Chapter 9
Complex Ground Beneath the Tung Chung Reclamation

Introduction

This chapter describes the geology associated with complex ground conditions at the Tung Chung reclamation. These complex ground conditions were first encountered during preliminary ground investigations for the Tung Chung reclamation in 1991 and have had a significant impact there on the design and construction of deep foundations for infrastructure development.

Much of the information presented here is taken from a report entitled "Geology of Tung Chung New Town" produced by the British Geological Survey (Gillespie *et al.,* 1998) under a Consultancy Agreement managed by the Geotechnical Engineering Office for the Territory Development Department. This detailed study was prompted by the need to establish a reliable geological model to assist further development in the area.

The geological model developed for Tung Chung has emphasised how the combination of several distinct geological processes, of widely differing age, has led to the development of the complex ground conditions. Useful related information is included in papers by Kirk (2000), Kirk *et al.* (2000), and Fletcher *et al.* (2000).

Background

Prior to its recent development, marble was unknown in the Tung Chung area. The nearest sedimentary rocks had been mapped at The Brothers islands, and marble was proved in offshore boreholes nearby and at Tai O. These marble occurrences had both been correlated with the marble-bearing Carboniferous sequence in the Yuen Long area. Skarn had also been reported from San Shek Wan and Sha Lo Wan (Langford *et al.*, 1995). The solid geology in the vicinity of Tung Chung was known to be dominated by granitoid dykes (feldsparphyric rhyolite, quartzphyric rhyolite, and microgranite), with some small intervening slivers of medium-grained granite (GEO, 1994).

According to GEO records, marble was first reported at Tung Chung reclamation in late 1992 during drilling at Housing Development Phase 1 ('Area 10'). Consequent geophysical surveys, undertaken by GEO during 1993, suggested that sedimentary rocks occurred offshore to the north of Lantau Island. However, the results for the existing reclaimed area remained inconclusive. In 1994, fragments of marble and small voids were noted from several boreholes at the Pedestrian Bridge site in Tung Chung Phase 1. In 1996, drilling for Tung Chung Town Lot 3 ('Site 3', Figure 13) encountered a range of problematic geological conditions including marble with cavities, steep weathering profiles reaching to depths of more than 170 m, and unconsolidated sediment to depths of at least 80 m. The complex geological conditions at Site 3, eventually led to the abandonment of a planned residential tower block in late 1996.

The preliminary geological model suggested that the marble and associated metasedimentary rocks occurred as small slivers within a fault zone (GEO, unpublished correspondence) although the scale and extent of the problematic ground conditions were unclear. Attempts to understand the geological controls on the distribution of the unusual materials were hindered at the time by inconsistent description and interpretation in borehole logs undertaken by different contractors. This made correlation or comparison between adjacent sites very difficult.

Tung Chung Study

The Geotechnical Engineering Office, on behalf of the Territory Development Department (TDD), and assisted by British Geological Survey consultants, carried out a geological study of the entire Tung Chung New Town area between 1997 and 1999. The objectives of the study were to collate all available ground investigation (GI) data; develop a geological model for the occurrence of complex geological conditions; provide guidance on the most appropriate GI techniques to enable early recognition and effective delineation of affected areas; and to evaluate the possibility of other areas being similarly affected. Follow-up studies, based on

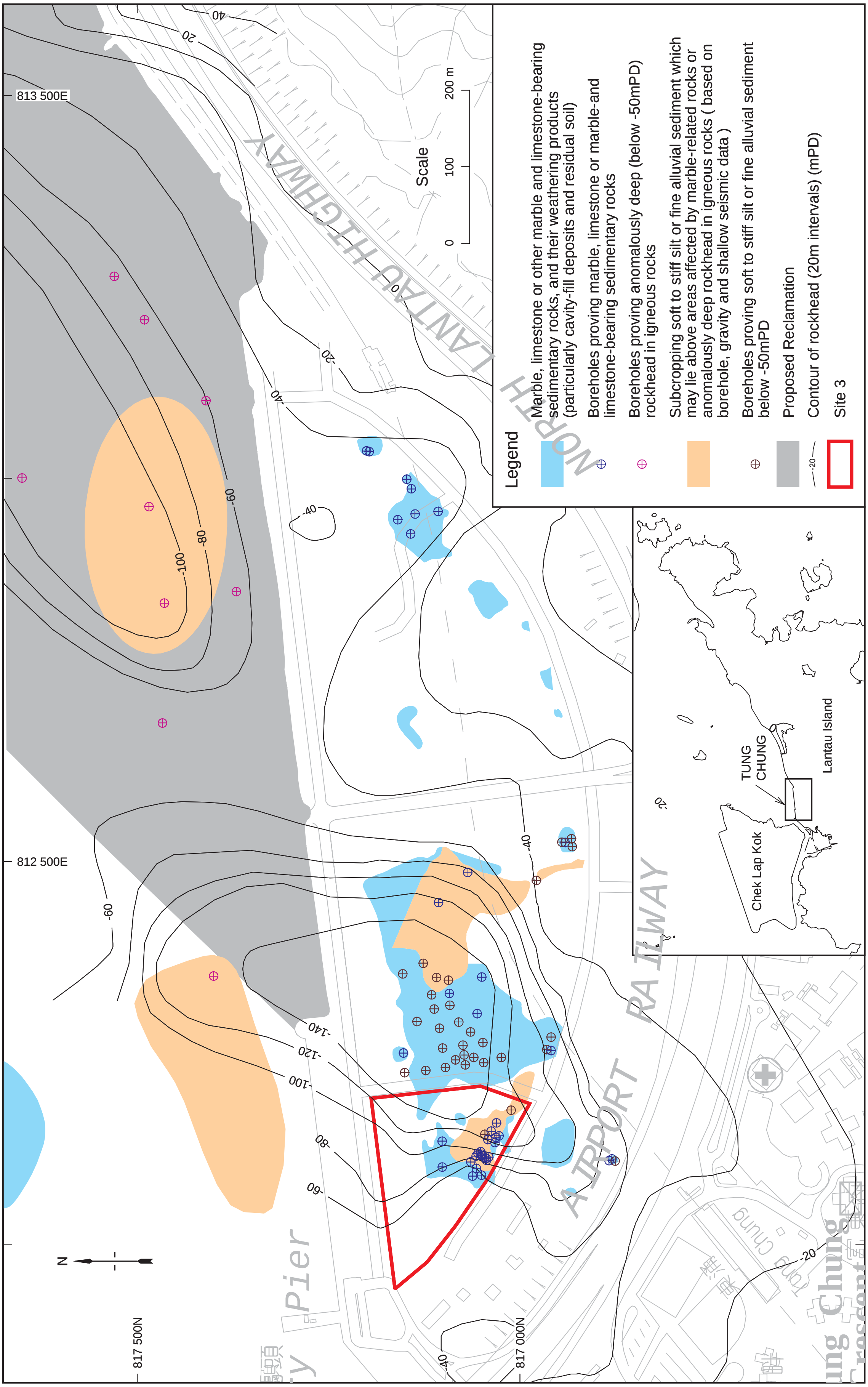


Figure 13 - Location Map of Part of the Tung Chung East Reclamation Potentially Underlain by Complex Geological Conditions

recommendations contained in the report (Gillespie *et al.,* 1998) included: further onshore and marine ground investigation to test models and investigation techniques, onshore and marine geophysical surveys, and development of a database for all archival and new information.

Data Sources

Some 2,500 boreholes have been drilled in the Tung Chung New Town area over the last 20 years. Most have been carried out within the last few years as the tempo of development has increased. Despite the volume of information available, there were problems in developing a geological model for the site. Problems arose mainly from the inaccurate or inadequate descriptions of geological materials, and widely differing interpretations of some of the less common lithologies. For example, the various logging geologists preparing the numerous GI reports from areas of the reclamation adopted a wide range of interpretations of the highly varied lithologies present. In some instances, several versions of logs existed for the same hole, probably reflecting the difficulties that contractors and consultants were experiencing while attempting to interpret the unusual materials (e.g. Figure 14). Logging problems were further compounded by sampling strategies. In most cases the very thick soils at the site were only logged from Standard Penetration Test (SPT) and Mazier cutting shoe samples. Numerous Mazier samples were reserved for future laboratory testing, but very few were used to help resolve the difficulties encountered in lithological description. Thus, it was not possible to build up a consistent geological model from the widely differing information, ranging across many sites.

As part of the GEO study, logs (and particularly core photographs, where available) of about 2000 boreholes were reviewed. Consistent terminology and classification were applied to a revised set of descriptions. About 400 boreholes were completely re-logged by re-examination of some or all of the samples from each hole. However, it should be noted that not all the borehole logs have been reviewed by GEO.

The re-logging undertaken in the GEO study is now stored digitally in Planning Division's Geological Modelling System. The original paper records, most of which are stored in the CEL GIU, have not been updated. Future workers accessing "factual data" for the Tung Chung reclamation from the GIU should therefore be aware of the difficulties of using the original paper records as outlined above.

Developing the Geological Model

The geological model developed from the reassessment of borehole logs during the Tung Chung study is described below in terms of three stages:

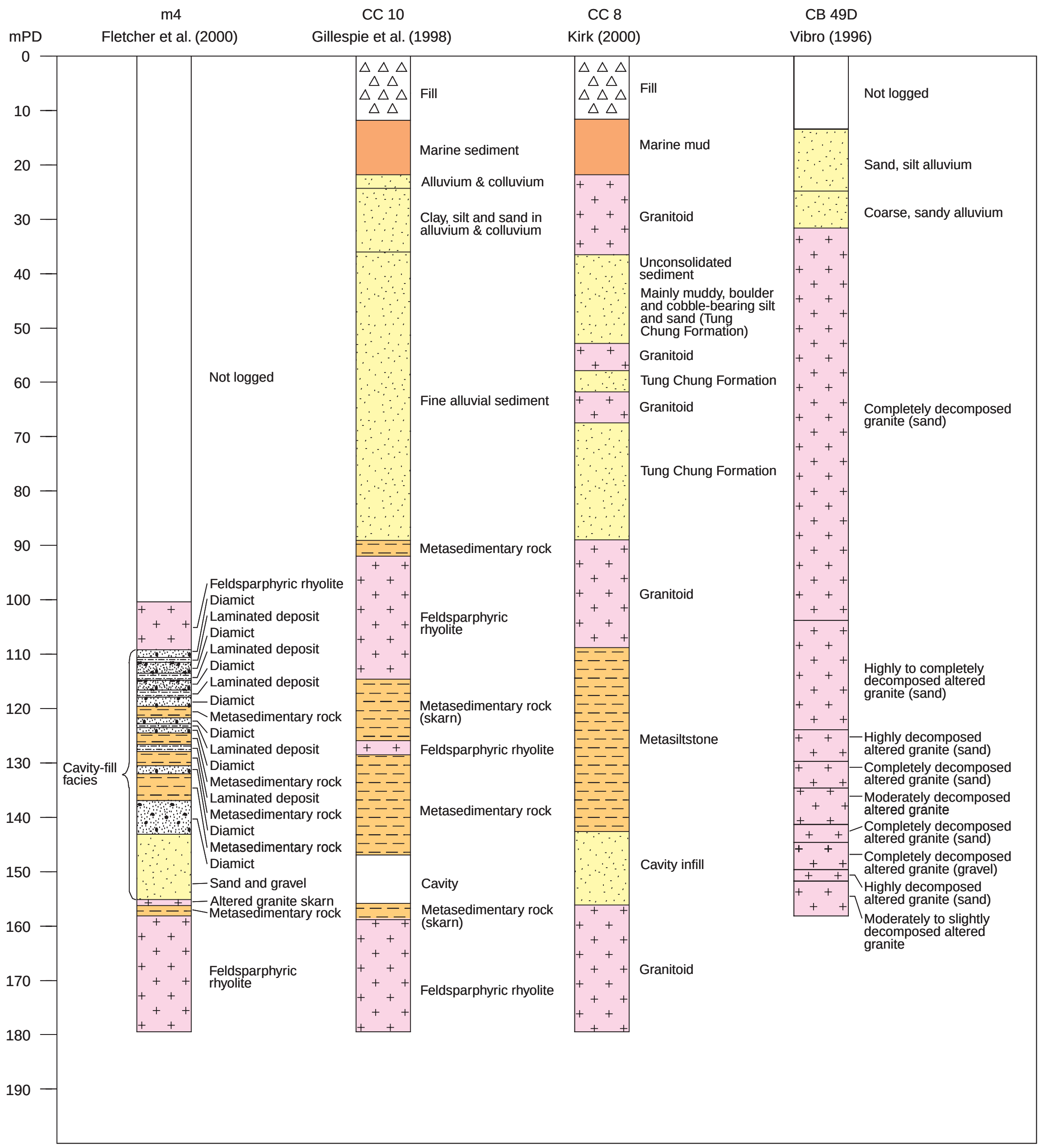
a) a description of the metasedimentary xenoliths, and their inclusion into the local granitic rocks;
b) a description of the deep weathering of the granitic rocks in the vicinity of some of the xenoliths; and
c) a description of the development of karstic features in and above those xenoliths that contain carbonate rocks.

Xenoliths

The area is underlain by granite, intruded by numerous granitoid dykes (mainly feldsparphyric rhyolite). The intrusive rocks enclose blocks (xenoliths) of metasedimentary rocks, predominantly of marble, sandstone and siltstone. The blocks range in size from a metre across to more than 300 m across. It is inferred that the blocks were incorporated during (Jurassic) intrusion, as they commonly exhibit effects of contact metamorphism. For example, skarn is well developed where carbonate rock (such as marble) has been in contact with the magma. The structural geology of the area is complex, and faulting further complicates the original distribution of xenoliths.

Weathering

Extreme depths of weathering are evident where the sedimentary rock xenoliths occur. In the Tung Chung area, continuous Grade III material and better, typically occurs at depths of 40 to 50 m. However, in the immediate vicinity of some xenoliths, many boreholes have been drilled to 150 m or more without reaching continuous Grade III or better material granite, and at least one borehole exceeds 200 m. These unusual weathering profiles are characterised by abrupt weathering fronts with transitions from Completely Decomposed Granite (Grade V) to Slightly or Moderately Decomposed Granite (grades II, and III) over only a few metres. The gradient on these transitions, also referred to as 'rockhead', is also locally very steep (up to 70°).



e 14 Examples Different Interpretations oblematic Materials Encountered Boreholes Drilled at various locations at Site 3 the T g Chung East Reclamation

The reason for the unusually extreme extent of decomposition is uncertain. It may be due to increased groundwater movement through cavitous marble, or alternatively, to increased susceptibility to weathering related to contact metamorphism (the granite may have been altered by circulating fluids) (Kirk, 2000).

Karst

Where meta-sedimentary rock was exposed at the middle Pleistocene palaeo-surface, thick residual soil has developed (Gillespie *et al.,* 1998; Kirk, 2000). Dissolution has occurred in many of the marble blocks, leading to the development of a range of karstic features. Cavities and fissures are common, and these range from less than 1 m up to 20 m. Most cavities are infilled with sediment, but voids up to 8 m in height have been recorded. Some boreholes have multiple intersections through cavity-infill deposits, and in these areas networks of large caverns are inferred to have existed.

In at least two localities, advanced dissolution has led to the formation of large sinkholes (or dolines) (Gillespie *et al.,* 1998; Kirk, 2000). One feature has been interpreted as an infilled solution doline, while the second is most likely a collapse doline. These features exceed 100 m and 60 m in width respectively, and are up to 130 m deep. Both are infilled with unconsolidated sediment, predominantly comprising boulders and cobble-bearing silt and sand. A new formation, the Tung Chung Formation, has been proposed (Kirk, 2000; Fyfe *et al.,* 2000) for these thick, though laterally restricted, deposits. Pollen dates, from serial samples, have suggested a mid-Pleistocene age (Fyfe *et al.,* 2000). The Chek Lap Kok Formation unconformably overlies the Tung Chung Formation.

Complex Ground Conditions at Site 3

Gillespie *et al.,* (1998), Kirk (2000), and Fletcher *et al.* (2000) have recently described the complex ground conditions encountered at Site 3, Tung Chung reclamation, which led eventually to the abandonment of Proposed Tower 5. Continuous mazier samples through karst deposits below 100 m from ground surface revealed the presence of two sedimentary facies (Fletcher *et al.,* 2000): a 'cavity-fill facies' and a 'collapse facies'. The 'cavity-fill' facies comprises laminated clay, silt and sand deposits, mixed debris-flow deposits, sedimentary breccias and colluvium (termed 'diamict'), and gravel. The 'collapse-facies' comprises boulders of completely decomposed granite and rhyolite in a matrix of diamict (see below), clay, silt and sand.

Laminated Deposits

Exceptionally well-preserved thin beds of clay, silt and fine sand, some of which have been highly contorted, are a feature of the laminated deposits in the cavity-fill facies. The laminations consist of orangish brown clay layers up to 20 mm thick, alternating with brown, silty clay layers (possibly organic-rich) and medium to fine sand layers from a few millimetres to 30 mm thick. The sand layers are commonly normally graded, with coarser sand at the base and fine sand at the top. Normal faults and sand injection structures are also present in the laminated deposits.

Diamict

Diamict deposits are present in both the cavity-fill and collapse facies, but are distinctive in terms of their matrix composition, grain size and the lithology of rock fragments. In all cases, the diamict deposits are chaotically arranged. In the cavity-fill facies, the diamict is characterised by completely decomposed granite, rhyolite and metasedimentary rock fragments, ranging from a few tens of millimetres to several metres across, set in a matrix of buff clay to silty clay with small angular fragments. Diamict in the collapse-facies consists almost entirely of large blocks of completely decomposed granite and feldsparphyric rhyolite, (possibly up to 10 m across), intercalated with fine-grained diamict, clay, silt and sand. A notable feature of diamict belonging to the collapse facies is that several of the decomposed granite boulders are cut by narrow, sub-vertical soil pipes, between 10 and 20 mm in diameter. A few small sub-rounded clasts of volcanic rock have been recorded among the intercalated fine-grained diamict layers.

Sand and Gravel

Thin, discontinuous layers of sand are present throughout most of the cavity-fill and collapse facies (Fletcher *et al.,* 2000). The sand is generally massive in appearance, and predominantly medium grained. Near the base of the cavity-fill facies, the sand layers appear to be thicker (some greater than 10 m) and more laterally continuous. Fletcher *et al.* (2000) have reported the presence of some deeply iron-stained gravels containing sub-angular rock fragments in a loose silty sand close to the bedrock surface.

Model for Formation of Karst Deposits at Site 3

Fletcher *et al.* (2000) have proposed that the laminated clay, silt and sand, loose sand and gravel, and diamict deposits accumulated in a cavity formed from dissolution of a marble block enclosed within the granite. Sedimentary structures displayed by these cavity-fill deposits are interpreted as indicating deposition in an underground lake or water-filled cavern. The diamict deposits are thought to consist mostly of detritus derived from the roof and sides of the cavity. As the cavity was enlarged, the decomposed granite roof became unstable and eventually collapsed onto the cavity-fill deposits, forming a chaotic mixture of large granite blocks and cavity-fill deposits. Voids between the large decomposed granite blocks were subsequently infilled with fine sand, laminated clay and silt. A network of sub-vertical pipes formed as water was expelled under pressure during compaction. These dewatering structures were later filled by fine sediment. A schematic representation of the evolution of karst deposits beneath Tower 5 is shown in Figure 15.

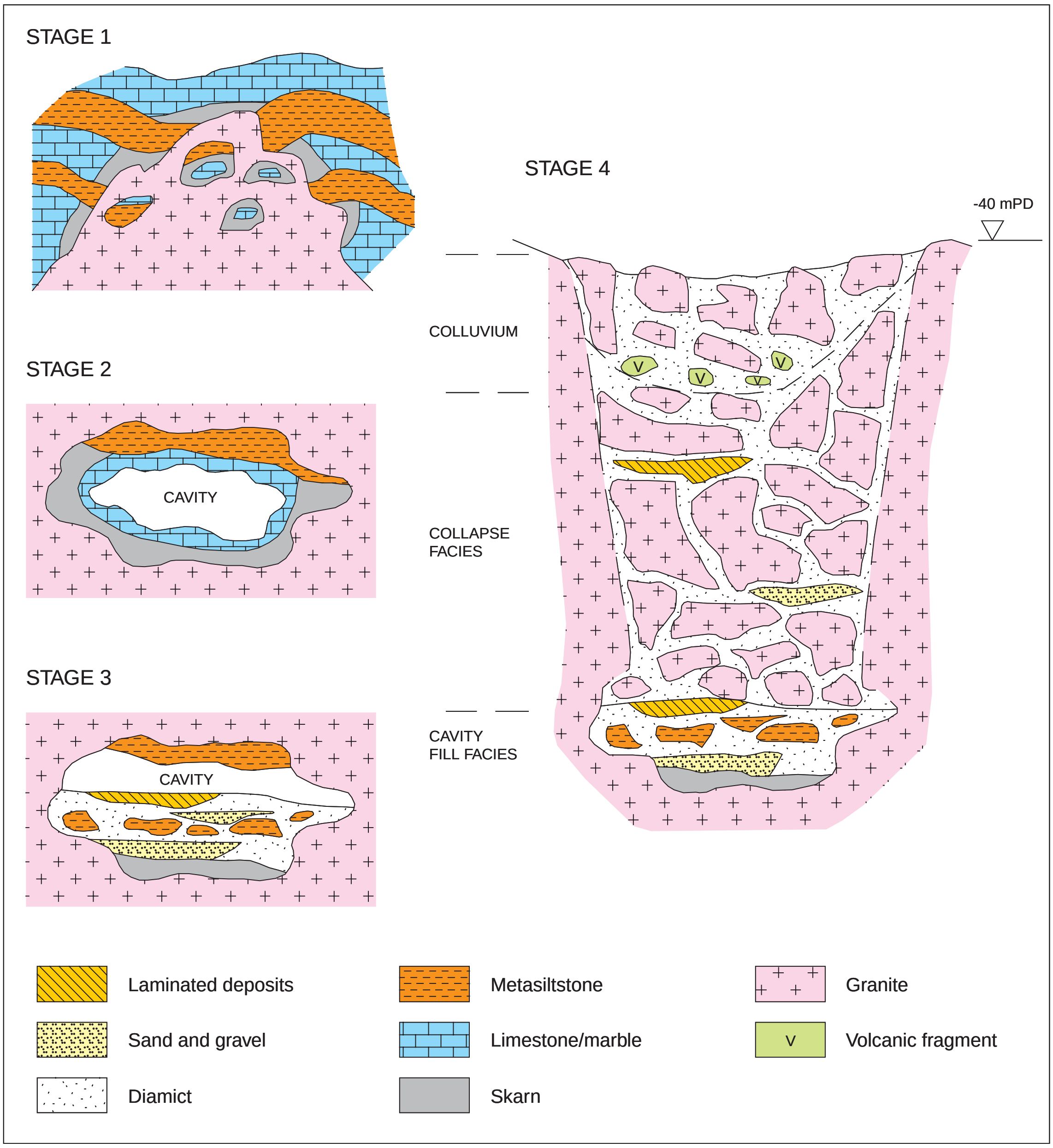


Figure 15 - Schematic Representation of the Development of Karst Deposits Beneath Tower 5, Site 3, Tung Chung East Reclamation (after Figure 6 in Fletcher et al., 2000)

Ground Investigation Techniques

One of the key objectives of the Tung Chung study was to identify a GI technique, or combination of techniques, that would enable early recognition of the occurrence of similar adverse ground conditions in other areas nearby. The microgravity technique was used to detect the relatively large masses of weathered granite associated with xenoliths. This utilised the density contrast between Completely Decomposed Granite and fresh granite, and the favourable geometry (i.e., steep rockhead gradients). It is important to note that the technique was not attempting to identify voids in marble (very low density), nor the marble itself (relatively high density). The technique was, however, successful in correctly identifying previously established rockhead levels on the basis of a 25 m –spaced grid. Negative gravity anomalies were also interpreted as further sites with depressed rockhead levels. Subsequent drilling confirmed the model, and in one case identified further marble and deep sediment.

A marine gravity survey was also carried out. Resolution of gravity anomalies is dependent on precise leveling, but this is not possible for the marine gravimeter, which therefore operates at rather lower resolution. Much wider grid spacing is therefore appropriate, and a 100 m grid was tried close to shore and a 250 m grid over

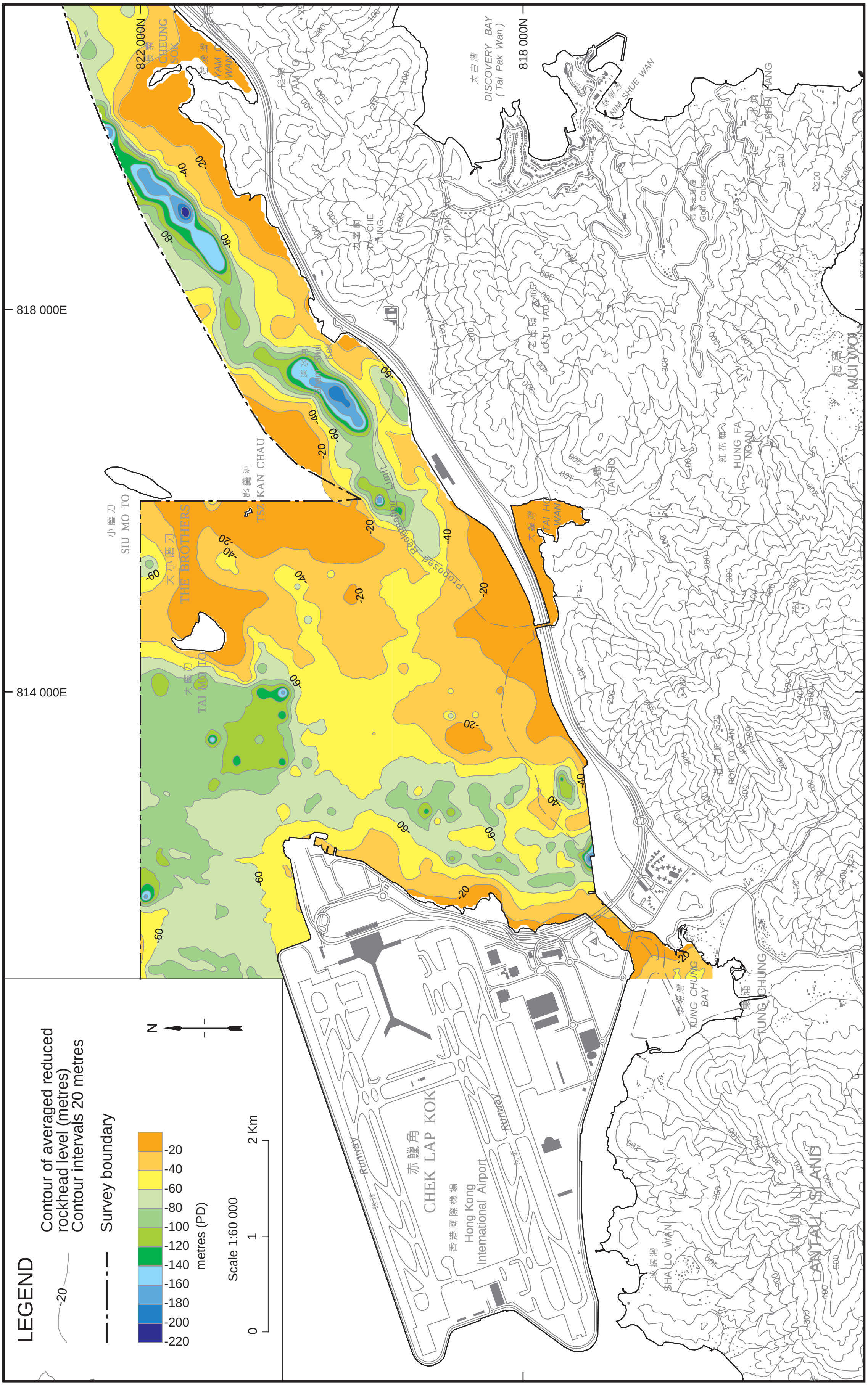


Figure 16 - Simplified Averaged Rockhead Models (Top of Grade III or Lower) for Offshore Parts of the District Based on 3-D Modelling of the Terrain Corrected Bouguer Anomaly (after EGS 1999a, 1999b).

a wider area. The survey results correlated well with seismic reflection profiles, and drilling confirmed interpretations of both lithological variation and rockhead levels. Further details and background to the processing of the raw gravity data are given in Kirk *et al.* (2000).

The anomaly maps and modelled depths (contour maps on rockhead) accurately identified the distribution of deep weathering, and correctly showed zones where the rockhead gradient was particularly steep (Figure 16).

3D-models of the superficial strata were created locally and densities of each lithology were measured in the laboratory. Fill, Hang Hau, Chek Lap Kok, and Tung Chung formations, together with the largest xenoliths, the shallower parts of the weathering profile and shallow man-made voids (MTR tubes) were all modelled. The component of gravity due to these materials was subtracted from the Terrain Corrected Bouguer Anomaly leaving a residual component due to deep weathering.

The refined model of rockhead generated by further processing of the data described above has provided structural information and details of variation in rockhead that would have been difficult to get by other means. In addition, detailed studies undertaken by Fletcher *et al.* (2000) have further refined the geological model for complex ground conditions beneath a single tower block on the Tung Chung reclamation. In this case, six new deep boreholes were drilled, and considerable care taken, to recover high quality samples.

Kirk (2000) proposed a revised geological model for the geology beneath the Tung Chung reclamation as comprising predominantly granite but with xenolithic blocks of meta-sedimentary rock, including marble. The igneous rocks adjacent to the xenoliths are unusually deeply weathered and characteristically have abrupt weathering fronts and steep gradients on 'rockhead'. In places, carbonate dissolution has produced karstic terrain (now buried) and cavities. Locally severe, dissolution has led to the development of sediment-filled collapse basins.

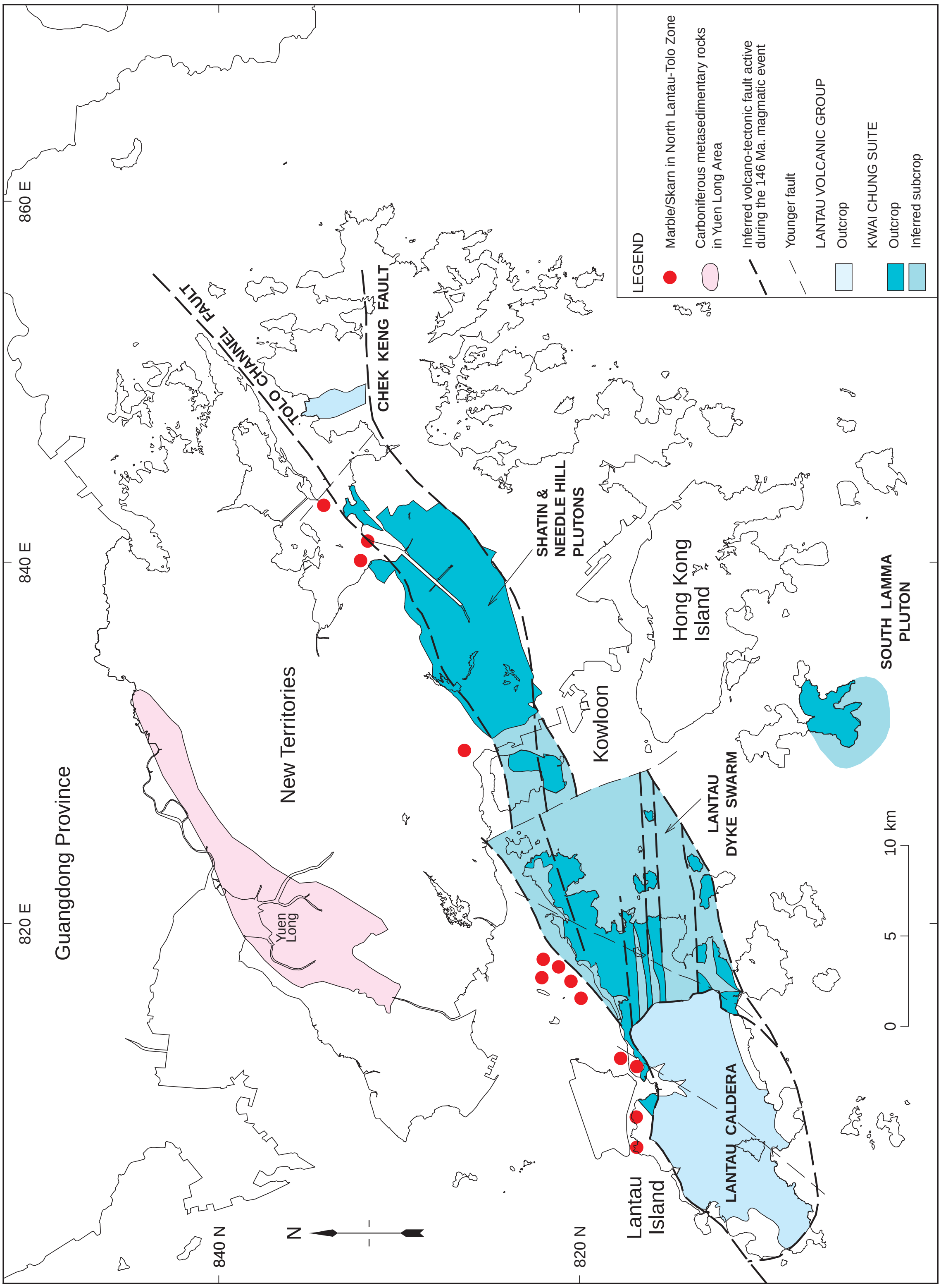
Implications of the Revised Geological Model

The revised geological model proposed for the Tung Chung reclamation implies local associations of materials that can pose geotechnical difficulties for some types of proposed development. A site investigation design that places a heavy reliance on drilling may not encounter these materials at an early stage, and may only intersect them during dense drilling for final design of foundations. However, if any one of these materials is intersected in any borehole, this should raise awareness as to the possibility of the occurrence of complex ground conditions in the locale, and further investigation should be undertaken.

Drilling and seismic reflection profiling have limitations as investigation methods in this geological environment but gravity surveying has proved effective in identifying the main occurrences of the low-density (e.g. marble) materials. The marble of Tung Chung is one of a series of local accumulations of meta-sediment in the district along the northern coast of Lantau Island. Further accumulations are likely to occur elsewhere in this region, and this should be taken into account in preliminary site investigations for future projects.

Complex Ground Conditions in Areas Adjacent to Tung Chung

Preliminary investigations for the proposed Northshore Lantau reclamation (at the eastern end of the North Lantau coast) have revealed the occurrence of deeply weathered structures associated with marble and a karstic palaeo environment similar to those found at Tung Chung (Kirk *et al.,* 2000). The extent of the marble farther north is difficult to evaluate and must be viewed in the context of Hong Kong's regional geology. It is noted that the marble at Tung Chung is one of a series of small, localised occurrences of meta-sedimentary rocks, including Ma On Shan, that lie along a northeast-trending structural zone extending from North Lantau to Tolo Channel. The style of these occurrences of marble contrasts with the laterally extensive Palaeozoic sequence of the Yuen Long area. The distribution of the marble at Tung Chung and Ma On Shan agrees well with the volcanotectonic reconstruction for the Late Jurassic of Campbell and Sewell (1997) (Figure 17, after Kirk, 2000). Campbell and Sewell (1997) have interpreted the volcanic and plutonic rocks of the *c.* 146 Ma volcanic event to represent magmatism during crustal extension or transtension. Incorporation of country rock into intrusive rocks (as at Tung Chung) and within controlling structures (as at Ma On Shan) also ties in well with this model. Therefore, it can be inferred that marble may occur, either within fault structures or associated with magmatism, anywhere along the eastnortheast-trending zone shown in Figure 17.



e 17 V lcanotectonic Map Hong Kong (c.146 Ma) Showing the Distribution the and Ma O Shan Marble Subcr and Major Faults that We e Active During Emplacement ocks Belonging to the Lantau Volcanic and Kwai Suite (Modified after Kirk, 2000)