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THE QUATERNARY DEPOSITS OF THE CHANGJIANG COASTAL PLAIN (SHANGHAI AREA)

LES DÉPÔTS QUATERNAIRES DE LA PLAINE CÔTIÈRE DE CHANGJIANG (RÉGION DE SHANGHAÏ)

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1. Introduction

The city of Shanghai is situated in the vast, low lying coastal plain bordering the East China Sea in the East and characterised by the lower reach or estuary of the Changjiang (Yangtze) River (Fig. 1). The city is crossed by a tide-influenced channel, called the Huang Pu river.

The Changjiang river is the largest river in China (about 6300 km long) and forms a primary source of sediments of the continental shelf of the East China Sea, especially the inner shelf. Because of the 2 to 4 m tidal range, the modern Changjiang estuary is a mesotidal estuary. The fine-grained nature of the nearshore sediments results from the very high rate of influx of riverine sediment which overcompensates reworking by storms and tides. In terms of its influence on the general hydrographic character of the estuary, tidal phase is as important as the amount or river runoff. However, river runoff is the dominant factor in controlling sediment transport to the ocean (Milliman & Qingming, 1985).

The Chiangjiang coastal plain (also erroneously called the Yangze Delta) was formed and shaped during the Holocene under the influence of rising sea level. But it is well known that all over the world estuarine and deltaic deposits rarely consist of a single fill sequence formed at only one high sea-level stand. At least during the Pleistocene and Holocene, it is believed that estuarine environments have reoccupied the same places during various transgressions (Nichols & Biggs, 1985). From a geological point of view these coastal lowlands consist of a considerable sequence of unconsolidated sediments, sensitive to compaction.

The Changjiang coastal plain is pre-eminently an environment where at one time coastal processes dominated the situation and at another fluvial processes showed an overwhelming activity. The Changjiang river, however, has been the primary factor in the entire Late Quaternary history. The river forms an estuary which has been shifting back and forwards in time, leaving a complexity of deposits in the stratigraphical sequence.

According to previous Chinese investigations, the compaction of the sediments due to ground-water withdrawal is mainly occurring in the upper 70 m (Su He Yuan). In order to control this very critical situation of land subsidence, the ground-water withdrawal is to be managed. Therefore a mathematical model was elaborated. The knowledge of the Quaternary geology, and more particularly of the Upper Pleistocene and Holocene deposits provided one of the basic elements for the design of the mathematical model.

2. Geological investigation of coastal plain deposits

It is not easy to interpret subsurface data of coastal plain deposits, investigated by means of drill-holes. Because of the similarity of the lithofacies, the stratigraphy of each drill-hole is extremely complex.

A total understanding of changes in coastal and alluvial configurations, or rates of change in the position of coastal and fluvial sedimentary environments, must include an understanding of the vertical sequence of the area being studied. This third dimension to the sedimentary environments represents the element of time, which is of overwhelming importance in understanding coastal and alluvial evolution (Kraft & Chrzatowski, 1985).

Inherent in the formation of coastal and alluvial plains are frequent lateral and vertical changes in the sedimentary sequence. While studying coastal and fluvial sedimentary bodies or stratigraphic sequences, it is important to remember that the unit being examined is the product of a depositional environment that is not fixed in time and space. Rather, this depositional environment will migrate laterally and vertically depending on the net effect of influential processes acting on the area (Kraft & Chrzatowski, 1985). Therefore it is

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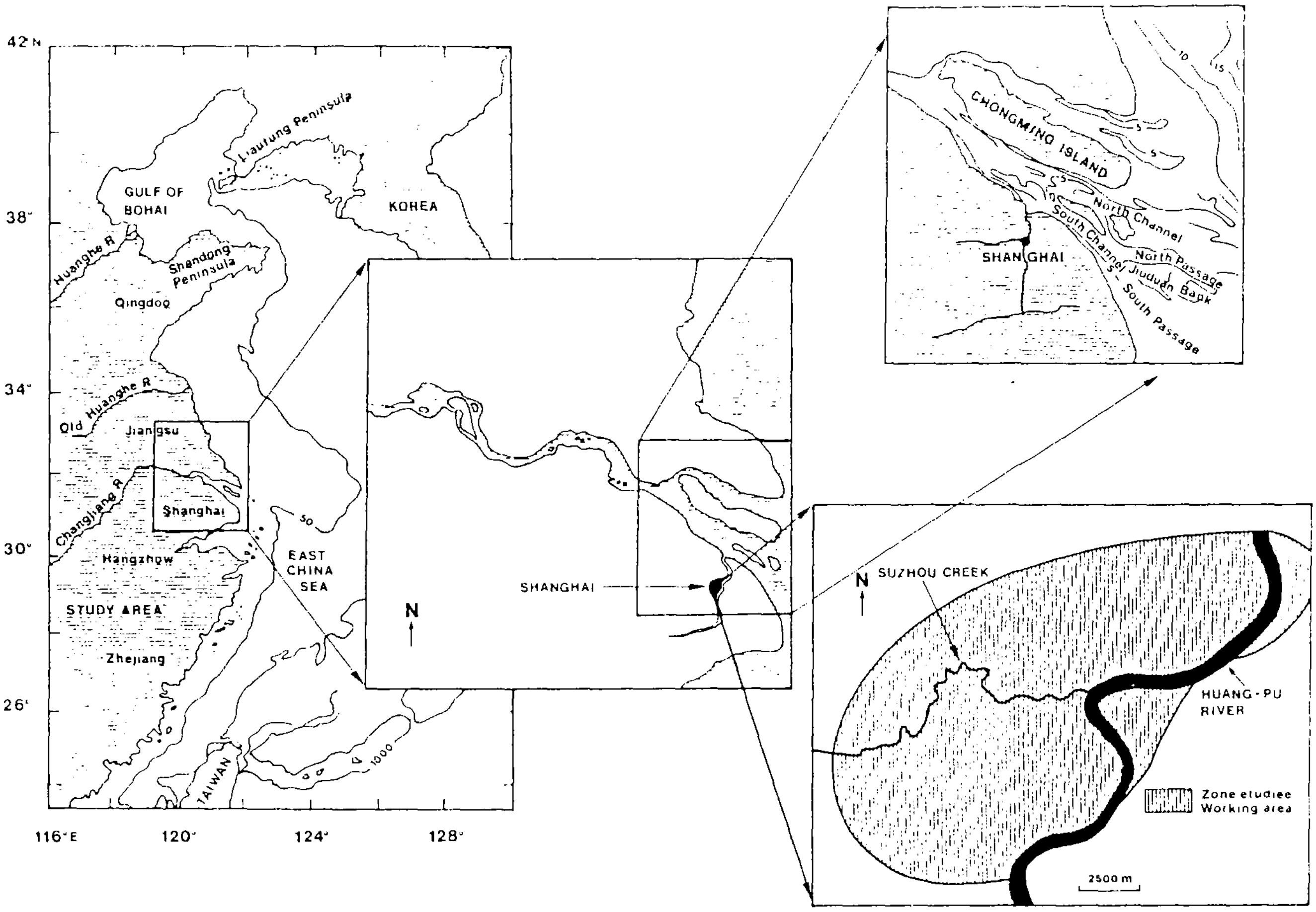


Fig. 1 : Location of the Changjiang estuary and the city of Shanghai crossed by the Huang Pu River and the Suzhou Creek.

impossible to recognize units and their succession from one single boring, because it represents only an isolated point in a complex entity.

Quaternary geology involves a lot more than only establishing the stratigraphical boundary between units from subsurface data at one or a few single spots. Such an approach does not reveal any information about the spatial distribution of deposits, which is essential for a fuller understanding of the development and evolution of an area through space and time. Moreover, such an approach only yields generalized cross-sections à la "pancake-geology" (Hageman, 1984), where broad stratigraphical units are correlated assuming that the units remain regular and uniform between the data points. Such a pancake-geology only leads to misinterpretation and false conclusions. Therefore it is imperative to establish the three-dimensional geometry of the deposits, i.e. the interrelationship between the different borings. Cross-sections must be made in detail with correlations based on sedimentary environmental interpretation.

Properly correlating a series of boreholes calls for knowledge of the processes and mechanisms responsible for the deposition of the sediments and the formation of their facies, thus making an environmental interpretation. In order to interpret facies of a depositional system which consists of an assemblage of interrelated environments and their associated processes, facies need to be analysed in terms of their spatial relationship. Furthermore, it is often impossible to make an unique environmental interpretation on the basis of a single depositional facies. Therefore facies associations and sequences must be studied rather than individual facies. Facies associations are groups of facies that occur together and are genetically or environmentally related. The sequence in which they occur thus contributes as much as the facies themselves (Boggs, 1987).

3. Late Pleistocene and Holocene of the Shanghai area. A review of the literature

The Changjiang Estuary and its huge coastal plain fascinated for the last hundred years many geologists from China as well as from abroad. This unique area indeed has a very interesting, but complex Quaternary geological history. On the geological maps it is generally indicated as alluvial and deltaic Pliocene-Quaternary sediments.

In more recent times considerable research has been carried out, but mainly concentrated on the nearshore and offshore zones of the estuary (Milliman & Qingming, 1985).

In a general study of the Quaternary System of China, Zhou Mulin *et al.* (1982) proposed a subdivision of the Quaternary into 5 glacial stages and 4 interglacial stages, based on Quaternary Stratigraphical Tables compiled by various geological institutions which focussed on biostratigraphy and climate changes.

The stages this study is concerned with are the 4[th] interglacial stage (Lushan-Dali interglacial stage). the 5[th] glacial stage (Dali glacial stage) and the post-glacial stage (Holocene).

Late Pleistocene

From the accessible literature it became clear that a lot of attention has been paid to the Dali glaciation and more particularly to the sea-level stand during that period. It was concluded by most of the authors that the Dali glaciation started about 70.000 years ago and the lowermost sea level of the Late Pleistocene must have occurred about 15.000y.B.P. (Emery *et al.*, 1971, Zhu *et al.*, Guo Xuemin, 1988, Zhou Mulin, 1986). By that time the East China shelf had emerged and developed into a river valley with lake basin bogs. Chen *et al.* (1985), however, timed the glacial low sea-level stand between about 22.000 and 19.000 y.B.P. based on a compilation of 14-C dates from marine sediments, shells from cheniers, Neolothic sites, peat and wood.

The Late Pleistocene has been subdivided into three stages (Zhu *et al.*). The Early Stage was characterised by a stable low sea level, situated at a depth of about 70-100 m. In the Middle Stage the ancient Yangtze Delta was much more influenced by the change of the sea level and around 35.000 y.B.P. the area developed into an estuarine environment with a maximum of transgression about 32.000 y.B.P. In the Late Stage the sea level dropped periodically. Between 26.000-23.000 y.B.P. there was first a relatively stable sea level and an abrasion terrace at the level of 100-120 m depth was formed where remains of an ancient coastline with evidence of river mouth bars and shell beaches were found. After 23.000 y.B.P. the sea level fell continuously until a depth of 150-160 m and shaped the second and third abrasion terrace. As from 15.000 y.B.P. a period which is considered to be the coldest one in the Late Glacial, the sea level started to rise rapidly until 12.000 y.B.P.

Zhou mulin *et al.* (1982) subdivided the Dali Glacial Stage into an Early and a Late Sub-glacial Stage separated by a short Interglacial Stage (Interstade) during which a global transgression took place which the author dated at 22.900-32.000 y.B.P. and later at 24.000-39.000 y.B.P. (Zhou Mulin, 1986).

Another aspect of the Late Pleistocene which is very often described in the (accessible) literature is the boundary between the Pleistocene and the Holocene (Wang *et al.*, 1981, Guo Xuemin, 1983 & 1988, Li Congxian, 1986, Zheng *et al.*, 1988, Tao *et al.*, 1988 & Yan Qinshang *et al.*, 1988). A dark green silty clay (or loam) layer, compact and characterised by the absence of marine fossils, is described as keybed between the Holocene and Pleistocene. Most authors agree that the clay was deposited in a cold and dry period, most probably during the Dali glaciation or also during the period of the last low sea-level stand of the Late Pleistocene. About the genesis of the clay, different opinions are expressed, such as : river-lake-marsh deposits, terrigenous origin, a continental deposit with fluvial facies, a continental deposit with a well-developed dark ancient soil, traces of the ancient Yangtze river sediments, continental sediments of flood-plain and freshwater swamp, and finally, windblown loess which through weathering, leaching and compression formed hard clay which then was transformed to a dark green hard clay by dissolving soluable organic matter from penetrating Holocene surface water.

In research papers dealing with the offshore area of the East China Sea, the Holocene-Pleistocene boundary is very often mentioned as well. A semi-consolidated clay, representing earlier Changjiang deposits possibly deposited during a lower stand of the sea level or a period of different dynamic conditions, is described by Keller *et al.* (1985). Butenko *et al.* (1985) also mentioned a very stiff clay supporting the concept of overconsolidated clays associated with subaerial exposure, as well as buried river channels and river bank features formed during the last low stand of the sea level.

Holocene and the post-glacial transgression

In the accessible literature on the Holocene of the Changjiang coastal plain and the Shanghai area, it is clear that full consideration was given to the chronostratigraphical subdivision of the Holocene on the one hand, and to the evolution of the so-called "subdeltas", which are occurring at the river mouth, on the other hand.

The sedimentary sequence as such and its interpretation were regarded in a rather general way, except for the research carried out on the offshore, adjacent to the estuary (Milliman & Qingming, 1985).

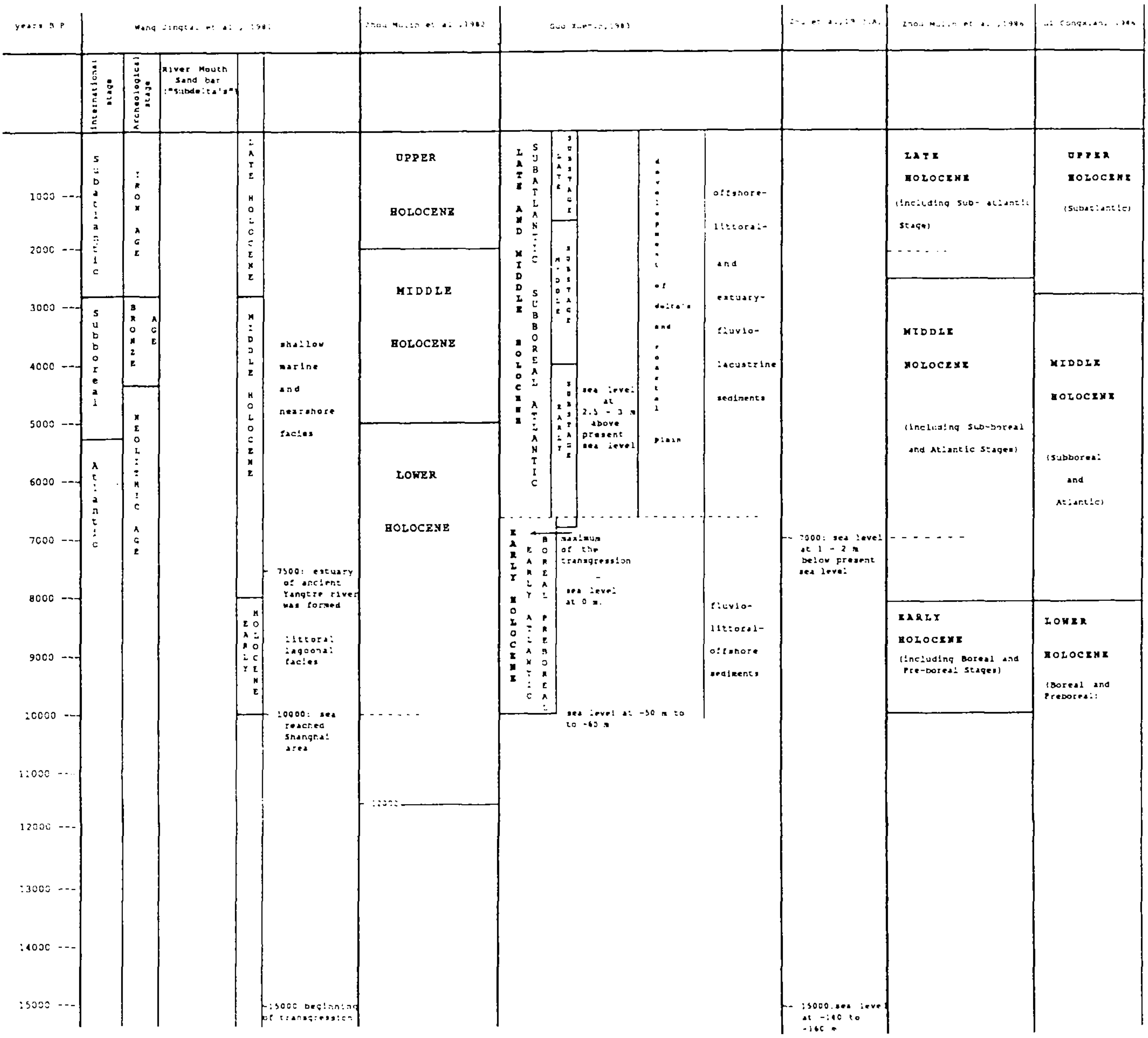
The basis for establishing the stratigraphical subdivisions are very seldom mentioned or elaborated in detail. Most often it is generally described as being "the palaeoclimate, reflected by pollen spore assemblage and stratigraphical age as determined by the 14-C method". In many cases palaeo-microfauna, grain size and heavy mineral analyses are mentioned as additional bases.

A rather great number of stratigraphical subdivisions, concerned with the Shanghai area and surroundings has been published. But it is most remarkable that only very few of them show any similarity; nomenclature and time boundaries do change a lot. Even a series of papers published in one and the same book (Yan Qinshang, 1988) exhibits important differences.

It is critical to evaluate the validity of the different classifications as it was impossible to find out what evidence and/or arguments have been used exactly to elaborate them (except some palynological data, giving however similar assemblages). The only way to demonstrate the differences without causing any further confusion, was to assemble all the classifications in a table (Table 1 & 2).

In publications about the Holocene, any attempt at lithostratigraphical classification or correlation is lacking. On the other hand some ideas about the palaeo-

Table 1 :



geographical implications of the coastal plain, describing sedimentary environments and their evolution, nearly always related to sea-level changes, were put forward by several authors (Wang Jingtai *et al.*, 1981, Chen *et al.*, 1982, Zhu *et al.*, Guo Xuemin, 1983 & Jia, 1985, Li Congxian, 1986, Yang Qinshang & Hong Xueqing, 1988, Tao Qiang & Qinshang, 1988, Li Jingan & Yan Qinshang, 1988). Most of the authors however, give very different results, mainly concerning the age and the altitude of the sea-level stands. An elaborated review of the different opinions is published in Baeteman (1989).

A better similitude has been found in the description of the so-called "subdeltas", also called river mouth bar or sand bodies in the Changjiang Delta system, or sand islands and shoals, or mouth sand bodies. Six stages were recognized during which the successive subdeltas developed (Wang Jingtai *et al.*, 1981, Guo Xuemin, 1983, Chen Jiyu *et al.*, 1985 and Li Congxian, 1986).

4. Geological setting of Shanghai

4.1. Stratigraphical sequence

The Upper Quaternary deposits of Shanghai have mainly been regarded by Chinese investigators on the basis of their geotechnical and hydrogeological properties. Hence the nomenclature of the deposits has been characterised by units identified as "Compressible Layer", "Aquifer" and "Dark Green Stiff Clay". In the present study this nomenclature has been maintained for the sake of clarity.

From a geological point of view the emphasis of the Chinese investigators was restricted to the chronostratigraphy of some isolated borings leading to the subdivision of the Quaternary in Q_4^3, Q_4^2, Q_4^1, Q_3^2, Q_3^1, etc. (Q_4 for the Holocene, Q_3 for the Upper Pleistocene deposits). The identified "Compressible Layers" and "Aquifers" were then labelled with this chronostratigraphy.

The present geological study was based on 42 boreholes to a depth of about 70 m, most of them already available and having a simple description. On the other hand, three borings, viz. CBG1-1 and CBG1-2, both located very close to each other, and K4 have been carried out in the framework of this study (Fig. 2). These borings were investigated in detail and consequently had to form the basis for the interpretation of all the other borings. The interpretation of the cone penetration tests and well-loggings has been used as complementary data. The boring CBG 1-1 was also investigated for clay mineralogy and, by the Chinese collaborators, for grain size distribution, palynology and micropalaeontology. The results are incorporated into this study.

Although the available data (literature and boreholes) was rather restricted, a stratigraphical sequence for the Upper Quaternary deposits could be put forward (Fig. 3).

The Upper Pleistocene deposits consist of a sequence showing the transition from an estuarine to a proper fluvial one. The estuarine environment is represented by a sandy deposit and forms, what is usually called, the Second Aquifer (2A-unit). In the sequence it is followed by a dominantly clay deposit (3C-unit) which is known to be sensitive to compaction. The latest unit of the estuarine environment is again formed by marine sand deposits (1A-unit, lower part) which gradually were replaced by fluvial sands and silts (1A-unit, upper part) heralding the (last) fluvial phase of the Upper Pleistocene sequence. Both sand deposits form the First Aquifer (1A-unit). Finally the silting up of the fluvial sequence is completed by the formation of a flood-basin clay. This clay deposit, known as Dark Green Stiff Clay

Table 2 :

years B.P.	Gu Jiayu, 1988	Tao Qiang, 1988	Yan Qinshang, et al., 1988	Guo Xumin, et al., 1988	Guo Xumin, 1988	
	Development of the coast (based on 14-C dates of cheniers)	Periods of evolution of the Holocene Sedimentary Environments	Evolution of the Holocene Sedimentary Environment	Holocene Series		
0 – 1000	EARLY STAGE (0 – c. 800)	LAST PERIOD (0 – c. 6600); sea level at present sea level to - 1 m	LATE PERIOD (0 – c. 2600)	UPPER PART – SUBATLANTIC: fluvial-lacustrine sand and sandy clay (0 – c. 2800)	LATE AND MIDDLE HOLOCENE (0 – c. 7200): LATE SUBSTAGE (0 – c. 1000)	SUBSTAGE
1000 – 4300	LATE STAGE (c. 800 – c. 6600)		MIDDLE PERIOD (c. 2600 – c. 7600)	MIDDLE PART – SUBBOREAL ATLANTIC: shallow marine mud, sandy clay, estuarine and shore related clayey silt (c. 2800 – c. 8100)	MIDDLE SUBSTAGE (c. 1000 – c. 4200)	
4300 – 7200					EARLY SUBSTAGE (c. 4200 – c. 7200)	MAXIMUM OF TRANSGRESSION; sea level at c. 2.5 - 3 m above present sea level; sea level at 0 m
7200 – 11000		EARLY PERIOD (c. 6600 – c. 9100)	EARLY PERIOD (c. 7600 – c. 10100)	LOWER PART – BOREAL PREBOREAL: fluvial-lacustrine sand clayey sand and shore related silty clay (c. 8100 –)	EARLY HOLOCENE: fluvial-littoral-offshore sediments	

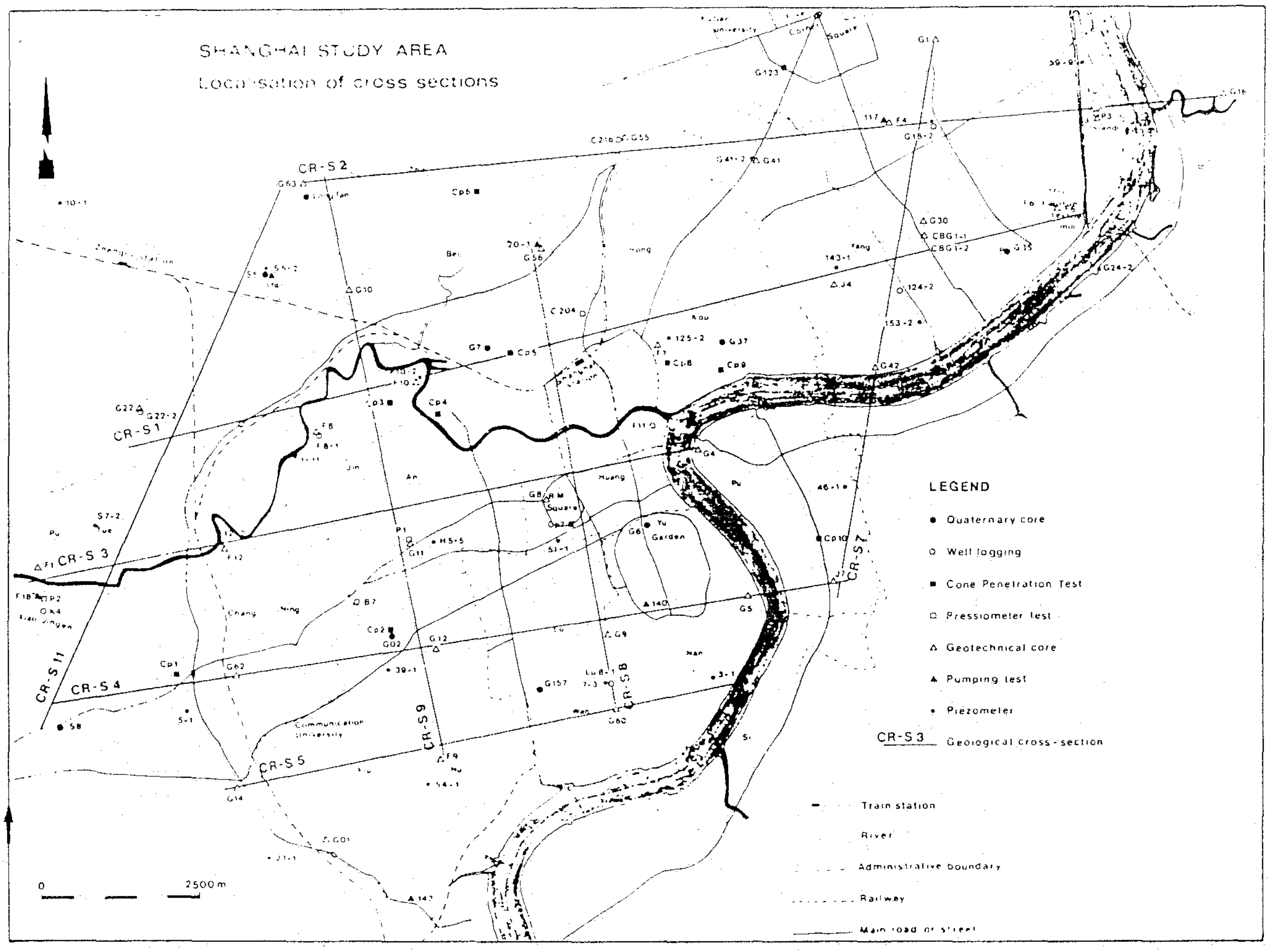


Fig. 2 : Location of boreholes, CPT's, well-loggings and geological cross-sections.

(DGSC), represents one of the most interesting deposits in the area of Shanghai from an engineering point of view, since it is the only unit characterised by a high bearing capacity, at least for the upper 70 m.

The Upper Pleistocene as it is considered here was characterised by two main events. The beginning of it shows a transgressive phase whereby the area becomes occupied by an estuarine environment. The lower part consists of a gradual transition from the channel and sandbar deposits (2A-unit) evolving towards less energetic environment areas such as a tidal flat, starting with mainly subtidal to finally intertidal sedimentation.

Such a transition in the vertical sequence can be explained in different ways.

As tidal channels in estuaries shift back and forth with time, vertical sequences of estuarine sediments are generated. As the channels migrate, that part of the vertical section formed by the accretionary bank consists of interbedded sand and mud, flaser bedding, some cross-bedded sand, and some laminated mud. The part of the sequence deposited on intertidal flats may be either bioturbated sand or mud, which grades upward into supratidal mud facies (Boggs, 1987). Still according to Boggs (1987) migration of sandy channels produces a vertical sequence that begins at the base with a lag deposit composed of sand, shells, gravels, mud pebbles and wood fragments. This lag deposit is typically overlain by cross-bedded or ripple-bedded sand, which in turn is overlain by intertidal-flat sediments and finally supratidal mud. Migration of muddy channels which are more common in the upper reaches of estuaries, produces a vertical sequence that begins with a lag deposit overlain by laminated mud. The laminated mud in turn may either be overlain by cross-bedded mud or grade upward into intertidal-flat mud, which grades upward into supratidal facies.

Another explanation for this kind of transition in the vertical stratigraphical sequence implies changes of greater importance with greater repercussion such as a change in sea level and/or change in sediment supply from the river.

During the process of submergence (by rising sea level) and sediment infilling, the locus of accumulation probably shifts from less energetic basins landwards to the current convergence zone (landward salt limit). In turn, this zone moves landward with rising sea level and up the river valley with rising base level. When finally the channels in the estuary are shoaled and convey much fluvial sediment directly to the sea, accumulation shifts laterally into remaining tidal flats, backswamps or marshes (Nichols & Biggs, 1985). With progressive infilling, the area shifts from estuarine-fluvial over es-

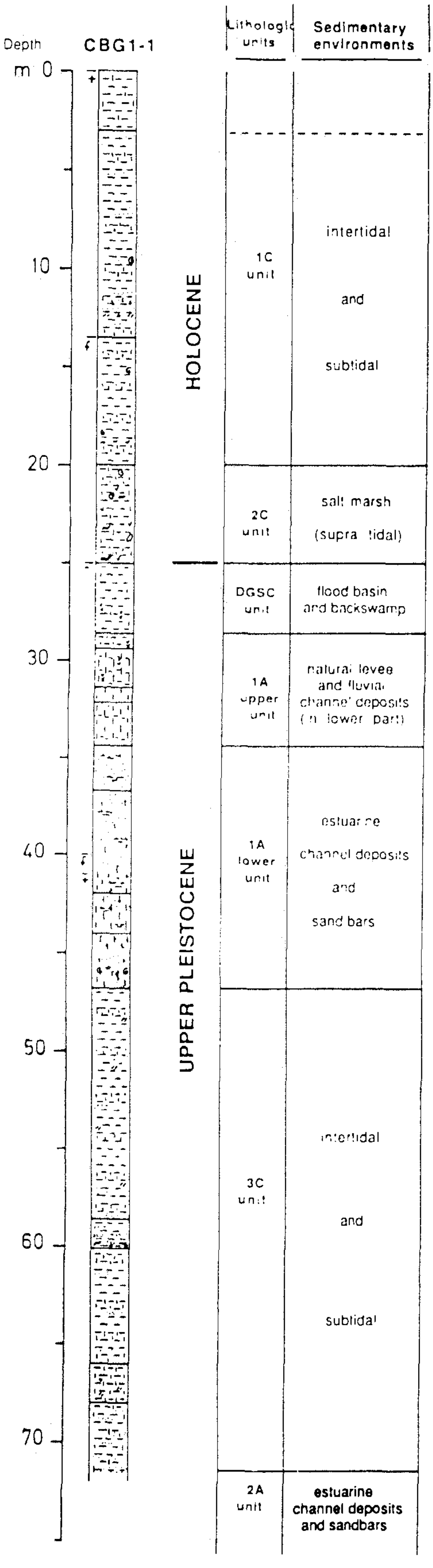


Fig. 3 : Lithological sequence of borehole CBG 1-1 with an indication of the units and related sedimentary environments.

tuary towards estuarine-marine and the function of the entire estuary changes from a sink for fluvial and marine sediments to a source of fluvial sediments for the ocean.

The vertical stratigraphical sequence in a transgressive environment is from the bottom up as follows: estuarine-fluvial, estuarine and finally estuarine-marine. The vertical succession of the 2A-unit, the 3C-unit and finally the 1A-unit (lower part) shows a great resemblance with such a transgressive sequence. The decrease of fluvial activity and the gradual overwhelming of the marine environment is clearly reflected.

Most probably, both situations occurred during the deposition of the 2A-unit, 3C-unit and 1A-unit (lower part), i.e. the lateral as well as back and forth shifting of the tidal channels and a general transgression (submergence by a relatively rising sea level). The maximum of the transgression is expressed by the deposits of the 1A-unit (lower part).

In the literature it is often mentioned that a transgression occurred during the Late Pleistocene. Zhou Mulin *et al.*, (1982) described a global transgression during an "*interglacial (or interstade) of the Dali Glaciation*" which the author situated at 22.900-32.000 years ago, and in 1986 (Zhou Mulin, 1986) at 24.000-39.000 y.B.P.

A fragment of transported wood in the top of the channel deposits of the 2A-unit was dated at 32.570 ± 770 y.B.P. (Irpa 975). Although the dated wood is not in situ, its age indicates at least that the top of the channel deposits is not older than about 32.000 y.B.P.. This age is in agreement with the first proposed age by Zhou Mulin *et al.* (1982) as the channel deposits (2A-unit) represent the beginning of the transgressive phase.

Due to the shifting of the channels with time, the vertical sequence is not developed in an exactly similar way over the entire estuarine reach. Indeed in some parts of the area the 3C-unit might be very well developed in the vertical sequence, while the 2A-unit will be restricted. On the other hand, in adjacent areas the accumulation of sand (2A-unit) in the channels and on the bars persisted, leaving no suitable environment for the tidal flat (represent by 3C-unit) to develop.

In fact such a situation occurred in the S-SE part of the Shanghai area, where the 3C-unit is very limited to completely absent due to the fact that in this particular zone channels and sandbars prevailed during the entire transgression.

This transgression was followed by a regression, the second main event during the Late Pleistocene. In the estuary the marine influence decreased gradually, while fluvial activity became predominant.

The beginning of the fluvial activity is represented by fluvial channel sand (at the base of the 1A-unit, upper part) followed by a well developed natural levee deposit, characterised by an intensive plant growth. In the vertical sequence, the natural levee deposit is overlain by the sediments of a flood basin, or the DGSC-unit. Such a vertical sequence is explained by the fact

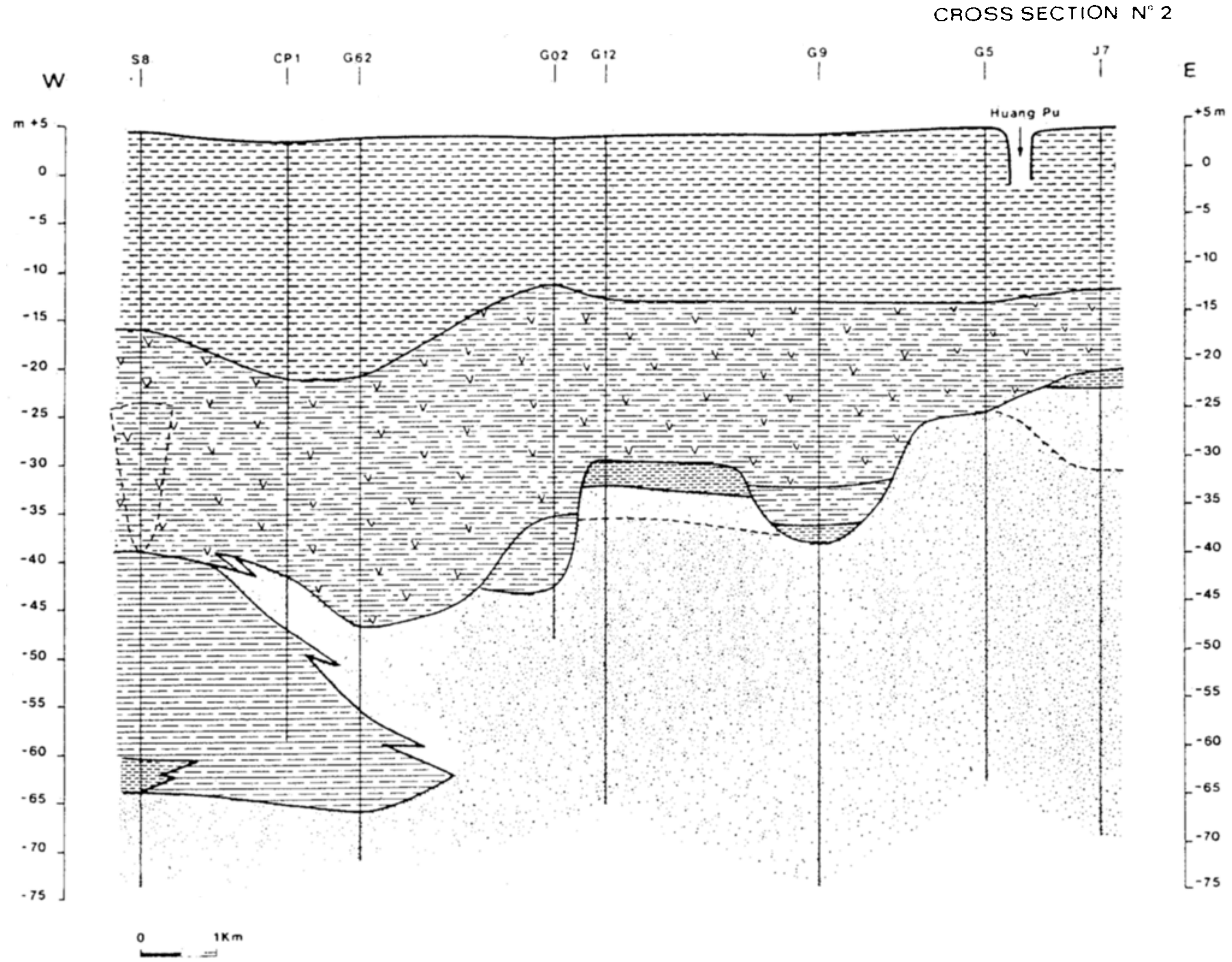


Fig. 4 : Cross-section of the northern part of the Shanghai area showing the erosion of the 2C-unit and the important development of the inter- and subtidal flat sediments in the vicinity of the Huang Pu River.

that in a meandering system, sedimentation takes place essentially simultaneously in the channel, on the point bars and in the various overbank environments (Boggs, 1987); in this case more particularly in the channel, on the natural levee and in the flood basin.

As lateral shifting on these different environments takes place owing to stream meandering, sediments from laterally contiguous environments will become superimposed or vertically stacked.

However, it is well known that natural levee deposits have a low preservation potential in the depositional cycle because they are eroded by the channel when shifting. The preservation of the natural levee deposits in most of the area here is due to the fact that the shifting, or natural migration of the channel in the entire area only happened once during that regressive phase, so that the natural levee was not eroded by the channel itself.

During the regressive phase, the entire area was finally occupied by an alluvial valley in which the river little by little raises the alluvial relief. Successive floods, each depositing a gradually outward-tapering layer of sediment, seem to be capable over the years of slowly elevating the active channel by building up its more immediate surroundings. The process of elevating the channel cannot proceed indefinitely, however, for the more the channel and its borders are raised, the easier it is for the river to abandon its elevated position in order to construct a new course at a lower level in another location (Allen, 1985). Nanson (1986) gave a rather different explanation about the process of abandoning a river course. The author stated that overbank deposition gradually builds a flood plain of fine-textured alluvium over a period of hundreds or thousands of years. Catastrophic erosion by a single large flood, or a series of more moderate floods, then strips the flood plain to a basal lag deposit from which it slowly recovers. This periodic destruction appears to be due to the progressive development of large levee banks and flood plain surfaces of highly variable relief. As the levees and flood plain grow, overbank flow is gradually displaced from the broad flood plain into main channel and flood-plain backchannels, with a resulting concentration of erosional energy. Vertical-accretion flood plains at different stages of development result in a wide range of bankfull recurrence intervals, even along the same river (Nanson, 1986).

Anyhow, the process of abandoning an alluvial ridge in favour of constructing a new one is known as river

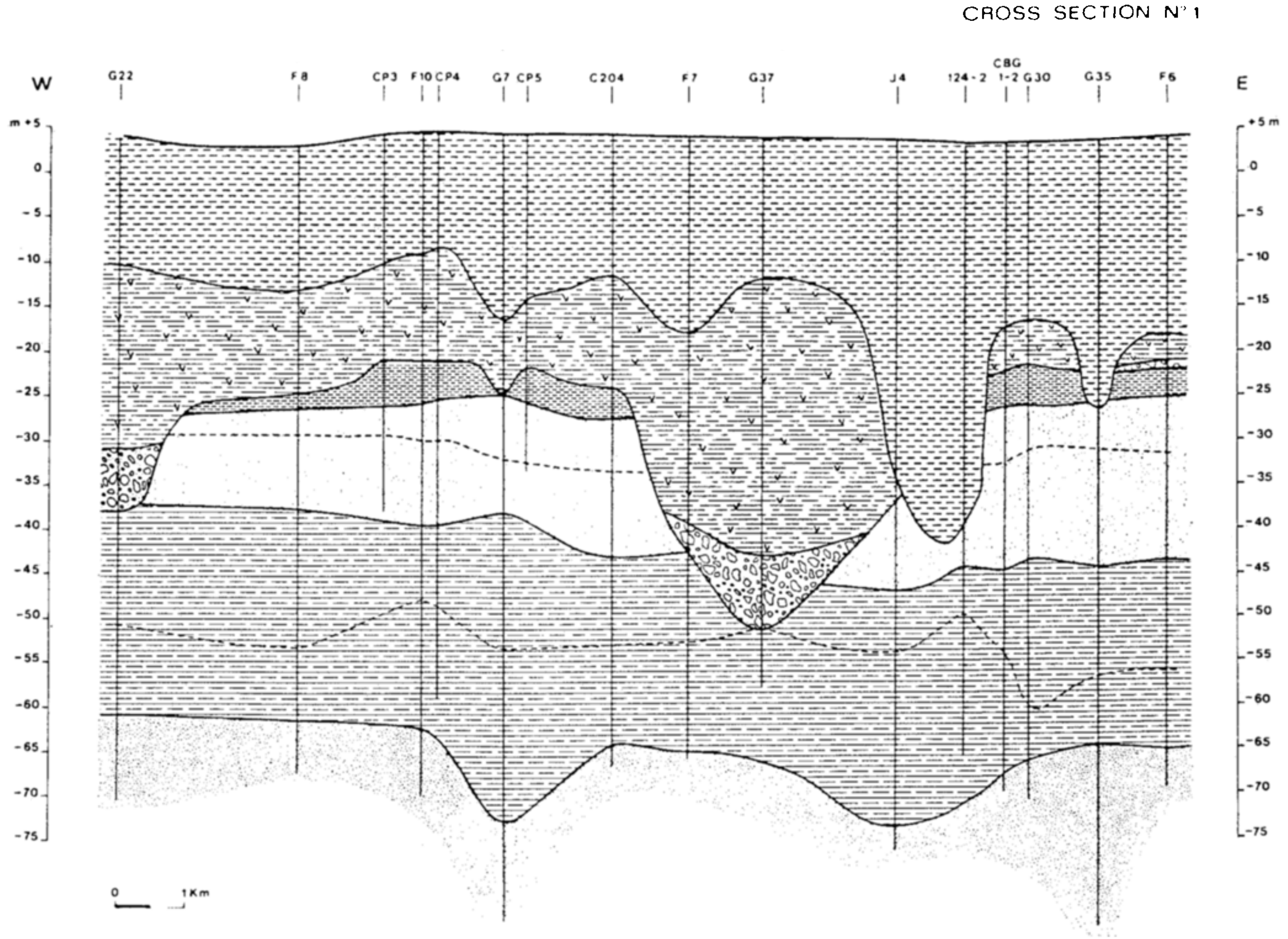


Fig. 5 : Cross-section of the northern part of the Shanghai area showing the discontinuity of the DGSC- and 1A-unit as a result of erosion.

avulsion and belongs to the most important of all fluvial processes.

The fluvial environment and more particularly the flood basin was charcterised by a vast extension (seaward of Shanghai) as the flood-basin clay (DGSC-unit) has been found in several locations of the (present) inner shelf (Milliman & Jing Qingming, 1985).

The period of regressive phase and fluvial predominance coincides with relative cold climatic conditions leading to a low sea-level stand. According to the literature, these conditions prevailed during the "Late Stage of the Late Pleistocene", and the occurrence of the lowest sea-level stand was about 15.000 years ago (Emery *et al.,* 1971, Zhu *et al.,* Guo Xuemin, 1988, Zhou Mulin *et al.*, 1982, Zhou Mulin, 1986).

In the Holocene period the area again changed to an estuarine environment, represented by dominantly stilty clayey sediments. Only two significant units could be recognized. The lower consists of mainly supratidal deposits and the upper represents the silts and clays deposited in the tidal flats of the estuary. Both deposits are very sensitive to compaction, and are called the "Second Compressible Layer" (2C) and the "First Compressible Layer" (1C), respectively.

The flood-basin clay from the Upper Pleistocene is directly overlain by fringing salt marsh deposits (2C-unit), representing the incoming Holocene marine influence and the very first deposits resulting from the postglacial sea-level rise. There is indeed no evidence of a basal peat, except in some cases. The basal peat, reflecting the initial rise of the sea level and the amelioration of the climatic conditions after the glacial period, most probably could not develop in the surveyed area due to the clayey substratum. Basal peat may be expected on the sandy facies of the Upper Pleistocene fluvial deposits.

The general amelioration of climatic conditions resulted in an overall renewed activity of all sedimentary depositional and erosional processes, not the least from the river itself. This is the reason why the depostis of the 2C-unit could reach thicknesses of up to 20 m. With a rapid sea-level rise salt marsh deposits very seldom reach a significant thickness as the environment quickly submerges and changes to intertidal and subtidal (Bouma, 1963, Frey & Basan, 1985). In the vertical sequence this results in an overlap of tidal flat on salt marsh deposits. Only when sea-level rise does not exceed the net rate of sedimentation, salt marsh development persists.

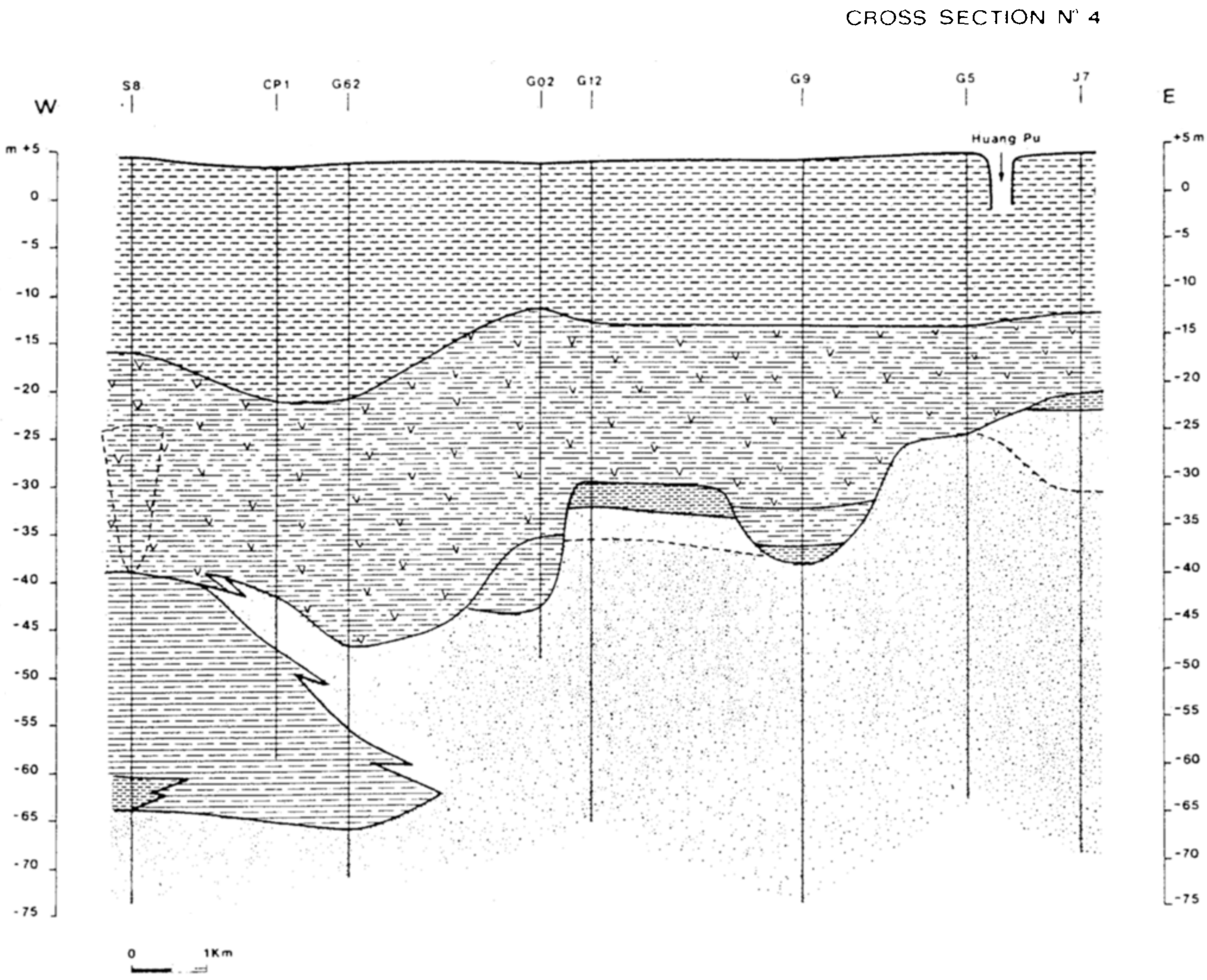


Fig. 6 : Cross-section of the southern part of the Shanghai area delineating the thinning of the 3C-unit, the discontinuity of the DGSC-unit and the important thickness of the 2C-unit.

In the surveyed area, however, the sea-level rise was very rapid in the beginning of the Holocene (Baeteman, 1989), so it must be deduced that a huge supply of sediment was involved to maintain the salt marsh and prevent it from submerging during a rather long period. The huge supply of sediment was provided by the Changjiang and Huanghe Rivers. Gamma ray investigations revealed also that the origin of the sediments is predominantly fluvial.

However, the salt marsh environment did not persist indefinitely and sea-level rise finally became predominant over all other features. The salt marsh was pushed landward and in the surveyed area the marine influence was more and more pronounced, leading to the development of tidal flats in an estuarine environment, reflected in the deposits of the 1C-unit.

In the tidal flats first an intertidal subenvironment generated, later evolving into a subtidal one. The tidal flats were characterised by relatively uniform conditions of very high mud supply from the rivers and very limited reworking by marine processes. This resulted in a nearly homogeneous thick sequence of silt and clay in which no significant changes in depositional conditions are recorded.

These subtidal deposits from the 1C-unit might coincide with the maximum of the postglacial transgression often mentioned in the literature and situated in the early Atlantic period (Baeteman, 1989). On many occasions in the literature it is concluded that after the maximum of transgression (with a sea level higher than the one at present) the sea level fell gradually to reach its present position. The sediments of the surveyed area exhibit no such evidence, however. On the other hand, a seaward growth of the flats by mud flat accretion, also called a depositional regression or coastal progradation, most probably did occur. This was possible at the open coast because of high rates of mud supply and low wave energy (Thompson, 1968). Such a depositional regression does not necessarily imply a lowering of the sea level.

The process of coastal progradation is supported by the occurrence of sand ridges which, judging from 14-C dates of mollusc shells, accreted in a seaward direction (Chen *et al.*, 1985).

4.2. *Geometry of the lithological units*

In the present geological study, the 42 boreholes as well as the CPT's and well-loggings have been correlated in a series of W-E and N-S cross-sections, covering the entire area surveyed (Fig. 2). The correlation of the boreholes was established on the basis of their sedimentary characteristics, facies association and sedimentary environmental interpretation.

From some of the cross-sections (Fig. 4, 5, 6, 7 & 8) the geological setting of the Shanghai area can be summarized and the most important features demonstrated. The W-E cross-sections # 2 and # 1 are located in the northern, the # 4 in the southern part of the area, while the N-S # 9 crosses the area in the centre.

In cross-section 2 (Fig. 4) a particular difference occurs between the western and eastern part. In the west the 3C-unit is situated at a significantly higher level than in the east. This difference is also expressed by the 1A-unit. In the west, only the upper part of the 1A-unit is present, while in the east the lower part is very well developed, although in the centre and east, the lower and upper part are both lacking. It is clear that the channel activity itself, reflected in the lower part of the 1A-unit, never occurred in that particular western part and only a natural levee was developed (except for the location at CPT 6). This explains at the same time the higher position of the top of the 3C-unit which was not, or only very little, affected by erosional activity of the channel in the western part. Moreover the accumulation of mud in the tidal flat of the estuary pre-

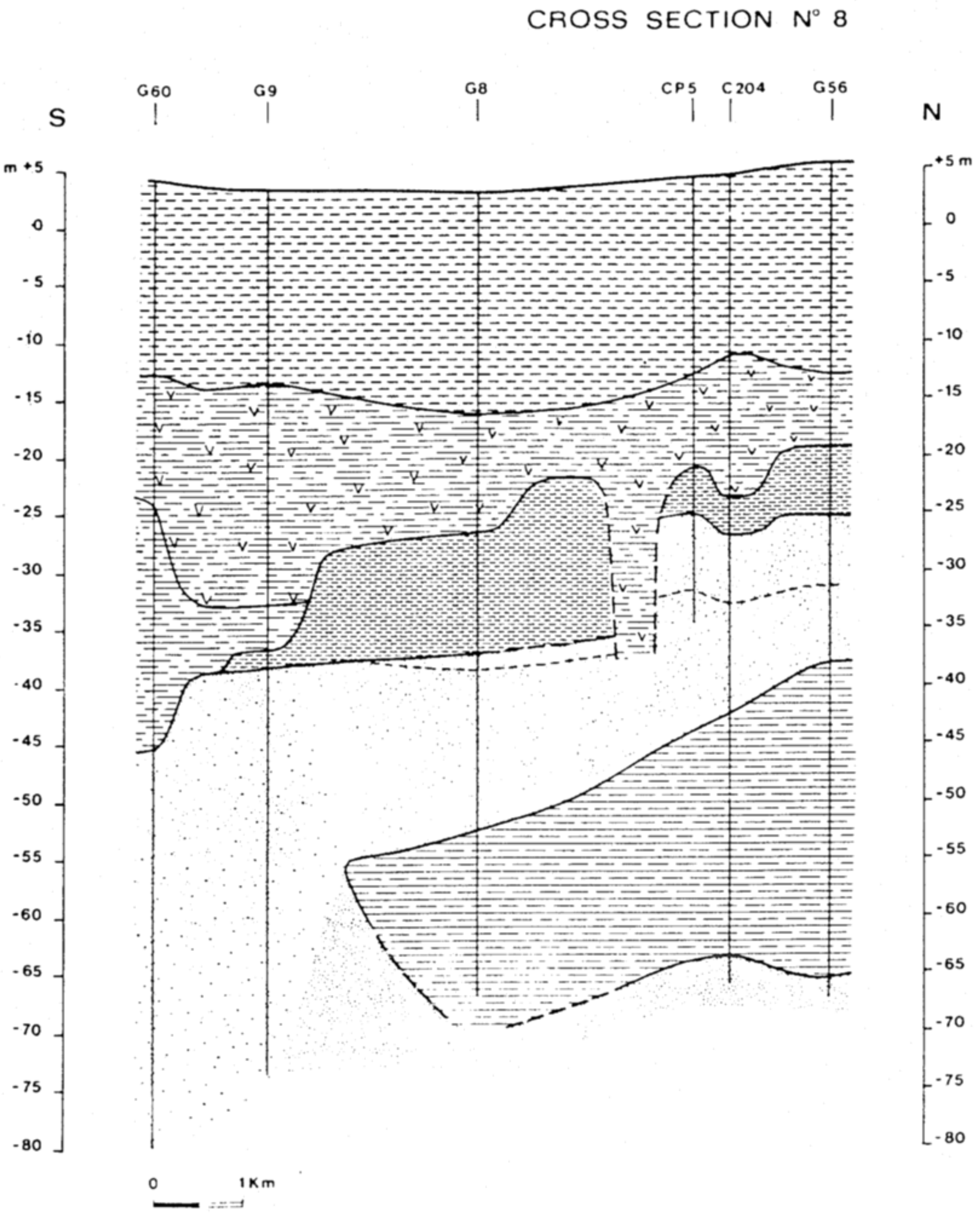


Fig. 7 : N-S cross-section showing the erosion of the DGSC-unit and the thinning of the 3C-unit towards the south.

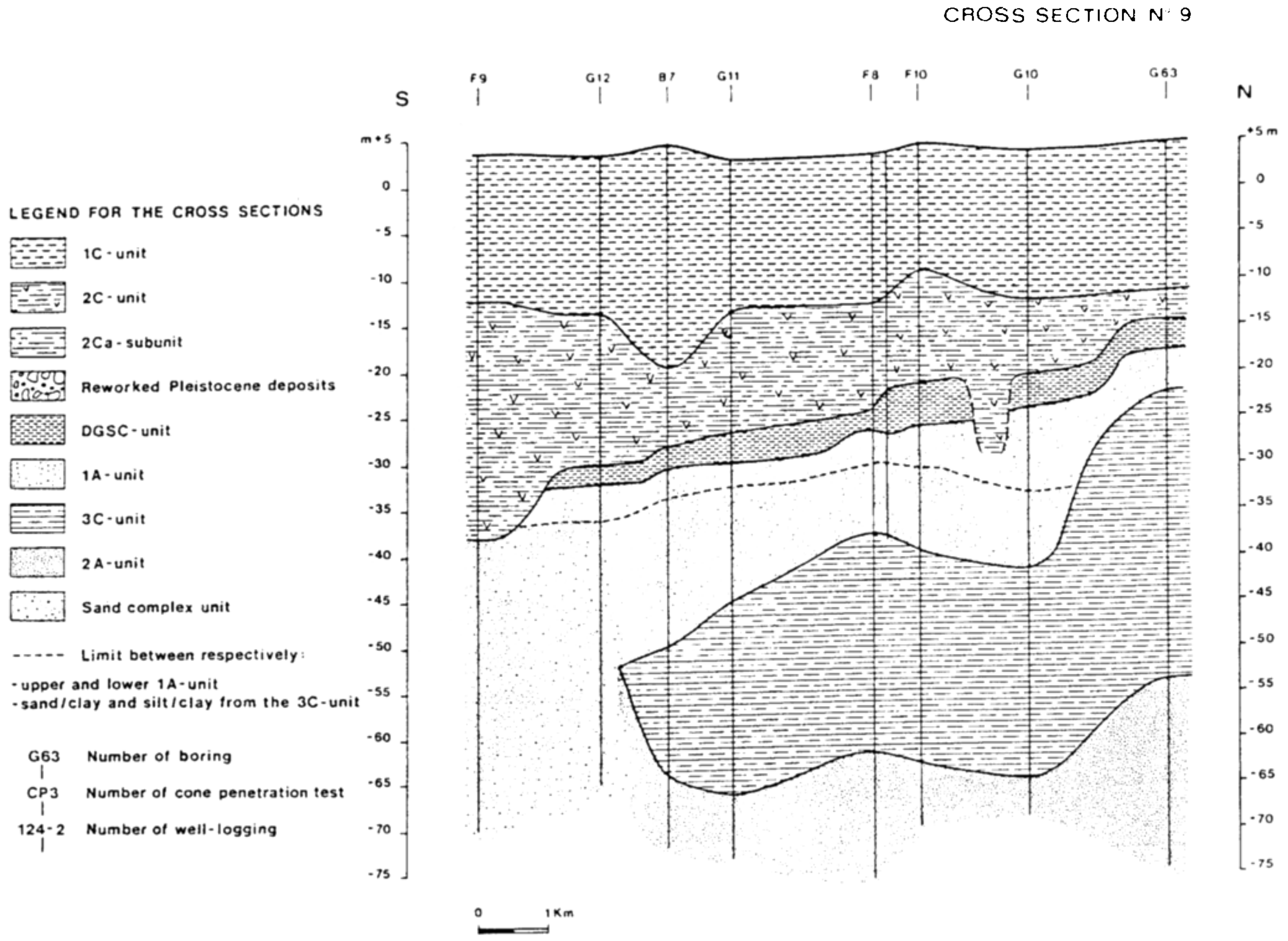


Fig. 8 : Cross-section demonstrating the steps in the topography of the DGSC-unit due to the process of river avulsion.

vailed for a much longer period in the western part, while in the east the channel environment developed earlier.

However, the most striking feature demonstrated by the cross-sections is the occurrence of zones where the Upper Pleistocene deposits, more particularly the compact impermeable flood-basin clay (DGSC-unit) and partly the 1A-unit, are lacking. The absence of these deposits has a dual cause. The geometry of the clay deposit obviously shows several steps in the process of river avulsion (Fig. 8 & Fig. 9). With the last (and lowermost) step, the river had not yet built up a new flood basin adjacent to its new position. So in some particular zones only dominantly sandy deposits from the channel itself are found.

The second origin is erosional, rather than depositional. Indeed, the beginning of the post-glacial period is characterised by a general amelioration of climatic conditions. This resulted in overall renewed activity of all sedimentary depositional and erosional processes. Especially, the river itself became very active again because it is known that, with large rivers, the channel regime is often controlled by climatic conditions of the source area rather than those prevailing in the flood plain (Collinson, 1979). Renewed activity of the river led to amongst others, important erosion resulting in deep incisions in its own former flood plain. Although sea-level rise was forthcoming, and the marine influence was extending more and more on the emerged offshore. the river eroded important parts of the Upper Pleistocene deposits from the existing flood plain. Some of these eroded deposits were found as channel lag at the base of the depressions (reworked Pleistocene deposits).

The absence of the flood-basin clay in certain zones of the Shanghai area is of great importance to the hydrogeological and geotechnical conditions. It must be surveyed in detail when evaluating the zones potentially sensitive to subsidence. However, it was believed that the flood-basin clay had a rather regular distribution. so that it sealed off the Pleistocene aquifers from the overlying compressible Holocene clay layers, thereby preventing leakage and compaction.

Based on the 42 boreholes a distribution map of the DGSC-unit was drawn (Fig. 9). The top of the DGSC-unit shows a rather regular configuration. This morphology, well depicted in the central part of the map, reflects the different cycles of river avulsion. occurring each time in a more south-eastern direction, and each time at a lower position. From a morphological point of view it is clear that the DGSC-unit cannot be interpreted as a lake facies, as

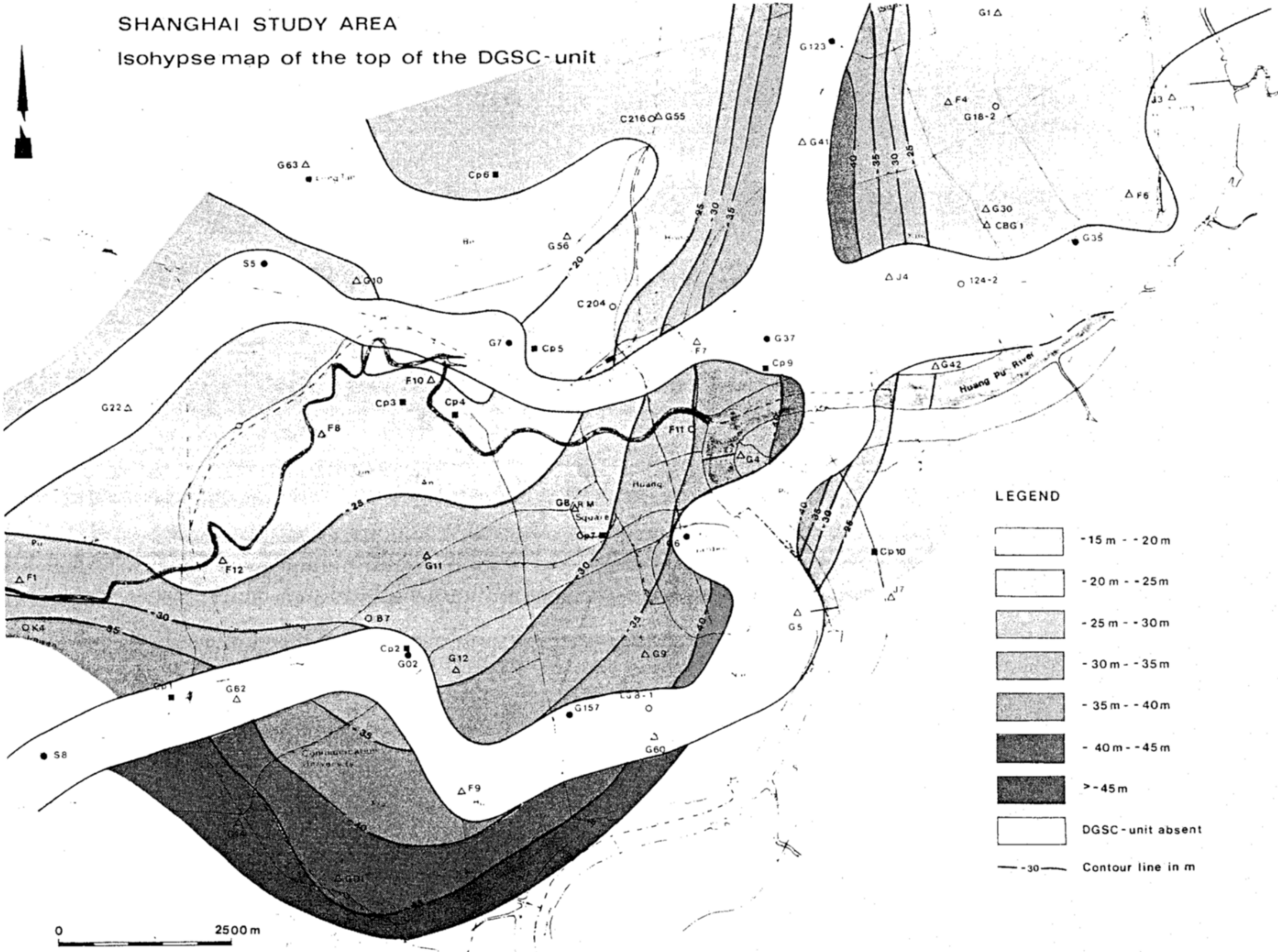
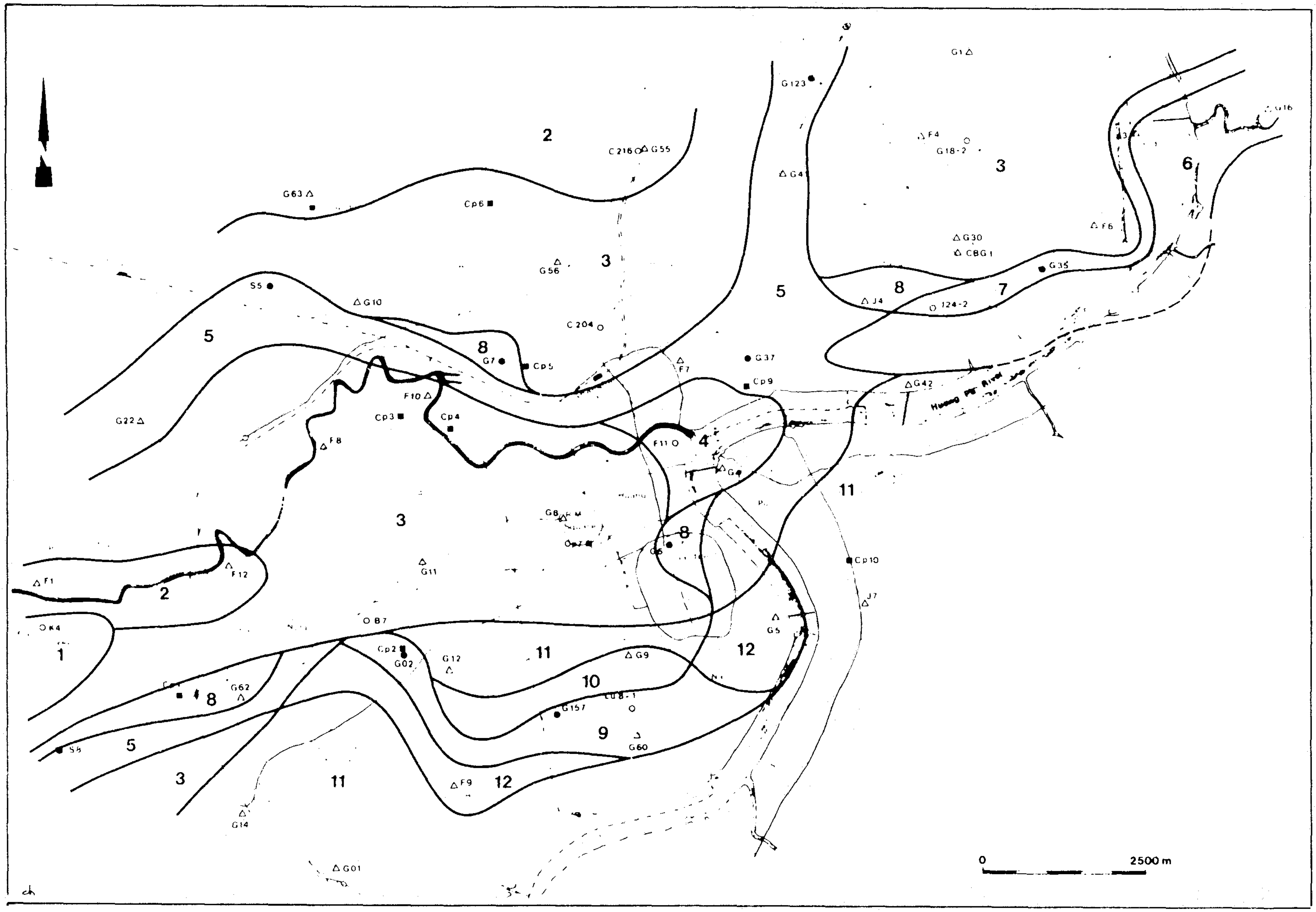
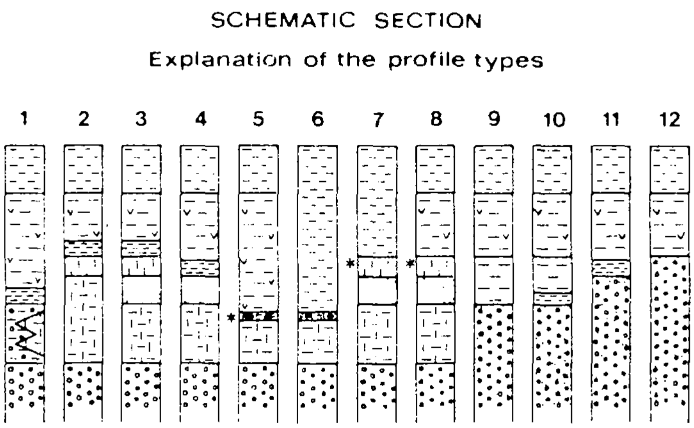


Fig. 9 : Isohypse map of the top of the impermeable compact flood-basin clay showing the zones of erosion.

PROFILE TYPE MAP OF THE HOLOCENE AND UPPER PLEISTOCENE DEPOSITS

SHANGHAI AREA





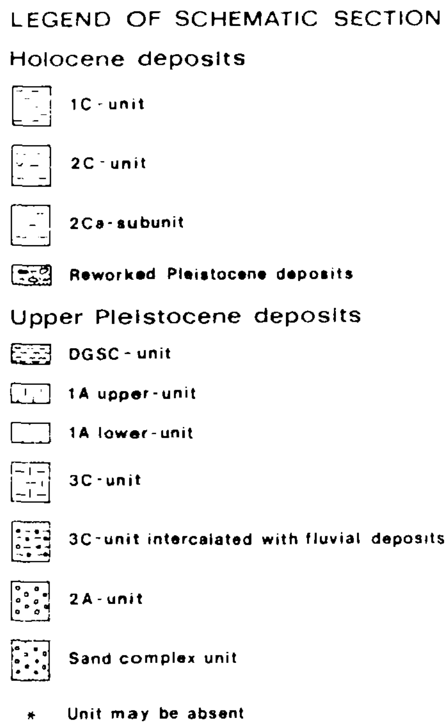


Fig. 10b : Legend of the profile type map.

is believed in general in the Chinese literature. Concerning the absence of the DGSC-unit, it is not inconceivable that in the N-S depression located in the central part of the map, the flood-basin clay never could develop because of the prevailing channel activity in that particular zone. But in the area bordering this depression in the west (e.g. G9 & G4) the flood-basin clay has been eroded partly (cf. cross-section # 8, Fig. 7) by the events which occurred at the very beginning of the Holocene just like in the W-E depression in the northern part of the area.

It is worthwhile mentioning that the configuration of the areas where the DGSC-unit is lacking has been drawn on the basis of relatively few data points which moreover are located far from each other. Therefore the configuration of these zones can only be looked upon as giving a general trend. It is self-evident that a denser boring grid would reveal a much more exact picture, and perhaps more zones where the clay is absent.

The geometry of the 2c-unit points to the fact that it has been eroded in turn during the Holocene (cross-section 1 & 2, Fig. 4 & 5). The process responsible for the erosional activity this time was not the river as at the very beginning of the Holocene, but the incision is caused by tidal channels. Erosion caused by tidal channels is inherent in their hydrodynamical system and does certainly not necessarily imply any change in sea level. During storm surges tidal channels can shift to another position or a new one can generate, causing significant erosion of the tidal flat.

However, it should be mentioned that this erosional phenomenon is located in the surroundings of the present Huang Pu river, an important tidal channel, and it is not inconceivable that the erosion is in close relation with the coming into being of the Huang Pu itself. In that case a change in the general sedimentary conditions and amongst others a change in the sea-level stand might be involved.

In the 1C-unit, reaching a thickness of nearly 20 m, almost every boring shows differences in lithological characteristics. The succession of layers with different lithologies (ranging from sand, silt to clay) changes from one boring to another, implying small lateral and vertical facies changes, which indeed are very typical for tidal flat deposits. But the data are not dense enough to make any significant correlation neither a conclusive interpretation. Hence the nearly 20 m thick deposit had to be considered as one single and entire unit. A denser boring grid and a detailed sedimentological study of the cores, certainly would reveal a better insight in the process of sedimentation and in the evolution of the sub-environments during the last silting up phase of the plain.

Another important feature of the geological setting of the Shanghai area is the thinning of the Upper Pleistocene compressible layer (3C-unit) in a southeastern direction and finally its complete absence in the southern part (Fig. 6, 7 & 8). In this area the channel activity from the estuary persisted during the entire period of the Upper Pleistocene transgressive phase so that no mudflats could develop there. This resulted in an important accumulation of sand deposits, called the Sand Complex-unit. This is the case in the southermost part of the city which, as a consequence, is less sensitive to land subsidence.

All the data have been represented in a profile type or sequence map (Fig. 10a & 10b) in order to demonstrate properly the spatial extension of the units for the entire sequence concerned thus giving the map a three-dimensional character. The sequence map consists of a series of 12 profile types, each representing a well-defined succession and combination of the distinct units.

In a general overview the profile type map of the Shanghai area shows three distinct zones depicting main differences. The first zone represents what could be called the complete or classical sequence consisting of, for the Upper Pleistocene deposits, the 2A-, 3C- and 1A-unit covered by the DGSC-unit, and for the Holocene deposits, the 2C- overlain by the 1C-unit. This zone is represented by the profile types 2, 3 and 4, covering the largest part of the map.

A second important zone is differentiated by the absence of the DGSC-unit. This is shown by the profile types 5, 6, 7, 8, 9 and 12 which are found in two west-east zones and in a north-south zone. A third zone is distinguished by the presence of the Sand Complex-unit, where the 3C-unit is lacking. This zone is represented by the profile types 9, 10, 11 and 12 occurring in the southern and southeastern part of the map.

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