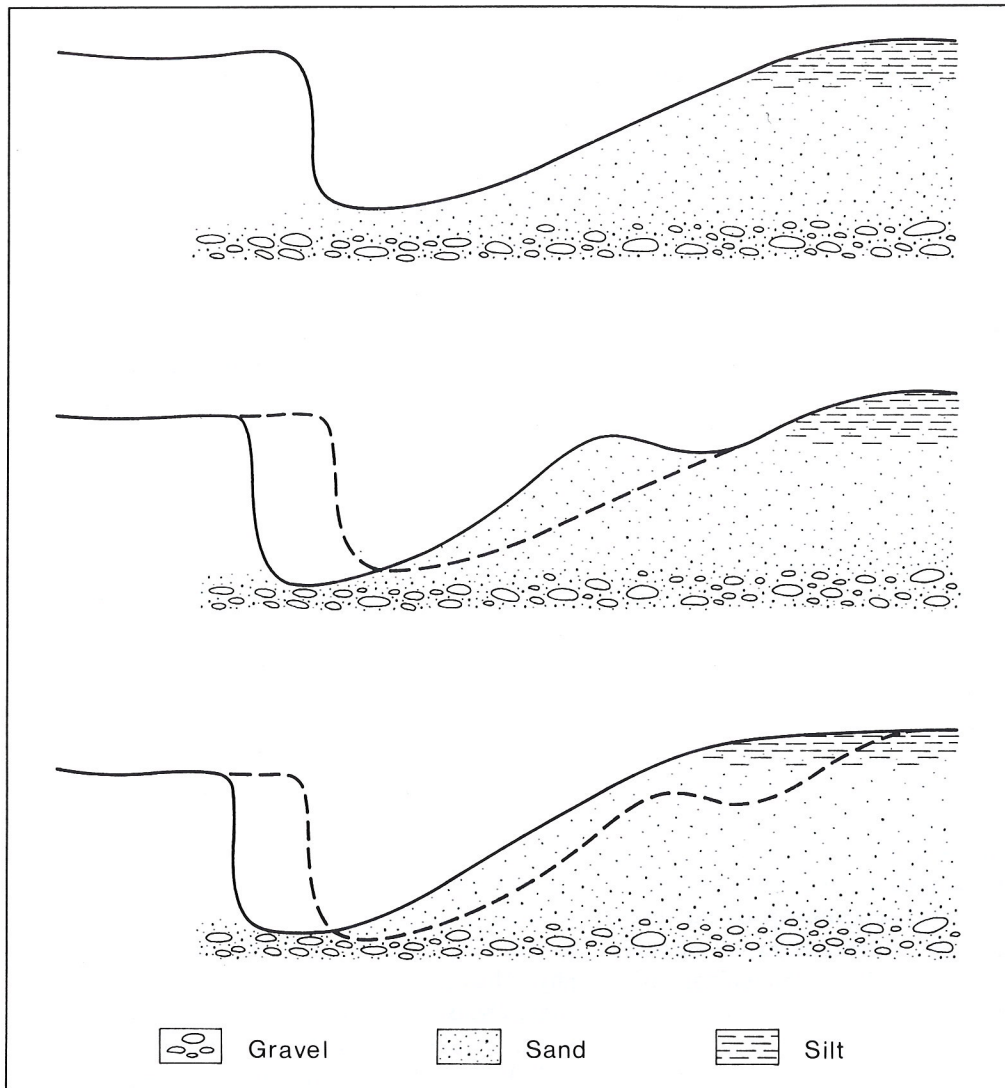


Figure 1 - Development of a floodplain as a stream laterally migrates. As the stream erodes the left bank a point bar is gradually constructed against the right bank and capped with overbank deposits.

ries separating the various sedimentary layers as time planes. The true time planes run horizontal to the point bar surface.

The Lam Tsuen Valley Example

River bank sections are more commonly sighted along the larger streams within the Territory. In particular, excellent sections are present along the middle reaches of the Lam Tsuen River, including in one case a terrace exposure near Tong Min Tsuen. Unfortunately these sites are under threat from the Hong Kong Government in its relentless pursuit to channelise all natural streams in Hong Kong, regardless of the availability of alternative, more attractive and environmentally acceptable technologies for bank control.

Figure 2 is a cross section obtained at 832160E 834230N. At this site the floodplain sediments were described and samples of bank material were collected

and measured for particle size.

This channel bank exposure is of a terrace (or abandoned floodplain) rather than the current floodplain which is covered in dense vegetation. The contemporary floodplain is about 2.5 m above the channel bed as compared with the 4.0 m terrace. Nevertheless the sedimentary patterns described in the previous sections still apply.

The lower sedimentary unit (up to 2.0 m above the channel bed) is a buried lag (bedload) deposit (B in Plate 1). The cobbles are moderate to well rounded and are of similar average size to modern day coarse channel deposits (average median diameter of 8 cm). These are overlain by predominantly fine to medium sands that represent point bar and overbank deposits (A in Plate 1). They are largely structureless and moderately well sorted, with median diameters of between 0.2 and 0.4 mm. A narrow unit of pebbles and cobbles at 2.7 to 2.85 m may be evidence of the occur-

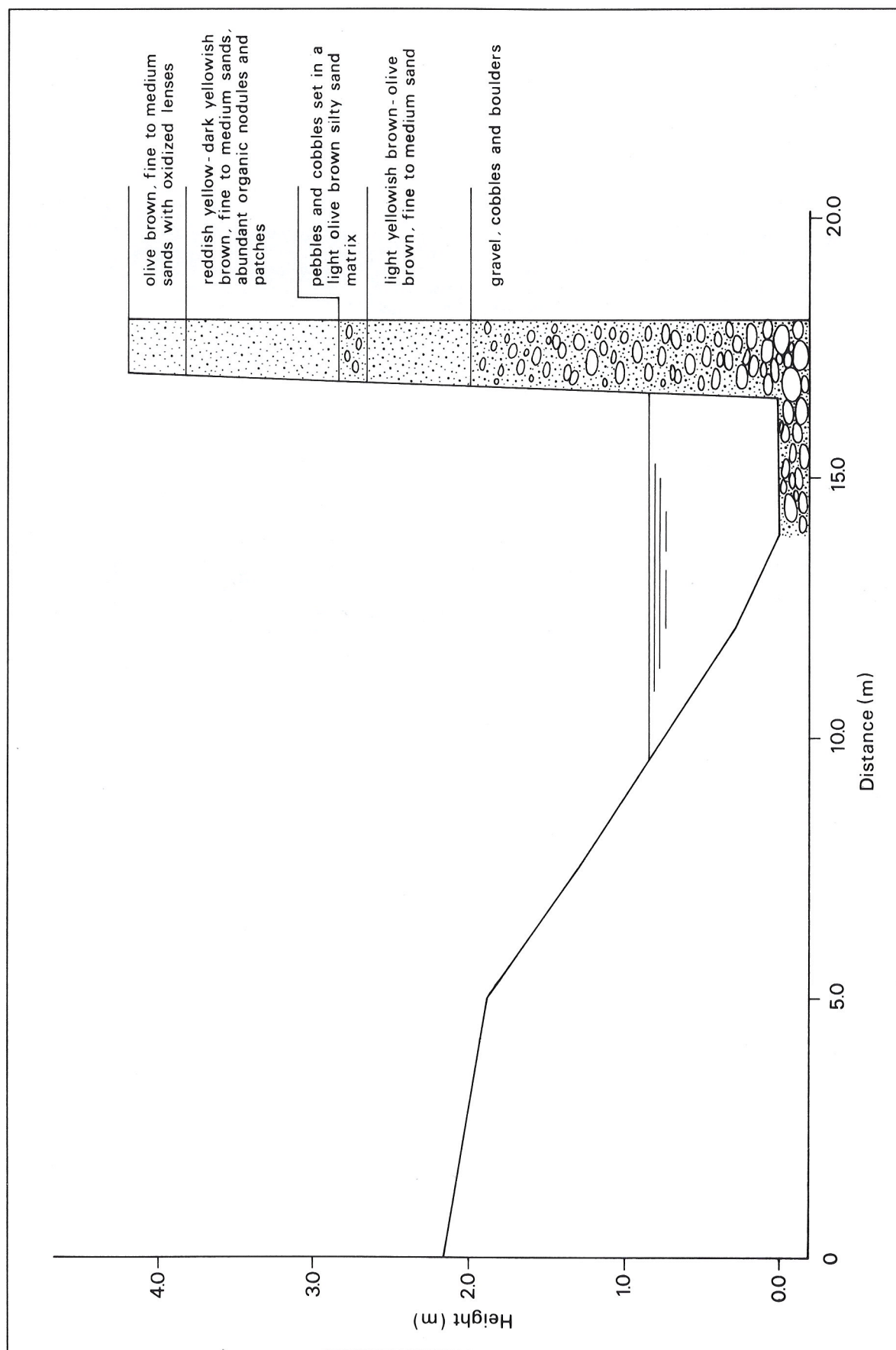


Figure 2 - A channel cross section obtained along the Lam Tsuen River near Tong Min Tsuen, showing an upward fining alluvial plain sedimentary sequence.



Plate 1 - Location of the cross section near Tong Min Tsuen on the Lam Tsuen River. Note the extensive lag deposit at the base of the exposure.

rence a larger flood event during the later stages of point bar development, at a time when the point bar was being incorporated into the floodplain. The Lam Tsuen Valley is subject to high energy flood events and the author has previously witnessed mature sand-capped point bars being covered with cobbles during a major flood.

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