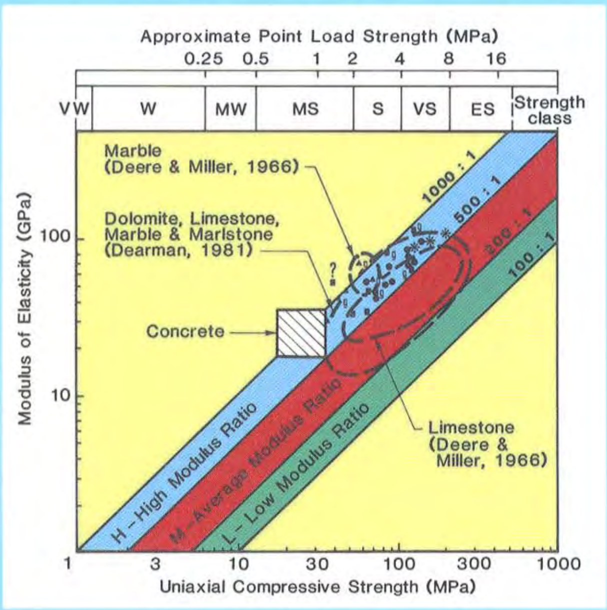
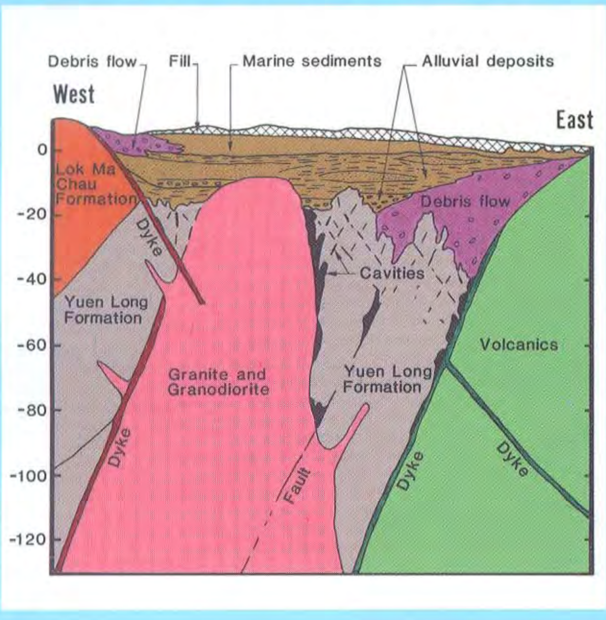
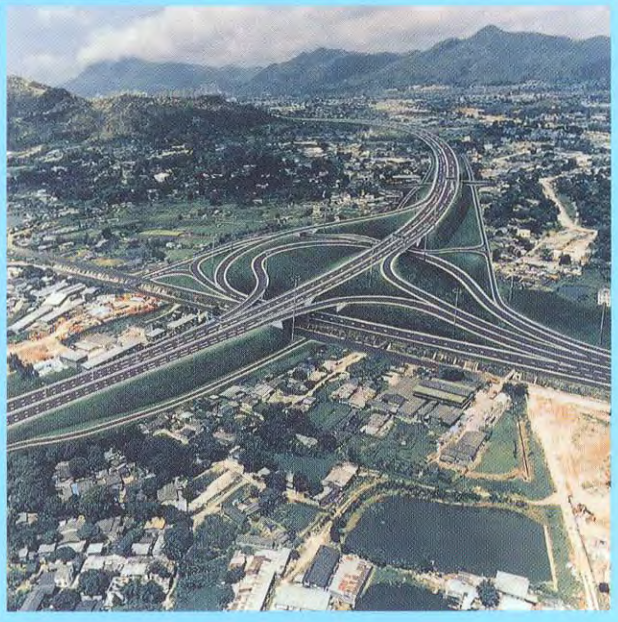
GCO PUBLICATION No. 2/90

FOUNDATION PROPERTIES OF MARBLE AND OTHER ROCKS IN THE YUEN LONG - TUEN MUN AREA







GEOTECHNICAL CONTROL OFFICE
Civil Engineering Services Department
Hong Kong

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GEOTECHNICAL CONTROL OFFICE
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First published, December, 1990

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This publication is available from :

Government Publications Centre,
General Post Office Building,
Ground Floor,
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Overseas orders should be placed with :

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Information Services Department,
1, Battery Path,
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Price in Hong Kong : HK$58

Price overseas : US$10 (including surface postage)

Cheques, bank drafts or money orders must be made payable to HONG KONG GOVERNMENT

FOREWORD

The Yuen Long-Tuen Mun Eastern Corridor project involves the construction by the Highways Department of a 7 km-long dual two-lane trunk road. The geology of the project area is complex and locally highly variable, giving rise to various concerns in relation to the design of bridge foundations, not the least being the occurrence of buried marble containing cavities.

The Geotechnical Control Office has been assisting the Highways Department with this project since 1986. Construction work is now underway and the road is scheduled for completion in 1993. Before construction commenced the Office undertook a feasibility study, planned and supervised the ground investigation and advised on the design of bridge foundations. Recommendations arising from the investigation have been presented to the Highways Department in the form of Advisory Reports.

The ground investigation included numerous deep boreholes and an extensive programme of laboratory testing of rock samples was carried out. In view of the lack of published local data on the engineering properties of the rock types likely to be encountered in deep foundations in this area, it was decided to publish the data obtained in this project along with an outline of the approach to the design of bored piles. This should serve as a useful source of information for other projects involving deep foundations in the Yuen Long - Tuen Mun area. It should be noted that this publication is not intended as a guide to standards of geotechnical practice nor is it a state of the art review.

Dr T. Y. Irfan drafted and produced the publication, with checking and editing by Mr J. B. Massey, Dr R. P. Martin and Mr Y. C. Chan. Drs A. Cipullo and P. C. Tsui assisted with the interpretation of the ground investigation data. Dr Cipullo also helped with the planning and execution of the laboratory testing programme. Messrs M. C. Chan and L. P. Ho carried out most of the point load tests.

(A. W. Malone)
Principal Government Geotechnical Engineer
December 1990

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1. INTRODUCTION

The Northwest New Territories has seen rapid construction activity for new town development in recent years. Foundation conditions in the Northwest New Territories are generally more varied and complex than in other urban areas of Hong Kong where only granitic and volcanic rocks are encountered. The presence of marble under a thick superficial soil cover was reported by Siu & Wong (1985). The discovery of marble with karstic features including large cavities (Pascal, 1987) led to special instructions being issued for foundation works within a Designated Area, i.e. that affected by marble bedrock (Lands and Works Branch Technical Circular No. 4/89 and Buildings Ordinance Office Practice Note 129). In 1990, the Buildings Ordinance and Regulations were amended to introduce new control provisions for the area within which marble may be found, referred to as "Area Number 2 of the Scheduled Areas". In addition to marble, which may locally contain large cavities, marble-clast bearing tuff breccia, pyroclastic volcanic rocks, granites, granodiorite, sedimentary and metamorphic rocks underlie the area. These are generally covered by a thick layer of superficial materials consisting of fill, alluvium, debris flow and marine deposits. The geology is further complicated by a number of faults and dyke intrusions.

The route of the Yuen Long to Tuen Mun Eastern Corridor, a proposed trunk road joining the two new towns (Figure 1, Plate 1), crosses this area of complex geology. Construction of the new road will involve a number of embankments across the alluvial plain, cut slopes through the hillsides and bridges across the stream courses and in the interchange areas.

The Geotechnical Control Office (GCO) has been assisting the Highways Department with the geotechnical aspects of the foundation and slope design, including the site investigation and interpretation of the foundation conditions at a number of bridge sites at Interchanges 1, 3 and 4. A laboratory testing programme involving determination of index, strength and deformation properties of the main rock units was undertaken in order to assess the properties of the foundation rocks at these bridge sites. The engineering properties of the local metamorphic rocks, particularly marble, are little known and no detailed test data have been published. The main testing programme was contracted out to the Department of Civil and Structural Engineering of the University of Hong Kong. This was supplemented by point load testing of the main rock units by technical and professional staff of the GCO.

In view of the general geotechnical interest of the area, it was decided to publish this information in order to provide data on the foundation conditions and the engineering properties of the rocks.

2. GEOLOGICAL SETTING

2.1 GENERAL GEOLOGY

Recent geological mapping by the Geological Survey of Hong Kong of the area between Tuen Mun and Yuen Long indicates that this portion of the Northwest New Territories is underlain by metamorphic rocks including marble of Carboniferous age, and by volcanic rocks and granite intrusions of Jurassic to Cretaceous age (Langford et al, 1989; Darigo, 1989; Frost, 1991) (Figure 2). Basalt dykes, probably Tertiary in age, are often found associated with faults. Superficial deposits (fill, alluvium, mud and debris flow deposits), usually 5 to 20 m thick, cover the bedrock which is generally deeply weathered in the low-lying areas. A generalized cross-section of the strata in the Yuen Long Area is shown in Figure 3.

The Carboniferous rocks belong to the Mai Po member of the Lok Ma Chau Formation and the Yuen Long Formation of the San Tin Group (Tables 1 and 2). Volcanic rocks belong to the Tuen Mun Formation of the Repulse Bay Group. The Mai Po Member consists of metasiltstones and metasandstones with phyllite layers, whereas the Yuen Long Formation consists of marble, dolomitic in part, interbedded with siltstones in the upper horizons.

Ground investigation carried out for the Highways Department project has shown that, in the southern portion of the area near Tuen Mun, the underlying bedrock consists predominantly of alternating layers of tuffaceous siltstone and tuff breccia with marble clasts. Also present in the southern portion of the area are predominantly andesitic volcanic rocks of the Tuen Mun Formation, Repulse Bay Volcanic Group. In the northern portion of the area, near Yuen Long, the dominant rock types are metamorphosed sandstones and siltstones of the Mai Po Member of the Lok Ma Chau Formation, and marble and interbedded marble and metasiltstones of the Yuen Long Formation. The hills between Tuen Mun and Yuen Long (Plate 1) are dominantly composed of fine- and fine- to medium-grained granite. Detailed (1:5 000 scale) geological maps of the area between the two towns, known as "the Designated Area", have been produced by the Geotechnical Control Office (see list of GCO publications at the back of this publication).

The broad structural geology of the Northwest New Territories indicates that the Carboniferous bedrock forms a wedge, bounded and controlled by faults, extending from Guangdong Province, and underlying much of the Lo Wu - Yuen Long - Tuen Mun Plain. The regional geological structure is dominated by a series of northeast-southwest trending faults generally dipping northwest, with more recent cross-faults trending northwest-southeast and offsetting the former. The overall regional dip of the foliation and bedding is towards the northwest at about 50°, but sharp variations in the dip and dip direction are also present, which complicate the geological succession in many areas.

2.2 DESCRIPTION OF THE LITHOLOGICAL UNITS

2.2.1 General

Examination of soil and rock samples obtained during the ground investigation suggests the presence of five broad lithological units.

These are, from the youngest to the oldest, as follows :

(a) Superficial deposits of Late Tertiary to Quaternary age, comprising alluvium, mud and debris flow deposits, plus recent fill.

(b) Intrusive dyke rocks of granite, rhyolite, andesite and basalt of probable Cretaceous and Tertiary age (Frost, 1991).

(c) Interbedded siltstone, sandstone, marble-bearing tuff breccia and tuffs of Jurassic age (Tuen Mun Formation of the Repulse Bay Volcanic Group).

(d) Interbedded metasiltstones and metasandstones of Carboniferous age (Mai Po Member of the Lok Ma Chau Formation).

(e) Marble and interbedded marble and metasedimentary rocks of Carboniferous age (Yuen Long Formation).

The weathering terms used in the following sub-sections are taken from a rock mass classification which is based on the scheme given by BSI(1981). The details of this classification are explained in Section 3.2. This classification was found to be the most appropriate for the purposes of the project.

Plates 2 to 15 illustrate the various rock units encountered in the boreholes in the project area.

2.2.2 Superficial Deposits

Fill occurs over much of the area, generally up to 3 m thick, but up to 6 m in some localities. It generally consists of loose to medium dense silty and clayey sands, locally gravelly and cobbly. Alluvium is the most widespread superficial deposit overlying bedrock in both the northern and southern portions of the site. It often occurs as interlayered soft to firm, grey or brownish grey, clayey silt, and loose to dense, light grey, coarse and occasionally fine sand. Its thickness is generally between 5 m and 15 m, but may be up to 24 m thick in areas underlain by old buried natural drainage channels. Mudflow and debris flow deposits, which are known to occur in the Yuen Long area above marble bedrock, were identified in one or two boreholes. No marine deposits were found in the boreholes inspected for the project.

2.2.3 Basic and Acidic Intrusions

Granite and rhyolite dykes were found intruding both the marble and the sedimentary rocks in a limited number of boreholes. The dykes are typically highly to completely weathered, with a thickness not exceeding 5 m. Frost (1991) reported the presence of granite and granodiorite in a number of deep boreholes, up to 250 m, drilled for the geological survey of the Yuen Long area.

Dykes of basic and intermediate composition also occur as thin to thick intrusions (Plate 5), often associated with faults, in the marble and metasiltstone at Interchanges No. 3 and 4 (Figure 1). The rocks are strong and dark grey to black when fresh, and become a dense to very dense greyish green sandy silt when completely decomposed. The major basic intrusions strike northeast-southwest and dip northwest with thicknesses ranging from 5 m to 15 m, following the general structural features of the area. Thermal metamorphism has obviously occurred along the contact zone between the dykes and the country rock (Plate 5), particularly the white and grey marble subunits (Tsui & Irfan, 1990; Frost, 1991).

2.2.4 Volcanic Rock Units

A sequence of marble-bearing tuff breccia and tuffs interbedded with tuffaceous siltstone/sandstone occurs at the location of Interchange No. 1. (Figure 1). This sequence has been named the Tin Shui Wai Member of the Tuen Mun Formation (Darigo, 1989). The sandstone and siltstone are weathered to a loose to very dense sandy silt and silty sand to depths of 60m or more (Plate 13). The tuff breccia is strong to very strong and widely jointed when fresh, containing 20% to 50% of subrounded to angular fragments of marble, quartzite and metasandstone embedded in a greenish grey to grey fine-grained tuff matrix. The fine-grained tuff may also occur as distinct bands which are easily recognizable in the moderately decomposed state (Plates 10 to 13) as they do not exhibit the typical honeycombed relict structure of the dissolved carbonate clast-rich zones.

A sequence of tuff of andesitic composition is present locally under one of the bridge foundations in the southern portion of the site.

2.2.5 Metasedimentary Rock Unit

Interbedded metasiltstones and metasandstones of the Mai Po Member of the Lok Ma Chau Formation (Table 1), overlying marble of the Yuen Long Formation, occur in the northern portion of the site. This unit is generally completely weathered to depths of 15 to 40 m, locally to 70 m or more. The rocks are generally grey or dark grey, strong in the fresh state and they may show a pronounced foliation (Plates 14 and 15). Graphitic siltstone, usually strongly foliated, is also known to occur at certain horizons.

2.2.6 Marble Unit

The marble unit belongs to the Carboniferous Yuen Long Formation and occurs in the northern portion of the site near Yuen Long. Boreholes have revealed the occurrence of three major, visually recognizable, marble subunits : white marble, grey marble, and interbedded marble and siltstone, all belonging to the Ma Tin Member (Plates 2 to 8). The former two subunits were encountered in boreholes at Interchanges No. 3 and 4, and the interbedded variety was encountered mainly at Interchange No. 4 (Figure 1). Stratigraphically, the interbedded marble is underlain by the grey marble subunit, which is in turn underlain by the white marble subunit. The oldest marble, the Long Ping Member (Plate 9), was not encountered in any of the boreholes put down during the site investigation for the project.

The interbedded marble and metasiltstone subunit is characterised by the presence of white to grey, fine-grained marble beds with narrow to thickly-laminated, light greenish grey metamorphosed siltstone (Plates 4 and 7). The siltstones are typically crushed and sheared, with smooth, polished and slickensided shear planes. The weathering profile is generally deep in this subunit, and all the weathered rock grades may be present (see Section 3.3). Large cavities are generally absent in the interbedded subunit but minor solution features are present.

The grey or bluish grey marble (Plates 2 and 6) is typically strong and fine-grained, with moderately to widely-spaced joints when fresh, while in its weathered state it generally becomes medium dense to dense, slightly clayey and silty, fine to occasionally medium sand. The latter product, generally very thin, represents the insoluble portion of the original rock, which was probably an impure argillaceous limestone prior to metamorphism. The grey marble subunit at some of the bridge sites has been locally affected by granitic intrusions and contains granitic veins and silicified patches (Plates 2 and 3).

The white marble subunit (Plates 5 and 6), which is known to underlie the alluvial cover at the eastern end of Yuen Long, has only been encountered at the Bridge No. 14 site at Interchange No. 4 and the Bridge No. 13A site at Interchange No. 3 (Figure 1). The white marble is a fine to coarsely crystalline, moderately strong rock with very widely-spaced joints. No soil residue is formed over this subunit because of its pure composition, except where it has been affected by acidic or basic intrusions.

Marble adjacent to the major basic and acidic dykes is altered to a rock varying in composition from a dark grey skarn-like material to marble with chloritic veins (Plate 5) as a result of contact metamorphism and hydrothermal alteration (Tsui & Irfan, 1990). The intensity of alteration decreases away from the contact. No mineralogical study of the effects of contact metamorphism of the basic dykes in the Yuen Long area has been undertaken. It is this contact metamorphic zone which is differentially weathered in the otherwise fresh marble underlying some of the bridge sites, particularly at Interchange No. 3 (Plate 5). In some cases, this altered and weathered layer directly underlies the superficial layers, resulting in the formation of a weathering profile showing a transition from completely weathered to slightly weathered and fresh marble (Figure 4).

Some small lengths of zero or very low core recovery are shown in the borehole logs in the grey and white marble, particularly near the top surface of the bedrock. These are thought to be associated with small solution cavities, some of which appear to have been partly infilled with soft to firm, light brown, clayey silt with marble fragments of gravel size. Most of the infill material has not been recovered.

No major cavities or other solution effects around joints were identified in the drillholes. However, the presence of such features at greater depths or in a thicker sequence of the pure white marble subunit cannot be discounted.

3. GEOTECHNICAL CHARACTERIZATION OF FOUNDATION ROCKS

3.1 GEOMECHANICS CLASSIFICATION OF ROCK MASSES

For sound foundation design, the engineering properties of the soil or rock masses must be known in order to determine the behaviour of the ground under the imposed load. The important engineering properties of the rock mass are deformability and strength, and these depend on :

(a) the properties of intact material,

(b) the discontinuity pattern and its characteristics, and

(c) the characteristics of the weathering profile.

The intact rock properties can be determined by laboratory tests. Measurement of rock mass properties by insitu testing is generally very expensive, and because of variations in geological conditions, can only provide data for a specific locality or a site. By classifying the rock mass into a number of broad classes or groups, each of which can be expected to show reasonably distinctive engineering behaviour, the limited field test data and experience gained at one site can be applied to other sites with similar characteristics.

A number of geotechnical rock classification systems have been devised. These take into account such factors as structure, discontinuities, details of the weathering profile, groundwater conditions and the material properties. Some of the best known systems have been developed for underground excavations (e.g. Bieniawski, 1976; Barton et al, 1974), where various rock material and mass characteristics have been given numerical weightings to arrive at a number of geomechanical classes. The classifications are then used to predict the rock mass deformation moduli (Bieniawski, 1978) or stand-up times in tunnels (Bieniawski, 1976; Barton et al, 1974). The assessment of weathering has become an important aspect of rock mass classification for engineering purposes in Hong Kong, where the rocks are deeply weathered.

In this investigation, a simplified engineering classification scheme based on lithological characteristics and mass weathering zones (Section 3.2) has been used to delineate the foundation layers. Laboratory testing has been carried out to determine the intact material properties of various rock types, particularly those of the marble subunits and the tuff breccia. The rock mass characteristics, together with intact rock properties, have then been used to assess the rock mass engineering properties of the various foundation units (Chapter 8).

3.2 WEATHERING/ALTERATION MASS AND MATERIAL CLASSIFICATION

A unified mass classification scheme broadly based on BS 5930 (BSI, 1981) has been used to characterize the weathering and alteration state of all the foundation rocks (Table 3). The application of this scheme, with modifications as explained below, to various igneous, volcanic and sedimentary rock sequences is decribed in several GCO unpublished reports and technical publications (e.g. Powell & Irfan, 1987 for volcanic and volcano-sedimentary rocks; Irfan & Powell, 1985 and Choy et al, 1987 for granites; Irfan, 1988 for metamorphic rocks). A brief discussion of weathering processes and the applicability of the scheme to carbonate rocks in general, and to the marble unit in Yuen Long in particular, is given in the next section.

The moderately weathered/altered rock mass zone has been separated into two sub-zones at about 10% soil content, based on Irfan & Powell (1985). For foundation purposes, a moderately weathered/altered rock mass in strong rock with less than 10% soil is considered to be a favourable foundation layer for end-bearing piles because of its high bearing capacity and low settlement properties, except for marble and other carbonate rocks affected by dissolution. In the latter case, the bearing capacity and settlement characteristics will depend on the size and distribution of dissolution features and the discontinuity pattern. The foundation problems associated with solution and discontinuity effects in soluble carbonate rocks have been discussed in detail by Sowers (1976a, 1984) and summarized by Dearman (1981).

For description of the weathering (including solution) and alteration state of the rock material, a uniform scheme has been used for all the rocks (Table 4). Based on visual recognition of weathering and alteration effects, three broad material classes have been identified :

(a) Fresh Rock (Grade 1)

(b) Decomposed/Disintegrated Rock (Grades 2, 3 and 4)

(c) Soil (Grades 5 and 6)

Solution has been included in the broader term of "Decomposition", as have the effects of alteration (e.g. hydrothermal alteration). It is usually difficult to visually distinguish the effects of hydrothermal processes from weathering effects in hand specimens, particularly in rocks where more recent weathering effects are superimposed on generally much older alteration effects. The suffix (A) in brackets can be used at the end of the decomposition term if such effects are clearly recognised, e.g. Slightly Decomposed (A) Granite.

The Decomposed/Disintegrated Rock material class has been subdivided into three grades :

(a) Slightly (Grade 2).

Material which is partially discoloured, with slight decomposition/disintegration of mineral constituents. Further sub-division has been made, where necessary, as follows :

(i) Rock with less than 50% discoloration (Grade 2i),

(ii) Rock with more than 50% discoloration (Grade 2ii),

based on the amount of staining of the rock material.

(b) Moderately (Grade 3).

Material which is completely discoloured, with one or more mineral constituents showing some degree of chemical alteration or a moderate degree of microfracturing, or both.

(c) Highly (Grade 4).

Material which is completely discoloured, with one or more mineral constituents showing a high degree of chemical alteration to gritty aggregates or a high degree of microfracturing, or both.

The Soil class has been subdivided into two grades :

(a) Completely Decomposed/Disintegrated (Grade 5).

Material which still retains the parent rock fabric as a result of weathering or alteration, but which behaves like a soil in terms of consistency and strength.

(b) Residual Soil (Grade 6).

Material which has lost all or most of the parent fabric.

The terms "Fresh" to "Residual Soil" used to describe the weathering grades in Table 4 broadly correspond to the decomposition grade scheme for rock material used in Geoguide 3 (GCO, 1988), which has been drawn up mainly with reference to granitic and volcanic rocks.

In pure carbonate rocks and evaporites, the intermediate grades between Fresh Rock and Residual Soil do not usually occur or are difficult to distinguish by simple visual means unless tested in the laboratory, e.g. increase in porosity due to solution of individual mineral grains or groups of grains or cementing material.

3.3 WEATHERING PROFILE IN CARBONATE ROCKS

A typical weathering profile developed in carbonate rocks is given in Figure 5. The characteristics of the weathering profile depend upon the impurities present in the rock as well as the discontinuity pattern, the structural features and environmental factors such as rainfall and temperature. The predominant weathering process is solution. In rocks composed of calcium carbonate ($CaCO_3$) with little or no impurities, there may be no intermediate grades between Fresh Rock and Soil, and Fresh Rock may be overlain by a very thin structureless soil ("Residual Soil") representing the insoluble residue of the original rock. The rock may contain solution cavities, partly or wholly infilled, particularly along discontinuities. Usually the surface of the rock is very irregular, with pinnacles and troughs of a metre to hundreds of metres across. Some very cherty or clayey carbonate rocks may develop a residual cover more than 30 m thick. In some cases, particularly in very impure carbonate rocks, a thick transition zone between Fresh Rock and Residual Soil may form which may be very variable laterally. Moneymaker (1968) reported a transition zone over 65 m thick beneath some dams in Kentucky, U.S.A. A true saprolitic soil which retains structural features of the rock may also develop as part of the transition zone (Deere & Patton, 1971).

The components of the weathering profile can hence be classified in terms of percentages of fresh rock, decomposed rock and soil (or void) as has been done for other rocks (Table 3). In impure carbonate rocks all the rock mass zones may be present, whereas in pure carbonate rocks a thin layer of Residual Soil is usually underlain by Fresh Rock (Figure 5).

In the project area, the white and grey marble subunits of the Yuen Long Formation are generally pure and only a thin (or missing) Residual Soil layer is present, usually underlain by Fresh Rock without any transition zones. In some cases, small cavities, partially or wholly filled, are present below a very irregular karstic surface. All the zones were seen to be present where the marble has been altered by intrusions (Figure 4). In the interbedded marble and metasiltstone subunit underlying some of the bridge sites, a gradual transition from a structureless sandy silt (Residual Soil) to Fresh Rock occurs (Table 3, Plate 7).

4. LABORATORY TESTING OF INTACT ROCK

4.1 TESTING METHODS

The laboratory testing programme primarily involved determination of strength and deformation properties of intact rock specimens, together with some selected index properties. Uniaxial compressive strength and deformation properties (Young's and Secant Moduli, and Poisson's ratio) were determined on oven-dried rock cores at the Rock Mechanics Laboratory of the University of Hong Kong in accordance with the specifications contained in ASTM Standard D3148-80 (ASTM, 1985). The cores were cut to a length/diameter ratio of 2 to 3 and the ends were machine-lapped. Physical index properties for each specimen, namely saturation moisture content, saturated and dry density and porosity, were determined in accordance with ISRM (1978). The core specimens tested and their locations are shown in Plates 2 to 13.

Point load testing of both core and irregular lump specimens was carried out in accordance with ISRM (1985). For cores which were tested in uniaxial compression, immediately adjacent core pieces of the same grade were subjected to point load tests in order to obtain a direct correlation between uniaxial compressive strength and point load strength for different rock types. Point load testing was also undertaken at selected locations on weaker, weathered specimens where uniaxial strength testing was not practical.

4.2 ROCK TYPES TESTED

The laboratory programme was limited by the financial and time constraints of the project. Strength testing was mainly concentrated on two of the three major rock units present in the project area, namely the tuff breccia unit of the Tuen Mun Formation underlying almost all the bridge sites at Interchange No. 1, near Tuen Mun, and the marble unit of the Yuen Long Formation underlying the bridge sites at Interchanges No. 3 and 4 (Figure 1). No laboratory testing was carried out for the metasedimentary rocks of the Mai Po Formation which are found under the bridge sites at Interchange No. 4, west of Yuen Long. This was because no cores of suitable length devoid of fractures were available, and because the rocks were found to be completely weathered in areas where they overlie the marble subunits. One specimen selected for testing was fractured during sample preparation.

Only two specimens of the basic dyke unit were tested since this rock type is only significant in the foundations of two proposed bridges. In addition, these rocks are very fractured, even in the fresh state; hence the strength of this unit was determined by point load testing of irregular samples and core specimens of short length. This was also the case with the metasedimentary rocks and the more intensely weathered specimens.

5. ENGINEERING PROPERTIES OF INTACT ROCK

5.1 UNIAXIAL COMPRESSIVE STRENGTH (UCS)

5.1.1 Tuff Breccia

The results of uniaxial compressive strength tests on tuff breccia specimens are tabulated in Table 5 and the ranges of values for each weathering grade are shown in Table 6. A few of the specimens failed prematurely along pre-existing fractures and veins. These are marked with an asterisk in the table and are not used in the following assessment.

Fresh rock was not present in the boreholes drilled to depths between 40 m and 100 m and hence was not tested. The freshest tuff breccia specimens tested were from the slightly discoloured rock grade (2i) and these showed strengths of UCS = 150 to 300 MPa (i.e. very strong to extremely strong). The variation in strength reflects the variation in lithology, with the specimens from the fine tuff bands (without any marble clasts) being generally stronger than the marble clast-bearing tuff. The highest strength in this investigation was however obtained on the latter variety of almost fresh rock (Table 5). There is a gradual decrease in strength values with increased decomposition in the early stages of weathering. However, the UCS is drastically reduced from about 150 MPa to 50 MPa or lower once solution of marble clasts, and possibly $CaCO_3$ bonding, results in a rock with a honeycombed texture (Plates 10 to 12).

The pure tuff bands do not show honeycombed texture and, in general, show only a gradual decrease in strength with increased weathering. However, no test results are available for more intensely-weathered tuffs from this investigation.

No uniaxial compressive strength testing was carried out on the sandstone and siltstone members of the Tuen Mun Formation as these rocks are too intensely weathered within the depths drilled to be suitable for this test.

5.1.2 Marble

The results of uniaxial compressive strength tests on marble specimens from the various subunits are tabulated in Table 7 and the ranges of values for each rock type and weathering grade are given in Table 8.

Variations in strength occur even within the same marble subunit due to variations in texture (including porosity), grain size and proportion of impurities present in the rock. Both grey and white marble are strong to very strong rocks in the fresh state, with UCS = 65 to 138 MPa and 86 to 122 MPa respectively. Recently, Yiu & Tang (1990) reported a UCS range of 40 to 136 MPa (except for one test result of 20 MPa) from limited tests on grey to white marbles of the Ma Tin Member found in the Tin Shui Wai area. Marble of more weathered grades (reflected by increase in porosity) do not usually occur in these two subunits unless affected by granite or basic dyke intrusions. For example, grey marble containing thin granite veins gave UCS = 72 to 122 MPa and 47 to 70 MPa in the case of partially discoloured (and possibly slightly dissolved) and completely discoloured specimens respectively (Table 8). The strength is significantly higher in silicified marble specimens, where UCS values of 121 to 188 MPa were obtained on fresh grey marble specimens which appeared to have been affected by a granitic intrusion nearby.

No fresh specimens of impure marble (termed "banded impure marble") interbedded with metasiltstone were available for testing. Specimens showing slight effects of solution (in the form of increased porosity and discoloration) gave UCS of 39 to 66 MPa (i.e. moderately strong rock).

5.2 STRESS-STRAIN BEHAVIOUR AND ELASTIC PROPERTIES

5.2.1 Tuff Breccia

The results of the uniaxial stress-strain tests for tuff breccia specimens are given in Tables 5 and 6 in terms of tangent Young's modulus, E_t, (at 50% of ultimate stress), secant modulus, E_s, (at 0 to 50% of ultimate stress), and Poisson's ratio.

The two freshest tuff breccia specimens showed very high elastic modulus values of E_t = 137 and 128 GPa. In general, pure tuff specimens gave lower modulus values, E_t = 50 to 75 GPa, compared to the specimens containing marble clasts, E_t = 62 to 137 GPa. The stress-strain curves show differences in behaviour (Figure 6). The marble clast-bearing specimens generally show curvilinear and concave-upward initial portions (the type IV behaviour of Deere & Miller, 1966, see also Hendron, 1968) indicating inelastic behaviour, while those of pure tuff specimens show steep straight line behaviour (type I behaviour). The typical stress-strain curves of Deere & Miller for various rocks in uniaxial compression to failure are given in Figure 10.

Tangent modulus values of E_t = 55 to 80 GPa were obtained for the highly discoloured (grade 2ii) tuff breccia specimens. The variation in E_t values with increased weathering, at least in the initial stages, is masked by that due to textural and compositional variation in the tuff breccia unit. The value drops to E_t = 17 to 37 GPa once the rock is completely discoloured and small voids are formed as a result of solution of marble inclusions in the rock (i.e. honeycombed texture). The secant modulus value correspondingly decreases with increased weathering. A relationship $E_t = 1.14\ E_s$ exists between the two moduli (Figure 7).

No systematic variation is apparent in the values of Poisson's ratio, both in terms of rock type and weathering grade, with slightly discoloured (grade 2i) and highly discoloured (grade 2ii) specimens having ν = 0.18 to 0.54 and ν = 0.22 to 0.45 respectively (Table 5). Slightly lower values of ν = 0.11 to 0.38 were obtained for the specimens showing honeycombed texture.

5.2.2 Marble

The results of the uniaxial stress-strain tests for marble specimens are given in Table 7 and are summarised in Table 8.

The purer white marble subunit shows a narrow band of tangent modulus values within the range of E_t = 65 to 83 GPa, with most test values falling around 66 GPa. The corresponding secant modulus values at 0 to 50%

ultimate stress level are E_s = 55 to 86 GPa. The grey marble specimens show a wider scatter of moduli values of E_t = 43 to 93 GPa and E_s = 30 to 83 GPa, reflecting the greater natural variation in texture and composition of this rock. The grey marble specimens affected by granitic intrusions gave values as high as E_t = 111 GPa in the case of slightly decomposed marble with granitic veins, and as low as E_t = 33 GPa in the case of silicified marble (Table 8). The impure banded marble specimens gave generally lower moduli values of E_t = 34 to 53 GPa and E_s = 22 to 56 GPa.

The Poisson's ratios vary between ν = 0.23 and 0.49 for the grey, white and banded marble varieties. No discernible differences were observed between these types except for the grey marble affected by intrusions, where lower values of ν = 0.16 to 0.28 were obtained, for example, on silicified marble specimens. The mean Poisson's ratio values are, respectively, 0.37, 0.30 and 0.31 for the fresh grey, white and banded marble subunits.

Some clear differences in stress-strain behaviour of the various marble types were observed in the specimens tested. While the grey marble generally displayed the type IV-V behaviour (i.e. plastic-elastic- plastic) the white marble showed type I behaviour (with a straight line in the initial stages of compression) in the case of strong specimens to type IV behaviour in the case of less strong specimens (Figure 8). The behaviour displayed by the impure banded marble is of type V (plastic-elastic-plastic), which is typical of schistose rocks, whereas the silicified marble and the marble with granitic veins showed straight lines typical of strong igneous rocks, limestones, etc. (Figure 9).

5.3 POINT LOAD STRENGTH (PLS)

5.3.1 Classification of Rocks in Terms of Point Load Strength

Extensive point load testing was carried out on a wide spectrum of materials from various weathering grades, including very weak rocks of all the major rock units present in the project area. The mean results of the point load tests carried out on the specimens adjacent to core sections tested in uniaxial compression are presented in Tables 5 and 7 for the tuff breccia and marble units respectively, and the ranges of values for each rock type and weathering grade are given in Tables 6 and 8. Figures 11 to 13 show the mean point load strength values obtained on all specimens including those prepared from the remainder of the UCS samples for the tuff breccia and various marble types. The mean results on specimens from the metasandstones and metasiltstones of the Lok Ma Chau Formation and basic dykes are presented in Figures 13 and 14 respectively. Table 9 gives a classification of the rock units in terms of point load strength and weathering grade of material.

5.3.2 Tuff Breccia

The grade 1-2i tuff breccia is a very strong rock with PLS $\geqslant$ 7 MPa. The fresher varieties and pure tuff bands have strengths up to 14 MPa (Tables 5 and 6). The strength is reduced with increased discoloration as a result of slight chemical alteration of tuff components (i.e. feldspars and biotite), and possibly slight solution of marble clasts. The highly discoloured tuff breccia specimens (grade 2ii) have strengths in the range of PLS = 4.5 to 11 MPa (Figure 11). The strength is drastically reduced when the rock is moderately decomposed (i.e. grade 3) and large pores are formed as a result of solution of marble clasts. The test is insufficiently sensitive to accurately determine the strengths of weaker material because of its honeycombed texture.

No testing was carried out on the tuffaceous sandstone and siltstone member of this unit, as the weathering profile is very deep and no suitable rock specimens were available for testing.

5.3.3 Marble

The point load strengths of the fresh white and grey marble subunits vary between PLS = 2.8 and 5.4 MPa (Figure 12, Table 8). The grey marble which has been affected by granitic intrusion and/or containing siliceous patches shows a wider range of weathering than the more pure variety, with the fresh rock having PLS $\geqslant$ 6.5 MPa. The strength gradually drops to about 3.0 MPa with increased discoloration and solution. More weathered material (i.e. grades 3 to 5), although present in the boreholes, was not tested.

The point load strength results are given separately for the interbedded impure marble and metasiltstones of the uppermost subunit of the Yuen Long Formation (Figure 13). Only one test result exists for the fresh marble from this subunit since fresh rock was not encountered within the depths reached by the boreholes sunk in the project area. The impure marble showing slight effects of decomposition (solution) has PLS = 1.5 to 4.0 MPa. The strength reduces gradually with increasing solution of $CaCO_3$ and disintegration before the rock is left as a sandy silty residue. The metasiltstones are slightly stronger, but highly fractured, with PLS = 2.0 to 5.5 MPa (Figure 13).

5.3.4 Metasiltstones and Metasandstones

The point load strength testing was limited to the moderately and highly decomposed/disintegrated rock specimens of metasiltstone and metasandstone from the Mai Po Formation . Fresh and slightly decomposed/disintegrated rock was not reached in any of the initial boreholes completed until the start of the testing programme. The strongest rock tested gave PLS = 3.4 MPa for a test carried out perpendicular to the foliation direction (Figure 13). The fresh metamorphic rock is expected to be very strong, with PLS $\geqslant$ 6 MPa. These rocks generally have a strong foliation and the PLS values are likely to be smaller for tests carried out in directions other than perpendicular to the foliation planes.

5.3.5 Basic Dykes

Limited point load testing was undertaken on specimens selected from the thick basic dykes, particularly those present in the foundations of Bridge Nos 13 and 13A. The freshest rock specimen tested showed slight effects of weathering in the form of slight discoloration, with PLS =9.0 MPa (Figure 14). The strength is reduced significantly from about 5 MPa to 0.4 MPa once the rock is completely discoloured. Some specimens which initially appeared to be fresh were observed to be affected by weathering and alteration when examined in detail after testing.

5.4 PHYSICAL INDEX PROPERTIES

5.4.1 Tuff Breccia

In the slightly discoloured and fresh states, the tuff breccia is a very dense rock having a very small saturation moisture content, i_s, of $\leqslant 0.2\%$, and a related effective porosity, n_{eff}, of $\leqslant 0.8\%$ (Tables 5 and 6). With increasing discoloration, these values increase to 0.4% and 1.0% respectively. Once the rock is completely discoloured, i.e. moderately decomposed, the values increase significantly, with i_s increasing to 5% or more and n_{eff} to 12% or more, particularly in the marble-bearing breccia member.

The variation in density with weathering is not clear at the early stages, with the highly discoloured specimens having generally a higher density than the slightly discoloured specimens. This discrepancy may be due to the limited testing carried out on the tuff breccia unit, which has a very variable composition. The slightly to highly discoloured tuff specimens gave generally lower dry density values (d_d = 2.70 to 2.82 Mg/m^3) than those of the marble-clast bearing specimens (d_d = 2.62 to 3.03 Mg/m^3). Once the rock is completely discoloured or affected by solution or both, the density drops significantly to d_d = 2.25 Mg/m^3 or lower.

5.4.2 Marble

Fresh grey and white marble have similar saturation moisture contents ($i_s \leqslant 0.2\%$), density (d_d = 2.70 to 2.85 Mg/m^3) and effective porosity ($n_{eff} < 0.5\%$). The freshest impure banded marble specimens tested gave slightly higher saturation moisture contents (up to 0.5%) and relatively high effective porosity (up to 1.4%) but similar density values (Tables 7 and 8). The dry density of the grey marble affected by granitic intrusion is higher than the pure marble (d_d = 3.07 to 3.23 Mg/m^3), contrary to the expected values based on mineralogical composition of these two rocks, i.e. the specific gravity of quartz is 2.65 whereas that of calcite is 2.72. Some heavy minerals (e.g. iron-oxides) may have been introduced into the marble by the granite intrusion. Higher saturation moisture contents and effective porosities were found in the marble specimens affected by intrusion (i.e. i_s = 1.5% and n_{eff} = 4.0%).

5.5 RELATIONSHIPS BETWEEN INDEX PROPERTIES AND STRENGTH PROPERTIES

For prediction purposes, and also to assess graphically the effect of weathering on each property, selected index properties were plotted against the strength properties of the marble and tuff breccia units. Plots of uniaxial compressive strength and point load strength versus saturation moisture content, effective porosity and dry density are given in Figures 15 and 16 for the tuff breccia specimens and in Figures 17 and 18 for marble specimens.

No statistical analysis of the correlations between the various properties has been attempted because of the limited test data.

5.6 CORRELATION BETWEEN POINT LOAD STRENGTH AND UNIAXIAL COMPRESSIVE STRENGTH

Point load strength has been widely used to estimate uniaxial compressive strength of rocks in the field and laboratory (Broch & Franklin, 1972; Bieniawski, 1975; Irfan & Dearman, 1978). A figure of 24 first proposed by Broch & Franklin (1972) and recommended by IAEG (1981) appears to be the most appropriate correlation factor for strong and isotropic rocks. For weaker rocks (i.e. strength less than 50 MPa) it is considered essential to establish a site-specific correlation factor.

No correlation factors have been determined for marble or tuff breccia, either in Hong Kong or elsewhere. However, correlation factors have been determined on various types of limestones. For example, Hawkins & Olver (1984) determined a factor of 26.5 for oolitic limestone of Jurassic age from England, while Carter & Sneddon (1977) obtained 26 and 28.5 for Carboniferous limestones from core samples. Norbury (1984) quoted correlation values of 24 to 54 for crystalline limestones.

The best-fit relationships obtained in this study for the marble subunits are UCS = 24 PLS for all specimens and UCS = 25.5 PLS for specimens without granitic veins (Figure 19). The test results on marble specimens significantly affected by granitic intrusions have been excluded.

For the tuff breccia unit, a significant number of failures occurred through pre-existing cracks or weak veins. These have been excluded from the calculation of the correlation factor. The best-fit relationship obtained for the tuff breccia unit is UCS = 22.5 PLS (Figure 19).

5.7 GEOMECHANICAL CLASSIFICATION OF MARBLE AND TUFF BRECCIA IN TERMS OF INTACT STRENGTH AND ELASTIC MODULUS

Geomechanical classification of intact rock material is commonly based on uniaxial compressive strength and the modulus of elasticity (Deere & Miller, 1966, see also Deere, 1968). The values of the compressive strength and the modulus are plotted on a logarithmic scale to accommodate a wide range of values. Three modulus classes are delineated based on the ratio of the modulus to the uniaxial compressive strength (H - High Modulus Ratio, M - Average Modulus Ratio and L - Low Modulus Ratio) with the class boundaries at E_t : UCS = 500 : 1 and 200 : 1.

The uniaxial compressive strengths and tangent elastic moduli of marble specimens determined in this study are plotted on Deere & Miller's strength classification chart in Figure 20. The strength envelopes of marble (based on limited test results) and limestone-dolomite determined by Deere & Miller (1966), and dolomite-limestone-marble given by Dearman (1981), are also shown in this figure. The range of strength and moduli values for concrete commonly used in foundations are plotted on the graph for comparison, i.e. UCS = 17.5 to 35 MPa and E_t = 17 to 34 GPa. All the results, with the exception of two which plot above the 1000 : 1 line, fall between the 1000 : 1 and 500 : 1 lines, i.e. all marble subunits have High Modulus Ratios. The uniaxial compressive strength values show a wider scatter than that determined by Deere & Miller, falling generally between the Strong (S) and Very Strong (VS) classes depending on the presence of impurities, banding, grain size, and the effects of solution and granitic intrusion.

The test values for tuff breccia fall in the Average Modulus Ratio class, with those of the pure tuff specimens plotting in the lower half of the class, i.e. nearer to the 200 : 1 line (Figure 21). The weathering scale of the material is also shown in the figure. The strength values fall in the range of Extremely Strong (ES) for the freshest specimens to Moderately Strong (MS) and even lower in the more weathered specimens showing honeycombed solution features (Figure 21). As expected, the strengths cover a wide range of values due to variation in mineralogy, porosity, grain size, weathering state and other fabric features which may be present in the specimens. No comparative envelopes exist for similar rocks tested elsewhere.

6. ROCK MASS PROPERTIES

6.1 GENERAL

There are no rock outcrops in the project area which can be used to directly assess the mass properties of the foundation rocks. The following description of rock mass properties is based on borehole records.

The weathering profiles formed in various rocks in the project area are very variable. This reflects the wide variation in rock type (even within the same unit), the discontinuity pattern and other structural elements of the area. In addition, the effects of contact metamorphism, hydrothermal alteration and mineralization, as related to acidic and basic intrusions prior to weathering and post-dating general metamorphism of the rocks, have contributed further to the formation of complex weathering profiles. The rock mass conditions are locally very variable under each bridge site, and sometimes across each pier location.

6.2 WEATHERING PROFILES

6.2.1 Volcanic Rock Units

The tuff breccia and tuffs which underlie the southern part of the route, near Tuen Mun, are generally deeply weathered. The weathering profile is deepest in the upper tuffaceous sandstone-siltstone member. The thickness of the completely to highly weathered rock is generally between 20 and 40 m underneath an alluvium/fill cover 5 to 12 m thick (Figure 22). Thin layers of more resistant highly/moderately decomposed rock, generally of sandstone or tuff breccia beds, are present in the completely weathered rock. In the moderately weathered rock mass, marble-clast bearing bands/beds are differentially weathered to honeycomb-textured rock as a result of solution of marble clasts, whereas the pure tuff bands are more resistant to weathering (Plates 10 to 13). The tuffaceous sandstone/siltstone beds are more intensely weathered to a clayey sandy silt to silty sand. Therefore, the moderately weathered rock mass zone may be made up of layers of very strong tuff with intervening porous tuff breccia and/or clayey silt and sand, generally following bedding structures which appear to dip towards the northwest. This zone, which can be extremely variable in terms of rock and soil proportions and mass permeability, is up to 10 m thick before the slightly weathered tuff breccia is reached.

Honeycombed structure may not form if the tuff breccia contains a high percentage of marble fragments, as observed in the Tin Shui Wai area (Darigo, 1989). Collapse of the rock mass may occur at an early stage in weathering due to dissolution of a large number of marble clasts. Relatively large cavities, up to a few metres in diameter, may occur if the rock is made up of large fragments of marble.

6.2.2 Metasedimentary Rock Unit

Metasedimentary rocks of the Mai Po Member (phyllites, metasandstones and occasionally quartzites) commonly underlie the northern part of the project area (Interchange No. 4) but also occur, overlying marble, on both sides of the nullah at Interchange No. 3 (Figure 1). The weathering profile developed over these metamorphic rocks is very similar to those developed in metasedimentary rocks elsewhere in the Territory (e.g. as described by Greenway et al, 1987). A thick completely weathered zone, consisting generally of yellowish brown (in the case of metasandstone) to purplish grey (in the case of metasiltstone and phyllite) silty sand to clayey sandy silt, passes into a highly weathered rock consisting of either very weak rock with little soil along discontinuities or as intervening bands of very weak to weak rock and soil (Plates 14 and 15). The total thickness of the completely to highly weathered rock is generally 15 to 30 m, but can be up to 60 m (Figure 23). Horizontal to subvertical zones of less weathered material may occur depending on the bedding direction and other structural features. Moderately and less weathered rocks occur at depths of over 30 m in areas where there is a thick metasedimentary succession. In areas where pure marble of the Yuen Long Formation underlies the metasedimentary rocks at shallow depths, there may be a sharp transiton from completely weathered rock (clayey silts and sands) to almost fresh marble. Slightly weathered and fresh metasandstones are very strong rocks but may show a strong strength anisotropy due to the presence of a pronounced foliation (Plate 15).

6.2.3 Marble Unit

In general, a complete weathering profile is absent in the white and grey marble subunits, and a thin or absent residual soil layer is underlain by marble containing solution features and cavities near its top. Fresh marble with no effects of solution was not generally encountered in the boreholes drilled for this project (up to 100 m). However, in almost all of the bridge sites underlain by marble, this simple picture of the weathering profile is complicated by faulting, dyke intrusion and the related metamorphism, and by the presence of impure marble and metasiltstone beds (Figure 4).

In the interbedded marble and metasiltstone subunit, a more or less complete weathering profile is present (Plate 7). This is formed by both solution of pure marble beds, and solution and disintegration of calcareous siltstone and sandstone beds. The thicknesses of the original strata have presumably been reduced greatly and the mass structure disturbed as a result of solution of pure marble beds and subsequent collapse of the overlying siltstone beds. Adjacent to the major basic and acidic dykes, the marble has been affected by contact metamorphism and hydrothermal alteration to varying degrees. A range of weathering zones are present as a result of variable solution of calcite minerals and decomposition of non-calcite minerals (see, for example, Figure 4). In such instances, vertical to subvertical layers of completely decomposed material can occur at great depths (Plate 5), in contrast to marble which has not been affected by alteration.

6.3 DISCONTINUITIES (RQD AND FRACTURE INTENSITY)

Discontinuities, particularly those which are weathered open or infilled with relatively weak material, significantly increase the deformability of the rock mass. The discontinuity state of the rock mass can be assessed by Rock Quality Designation (RQD) values determined on cores, but it should be noted that RQD does not take into account the discontinuity roughness, opening, continuity or condition, or the presence and nature of any infilling material (Irfan & Powell, 1985). However, RQD is useful in classifying rock masses for the selection of tunnel support systems and for foundations when used with other parameters (e.g. strength of intact rock, weathering state, etc.). Fracture intensity (number of fractures per metre) is preferred to RQD, particularly in weathered rocks, because of inherent errors in determining the latter.

For the present investigation, the RQD values given on the contractor's logs have been plotted against the fracture intensity for various rock units and weathering zones (Figures 24 and 25). RQD values have been standardized to about 1.5 m core lengths, where necessary, to be compatible with the normal practice of determining RQD for use in foundation design. No fracture intensities were determined by the contractor where the rock was very fractured. These were determined by GCO staff, either by counting the pieces or by measuring the average size of core pieces from the good-quality photographs provided. A classification of various foundation units in terms of RQD and fracture intensity, based on the borehole records and Figures 24 and 25, is given in Table 10.

In general, the grey and white marble subunits in the fresh state have widely- to very widely-spaced discontinuities (i.e. 0.6 to 6 m). The discontinuity spacing in the interbedded marble and metasiltstone subunit depends on the thickness of the siltstone layers, which are generally very closely-spaced (i.e. 0.06 to 0.2 m). Pure marble layers in this subunit have widely-spaced discontinuities. The tuffs and tuff breccia of the Tuen Mun Formation in the fresh to slightly weathered state have moderately- to widely-spaced discontinuities, with tuffaceous siltstone and sandstone units having more closely-spaced bedding planes, foliation and joints. The metasedimentary rocks of the Mai Po Member are generally closely-bedded or foliated with discontinuity spacings of less than 0.2 m, except in unfoliated metasandstones where these may be up to 0.6 m or larger. In thick basic dyke intrusions, the discontinuities are generally moderately-spaced (i.e. 0.2 to 0.6 m) in the fresh to slightly weathered state. In rocks affected by faulting and dyke intrusion, the discontinuity spacing is closer and the rocks are more intensely weathered or altered. The discontinuity dip and dip directions, particularly bedding and foliation planes, can vary widely as a result of faulting and folding. The general structural features of the project site have already been described in Chapter 2.

7. PRELIMINARY ASSESSMENT OF BEARING CAPACITY OF FOUNDATION ROCKS

7.1 GENERAL

As part of the GCO involvement in the Yuen Long - Tuen Mun Eastern Corridor project, the site investigation results and an outline of methods for preliminary assessment of bearing capacity for large-diameter bored piles and hand-dug caisson piles were compiled in an internal report. The approach adopted for bearing capacity assessment is summarised in this Chapter. It should be emphasised that this is not intended to be a state of the art review of the subject nor is it a guide to standards of practice.

Allowable bearing pressures for the design of deep foundations on rock can be selected on the basis of one or more of the following :

(a) building codes,

(b) empirical rules,

(c) rational methods based on bearing capacity and settlement analysis, and

(d) field load tests.

Building codes are traditionally conservative. Theoretical considerations and field test results suggest that the ultimate bearing capacity of a rock mass is unlikely to be reduced much below the uniaxial compressive strength of the intact rock material even if open vertical discontinuities are present (Poulos & Davis, 1980). The presence of large voids below the foundation would of course be an exception to this general rule.

The allowable bearing pressure depends on the compressibility and strength of the rock mass and the permissible settlement of the structure. Both the compressibility and the strength of the rock mass are related to the strength of the intact rock, the lithology, the frequency, nature and orientation of the discontinuities, and the weathering and alteration state. The compressibility of the intact rock is dependent on the degree of decomposition and disintegration.

The compressibility and strength of rock masses are difficult to quantify and even large scale test results on individual piles may not be representative of the bearing characteristics of the foundation as a whole.

7.2 ALLOWABLE BEARING PRESSURES FOR DEEP FOUNDATIONS IN THE PROJECT AREA

7.2.1 Code Values

The "presumed bearing values", i.e. the presumptive allowable bearing pressures specified by various building codes and authorities are invariably very conservative. They also differ in their recommendations for the same rock. Many design codes relate the presumed bearing values to a geological rock classification (e.g. BSI, 1986), while others base them on a proportion of the unconfined compressive strength of the intact rock, generally 0.2 x UCS.

Table 11 gives a comparison of presumptive allowable bearing stresses for various rock types including partially weathered and intensely fractured rocks. The broad foundation rock groupings in Table 11 have been assigned approximate mass weathering and discontinuity classes in accordance with the terms used elsewhere in this document. No specific values are given for marble, nor for the volcanic rocks common in Hong Kong. With reference to the rock types present in the project area in particular, and the Yuen Long area in general, in the fresh or slightly weathered state, the metasedimentary rocks of the Lok Ma Chau Formation and the interbedded marble and metasiltstones of the Yuen Long Formation would be included under the "foliated metamorphic rock" category in Table 11. The grey and white marble subunits would be included in either the metamorphic group or the sedimentary group, being similar to many limestones of medium strength. The tuff breccia unit could be placed in any of the first three groups, depending on whether it is composed of pure tuff, marble clast-bearing tuff or interbedded tuff and sandstone/siltstone. Moderately weathered rocks could be classified as the fourth category in Table 11, i.e. "badly fractured, or broken, or partially weathered rocks", and the highly weathered rocks would come under the fifth category where no stress values are specified.

7.2.2 RQD Method

Table 12 presents values of allowable contact pressure for jointed rocks on the basis of their RQD (Peck et al, 1974). The values refer to average RQD within a depth below the foundation level equal to the width of the foundation, provided that the RQD is fairly uniform. Peck et al (1974) state that the values are based on settlement criteria, with settlement not exceeding 12.5 mm.

The ranges of RQD values and the fracture intensities are given in Table 10 for each weathering grade in each rock type. These values can be used to calculate the allowable bearing stress for each foundation unit for preliminary design purposes. However, as discussed in Section 6.3, there are drawbacks to using RQD to assess rock quality, particularly for closely-jointed or bedded rocks and for rocks containing thick compressible discontinuity fillings and voids.

7.2.3 Canadian Foundation Engineering Method

Allowable bearing pressure for "sound rock" foundations can be calculated by using the following formula, as given in the Canadian Foundation Engineering Manual (Canadian Geotechnical Society, 1985) :

$$q_a = K_{sp}\, q_u\, d \qquad (1)$$

where q_a = allowable bearing pressure on the rock,

q_u = average uniaxial compressive strength (UCS) of rock core,

K_{sp} = 0. 1 to 0.4, an empirical coefficient depending on the joint spacing and including a factor of safety of 3,

d = depth factor, given by :

$$d = 1 + 0.4 \frac{L_s}{b_s} \leqslant 3.4 \quad \ldots\ldots\ldots\ldots \quad (2)$$

where L_s = depth (length) of the rock socket,

b_s = diameter of the rock socket.

Ranges of uniaxial compressive strength that can be used for the computation of q_a are given in Tables 6 and 8 for the rocks in the project area. K_{sp} can also be calculated from the following formula :

$$K_{sp} = \frac{3 + c/B}{10\sqrt{1 + 300\delta/c}} \quad \ldots\ldots\ldots\ldots \quad (3)$$

where c = discontinuity spacing,

δ = thickness of infilling of discontinuity,

B = foundation width.

The mean discontinuity spacings for each foundation unit are given in Table 10 and the properties of the discontinuities are discussed in Section 6.3. The Canadian Foundation Engineering Manual (Canadian Geotechnical Society, 1985) states that the above relationship is valid for thicknesses of discontinuity less than 25 mm, if filled with soil or rock debris. While the formula may be valid for fresh to moderately weathered meta-sedimentary, igneous and volcanic rocks, and marble with no solution features, it will not be applicable to the white and grey marble subunits containing voids, nor to the highly and completely weathered rocks.

7.2.4 Settlement Calculations : Rock Mass Factors and Rock Mass Deformation Moduli

The settlement of a rigid foundation or average settlement, S, of a flexible foundation at the surface of a rock mass modelled as an homogeneous elastic half-space can be calculated by the following formula :

$$S = \frac{q_a B(1 - \nu^2)}{E_m} I \quad \ldots\ldots\ldots\ldots \quad (4)$$

where q_a = average bearing pressure on the rock,

B = width or diameter of the foundation,

ν = Poisson's ratio of the rock mass,

E_m = deformation modulus of the rock mass,

I = influence value, which is dependent upon the shape of the foundation (see, for example, BSI, 1986).

Solutions also exist for piles embedded in an elastic medium (e.g. Poulos & Davis, 1980).

The following approach can be used as a simple means of determining approximate values of the rock mass modulus.

The rock mass deformation modulus, E_m, can be calculated by :

$$E_m = j\ E_i \quad \ldots\ldots\ldots \quad (5)$$

where E_i is the Young's modulus of the intact rock and j is the Rock Mass Factor (Hobbs, 1975). The latter reflects the effects of discontinuities on the expected performance of the intact rock. The Rock Mass Factor can be assessed for each structural or lithological unit from the discontinuity spacing or RQD (Table 13). If elastic properties of the intact rock have not been determined, E_i can be calculated by :

$$E_i = Mr\ q_c \quad \ldots\ldots\ldots \quad (6)$$

where Mr is the modulus ratio of intact rock (Deere & Miller, 1966) and q_c is the uniaxial compressive strength of intact rock.

Table 13 gives a rock mass quality classification based on approximate relationships between RQD, discontinuity spacing and rock mass factors. For practical purposes, BS 8004 (BSI, 1986) suggests that the value for j can be approximated by the average discontinuity spacing in metres, if the discontinuities are reasonably tight.

Alternatively, the rock mass deformation modulus can be assessed from the rock mass class. For example, Bieniawski (1978) proposed the following formula:

$$E_m = 1.76\ RMR - 84.3 \quad \ldots\ldots\ldots \quad (7)$$

where E_m is the insitu static modulus of deformation in GPa and RMR is the Rock Mass Rating in accordance with the geomechanics classification of Bieniawski (1978). This formula is not applicable to rock masses of relatively low quality (i.e. with RMR values $\leqslant 48$).

For preliminary settlement analysis, mean rock mass factors that can be used to determine rock mass moduli are given in Table 10 for each main lithological unit. The deformation moduli, Poisson's ratios and uniaxial compressive strengths of intact rock material are given in Tables 5 to 9 for each grade of material in each rock type (tuff breccia and marble units only).

8. GENERAL COMMENTS ON FOUNDATIONS WITH RESPECT TO THE MARBLE UNIT

Foundation conditions within the marble unit are very complex, particularly near the top of the succession, due to :

(a) the presence of a karstic surface with extremely variable rockhead levels (the legacy of weathering and erosion before the deposition of the superficial deposits),

(b) the weathering state of the rock mass, particularly with regard to voids and widened discontinuities formed by solution weathering in the pure marble subunits,

(c) the presence of alternating competent and incompetent beds or layers in the interbedded subunits formed as a result of differential weathering of marble, impure marble and metasiltstone members,

(d) the presence of folding and faulting, particularly the thrust faults bringing older strata above the younger strata, and

(e) the dyke intrusions and associated alteration (e.g. contact metamorphism, hydrothermal alteration and mineralization), with differentially weathered/altered, near-vertical to vertical zones extending to great depths in the marble and dyke rock.

The presence of voids and enlarged discontinuities, and the extremely variable karstic surface, are likely to be the major geotechnical constraints in the design of deep pile foundations on marble bedrock. The bedrock surface (defined as moderately weathered/altered rock mass or better) may vary very rapidly, particularly in the pure marble members, which contain individual pinnacles of rock up to many metres high. The rock surface underneath a residual soil or superficial soil cover may also be uneven at a small scale. The marble most susceptible to void formation is the pure white marble subunit. The voids generally occur near the karstic surface in this rock and range in height from 0.1 to 2 m in the boreholes drilled in the project area. Pascal (1987) and Langford et al (1989) reported void heights of 5 to 15 m, occasionally 25 m, under Yuen Long town itself. Most cavities appear to be confined to a level above -70 mPD (Langford et al, 1989). It is therefore very important to ensure that sufficient boreholes are drilled at all deep foundation sites in order to adequately investigate the variation in the bedrock profile and the presence of voids. Houghton & Wong (1990) state that cross-hole seismic surveys can be used to define the lateral continuity of dissolution features.

Chan & Hong (1985) reported the presence of a "weak compressible layer" with SPT 'N' values less than 5 just above the limestone bedrock in Malaysia. Sowers (1976b) also reported that the residual soil close to the contact with limestone is much softer and sometimes "pasty". The formation of this weak compressible clayey soil layer is attributed by Sowers to the downward percolation of water which then flows laterally across the rock surface. Such a layer was not detected from SPTs in this investigation, but there were no undisturbed drillhole samples available to check for its existence: thus its presence cannot be precluded in the project area (and in the Yuen Long area in general). Weak and compressible clayey soils may also occur inside cavities and close to dyke contacts in the altered marble. The possible presence of these compressible pockets may need to be taken into account in foundation design, since they could lead to large differential settlement of individual piles or pile groups.

Other problems to be considered in the design and construction of piled foundations in the Yuen Long area are similar to those described by Sowers (1976a) and briefly summarized by Dearman (1981). Some of these problems have been highlighted by Pascal (1987), McNicholl et al (1989) and Houghton & Wong (1990) in the Yuen Long and Tin Shui Wai areas. For driven piles, the common design and construction problems are likely to be pile buckling, pile deflection, tip damage and uncertain support, particularly for piles founded on a sloping "bedrock" surface (see, for example Houghton & Wong, 1990). Uncertain or discontinuous support due to the presence of compressible layers or voids, sudden loss of bentonite support (during boring) and dewatering are the likely major problems for cast-insitu piles. Another problem which often affects shallow foundations above marble bedrock is collapse or subsidence of the ground surface due to the upward migration of voids through the soil cover by erosion (Sowers, 1976b). This is aggravated by changes in the groundwater table due to seasonal variations or dewatering. Pascal (1987) reported formation of such collapse features during a pumping test carried out in Yuen Long. Sinkholes and collapses may also occur when the rock roof of a cavity eventually becomes incapable of supporting its own weight. Changes in pH of the groundwater, for example as a result of contamination, can also result in solution of marble.

The bearing capacity of unweathered marble rock masses with widely-spaced tight discontinuities is likely to be high and the compressibility low. Both the white and grey marble subunits are strong rocks with intact UCS values in excess of 60 MPa (Table 8), i.e. stronger than the concrete used for pile foundations. These rocks also have very high intact elastic modulus values of over 45 GPa. However, the impure marble, which is generally found interbedded with metasiltstone of varying thickness, can have values of UCS of less than 40 MPa and elastic modulus of less than 35 GPa in their more weathered states. Although the marble slightly affected by granitic intrusions can have a higher strength in the fresh state than the unaltered marble, the strength reduces drastically once the rock is affected by both decomposition and solution (Table 8). This type of rock was found locally in one or two boreholes. It appears that the marble adjacent to thick basic dykes has generally been altered to a mixture of weak rock and soil for some distance away from the dyke.

Fresh marble with a high bearing capacity is generally found only at a significant depth, over 30 m, in the Yuen Long area. In cases where end-bearing piles are chosen as the foundation type, the marble bedrock needs to be properly investigated, with particular emphasis on the possible presence of cavities near the bedrock surface. Design revisions or remedial works during construction may need to be considered, since the size and distribution of cavities cannot generally be economically determined by normal site investigation techniques. Probing below the founding level by coring is one means of ensuring that no opening or compressible filling of significant thickness exists below the pile. Alternatively, the defects can be treated by grouting or minipiling, or can be allowed for by building in a suitable degree of redundancy into a revised foundation design.

9. CONCLUSIONS

Foundation conditions in the area between Tuen Mun and Yuen Long are varied and locally very complex. This reflects the variable geology and alteration and weathering processes. Marble is present in the northern portion of the area near Yuen Long, underlying superficial deposits or intensely weathered metasedimentary rocks, whereas the southern portion of the area near Tuen Mun is dominantly underlain by a marble-clast bearing tuff breccia and other tuffaceous rocks. The marble locally contains cavities and generally has a very irregular karstic surface.

The complex foundation conditions have been characterized by a simplified geomechanical classification based on lithological characteristics, discontinuity properties and mass weathering/alteration classes, primarily as determined from borehole logs. A laboratory testing programme was carried out to determine the intact properties of the various rock types, particularly the marble and marble-clast bearing tuff breccia. These properties can be used as the basis for calculating the bearing capacity and settlement of foundations by various methods.

No material weathering grades between fresh rock and residual soil states are present in the pure marble (or at least are not recognisable in hand specimens). However, various weathered states of rock material can be present in the very impure marble members and those subunits affected by acidic and basic intrusions.

The pure marble subunits (the white and grey marble) are strong rocks in the fresh state with uniaxial compressive strengths in excess of 65 MPa and up to 140 MPa, and elastic modulus values of over 45 GPa and up to 95 GPa. The impure marble is generally weaker than the pure white and grey marble, with specimens showing slight affects of weathering having uniaxial strengths of 40 to 65 MPa. No fresh impure marble specimens were recovered in the boreholes. When the rock is affected by granitic intrusions, the strength is increased, up to a value of 190 MPa.

On the strength versus modulus chart, all the marble types plot in the High Modulus Ratio class. The stress-strain behaviour of the intact rock is variable, depending on the rock type, presence of impurities, foliation/bedding and other characteristics.

The relationships between the uniaxial compressive strength, UCS, and the point load strength, PLS, determined for the marble are UCS = 24 PLS for all specimens and UCS = 25.5 PLS for specimens not affected by intrusions (i.e. without granitic veins).

The tuff breccia is a very strong to extremely strong rock in the slightly decomposed to fresh state, with uniaxial strength in excess of 150 MPa and elastic modulus of over 50 GPa. The strength and moduli values vary according to the different lithologies. The pure tuff bands are stronger than those containing marble clasts. There is a gradual decrease of strength and moduli with decomposition in the early stages of weathering. The strength and moduli are drastically reduced in the tuff breccia once the solution of marble clasts produces a honeycombed texture.

The stress-strain behaviour of the tuff breccia is also affected by the lithology. The pure tuff specimens show elastic behaviour, whereas the marble-clast bearing specimens display a plastic-elastic-plastic behaviour. These rocks have Average Modulus Ratios. No comparative stress-strength envelopes exist for similar rocks elsewhere.

The relationship between the uniaxial compressive strength and the point load strength determined for the tuff breccia is UCS = 22.5 PLS.

The UCS/PLS correlation factors determined in this investigation for the marble and tuff breccia units are similar to the value of 24 recommended by many researchers for isotropic rocks.

No correlations have been attempted between the index and strength properties of the rocks because of limited test results. Except for point load strength, no strength and deformation properties were determined for the metasedimentary rocks and the dyke intrusions present in the project area, since no suitable cores were available for testing.

A preliminary assessment of the bearing capacity of the foundation rocks has been carried out and various material and mass parameters that can be used to calculate bearing capacity and settlement by a number of methods have been presented. These are summarised in Tables 5 to 10.

A number of problems to be considered in the design and construction of foundations on marble in the Yuen Long area have been outlined. For piles founded on marble bedrock, the irregular nature of the karstic surface and the possible presence of cavities are two important factors that deserve careful attention during detailed ground investigation. Consideration may need to be given to design revisions and remedial works during construction, since the size and distribution of cavities cannot generally be economically determined by normal investigation techniques.

REFERENCES

ASTM (1985). Standard test method for elastic moduli of intact rock core specimens in uniaxial compression. Test Designation D 3148-80. 1985 Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, vol. 04.08, pp 519-525.

Barton, N., Lien, R. & Lunde, J. (1974). Engineering classification of rock masses for the design of tunnel support. Rock Mechanics, vol. 6, pp 189-236.

Bieniawski, Z.T. (1975). The point load test in geotechnical practice. Engineering Geology, vol. 9, pp 1-11.

Bieniawski, Z.T. (1976). Rock mass classification in rock engineering. Proceedings of the Symposium on Exploration for Rock Engineering, Johannesburg, pp 97-106.

Bieniawski, Z.T. (1978). Determining rock mass deformability : experience from case histories. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, vol. 15, pp 237-247.

Broch, E. & Franklin, J.A. (1972). The point load strength test. International Journal of Rock Mechanics and Mining Sciences, vol. 9, pp 667-697.

BSI (1981). Code of Practice for Site Investigations, BS5930: 1981 (Formerly CP 2001). British Standards Institution, London, 147 p.

BSI (1986). British Standard Code of Practice for Foundations, BS 8004: 1986 (Formerly CP 2004). British Standards Institution, London, 149 p.

Canadian Geotechnical Society (1985). Canadian Foundation Engineering Manual. Second Edition. Canadian Geotechnical Society, Ottawa, 456 p.

Carter, P.G. & Sneddon, M. (1977). Comparison of Schmidt hammer, point load and unconfined compression tests in Carboniferous Strata. Proceedings of the Conference on Rock Engineering, Newcastle, U.K. pp 197-210.

Chan, S.F. & Hong, L.P. (1985). Pile foundations in limestone areas of Malaysia. Proceedings of the Eighth Southeast Asian Geotechnical Conference, Kuala Lumpur, pp 4.17-4.28.

Choy, H.H., Earle, Q.C., Irfan, T.Y. & Burnett, A.D. (1987). Studies for the extension of a major urban quarry in Hong Kong. Planning and Engineering Geology, (edited by M.G. Culshaw, F.G. Bell, J.C. Cripps & M. O'hara), Geological Society Engineering Geology Special Publication No. 4, London, pp 367-377.

Coon, R.F. & Merritt, A.H. (1970). Predicting insitu modulus of deformation using rock quality indexes. In Situ Testing in Rock, American Society for Testing and Materials, Special Technical Publication No. 477, pp 154-173.

Darigo, N.J. (1989). A volcanic breccia in the buried karst of Hong Kong. Proceedings of the Third Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Florida, pp 225-232.

Dearman, W.R. (1981). Engineering properties of carbonate rocks. (General Report). Proceedings of the Symposium on Engineering Geology Problems of Construction on Soluble Rocks, Istanbul. Published in Bulletin of the International Association of Engineering Geology, No. 24, pp 3-17.

Deere, D.U. (1968). Geological considerations. Rock Mechanics in Engineering Practice, (edited by K.G. Stagg & O.C. Zienkiewicz), John Wiley, New York, Chapter 1, pp 1-20.

Deere, D.U. & Miller, R.P. (1966). Engineering Classification and Index Properties for Intact Rock. Report AFWL-TR-65-116, Air Force Weapons Laboratory (WLDC), Kirtland Air Force Base, New Mexico, 273 p.

Deere, D.U., Merritt, A.H. & Coon, R.F. (1969). Engineering Classification of In Situ Rock. Report AFWL-67-144, Air Force Systems Command, Kirtland Air Base, New Mexico.

Deere, D.U. & Patton, F.D. (1971). Slope stability in residual soils. Proceedings of the Fourth Panamerican Conference on Soil Mechanics and Foundation Engineering, San Juan, Puerto Rico, American Society of Civil Engineers, pp 87-170.

Frost, D.V. (1989). Palaeokarst of Yuen Long, northwest New Territories, Hong Kong. Proceedings of the Third Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Florida, pp 239-246.

Frost, D.V. (1991). Geology of the Yuen Long Designated Area. Geotechnical Control Office, Hong Kong, (Hong Kong Geological Survey Memoir no. 7), (in press).

GCO (1988). Guide to Rock and Soil Descriptions (Geoguide 3). Geotechnical Control Office, Hong Kong, 189 p.

Greenway, D.R. , Powell, G.E. & Irfan, T.Y. (1987). A case history of slope design in complex weathered low grade metamorphic rock. Geotechnical Engineering, vol. 18, pp 145-166.

Hawkins, A.B. & Olver, J.A.G. (1984). Point load tests. Correlation factors and contractual use, an example from the Corallian at Weymouth. Site Investigation Practice : Assessing BS 5930, (edited by A.B. Hawkins), Geological Society, Engineering Geology Special Publication No. 2, 1986, London, pp 269-271.

Hendron, A.J. Jr. (1968) Mechanical properties of rock. Rock Mechanics in Engineering Practice, (edited by K.G. Stagg & O.C. Zienkiewicz). John Wiley, New York, Chapter 2, pp 21-53.

Hobbs, N.B. (1975). Factors affecting the prediction of settlement of structures on rock : with particular reference to the Chalk and Trias. (Review Paper). Proceedings of the Conference on Settlement of Structures. Pentech Press, London, pp 529-610.

Hong Kong Government (1985). Buildings Ordinance (and Building Regulations). Laws of Hong Kong, Chapter 123, revised edition 1985. Hong Kong Government Printer, 387 p. (Amended from time to time).

Houghton, D.A. & Wong, C.M. (1990). Implications of the karst marble at Yuen Long for foundation investigation and design. Hong Kong Engineer, vol. 18, no. 6, pp 19-27.

IAEG (1981). Rock and soil description for engineering geological mapping. Report by the IAEG Commission on Engineering Geological Mapping. Bulletin of the International Association of Engineering Geology, no. 24, pp 235-274.

Irfan, T.Y. & Dearman, W.R. (1978). Engineering classification and index properties of a weathered granite. Bulletin of the International Association of Engineering Geology, no. 17, pp 79-90.

Irfan, T.Y. & Powell, G.E. (1985). Engineering geological investigations for pile foundations on a deeply weathered granitic rock in Hong Kong. Bulletin of the International Association of Engineering Geology, no. 32, pp 67-80.

Irfan, T.Y. (1988). Rock Weatherability Tests on Metamorphic Rocks from Seung Ma Lei Yue. GCO Advisory Report, ADR 8/88, Geotechnical Control Office, Hong Kong, 40 p. plus plates (Unpublished).

ISRM (1978). Suggested methods for determining water content, porosity, density, absorption and related properties and swelling and slake-durability index properties. International Society for Rock Mechanics Committee on Laboratory Tests. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, vol. 16, no. 2, pp 141-156.

ISRM (1985). Suggested method for determining point load strength. International Society for Rock Mechanics Commission on Testing Methods. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, vol. 22, no. 2, pp 51-60.

Langford, R.L., Lai, K.W., Arthurton, R.S. & Shaw, R. (1989). Geology of the Western New Territories. Geotechnical Control Office, Hong Kong, 140 p. (Hong Kong Geological Survey Memoir No. 3).

McNicholl, D.P., Yiu, M., Mak, L.M., Clover, A.W. & Ho, H.Y.S. (1989). Piled foundation in Tin Shui Wai Area 5, Yuen Long marble area, Hong Kong. Proceedings of the Second International Conference on Foundations and Tunnels, London, pp 181-193.

Moneymaker, B.C. (1968). Reservoir leakage in limestone terranes. Proceedings of the Symposium on Reservoir Leakage and Groundwater Control. Association of Engineering Geologists, Seattle.

NAVFAC (1982). Design Manual 7.2 - Foundations and Earth Structures, Department of the Navy, Naval Facilities Engineering Command, Washington, D.C., 244 p.

Norbury, D.R. (1984). The point load test. Site Investigation Practice : Assessing BS 5930, (edited by A.B. Hawkins), Geological Society Engineering Geology Special Publication No. 2, 1986, pp 325-329.

Pascal, D. (1987). Cavernous ground in Yuen Long, Hong Kong. Geotechnical Engineering, vol. 18, pp 205-221.

Peck, R.B., Hanson, W.E. & Thornburn, T.H. (1974). Foundation Engineering. (Second edition). John Wiley, New York, 514 p.

Poulos, H.G. & Davis, E.H. (1980). Pile Foundation Analysis and Design. John Wiley, 397 p.

Powell, G.E. & Irfan, T.Y. (1987). Geotechnical design for a controlled tip in Hong Kong. Planning and Engineering Geology, (edited by M.G. Culshaw, F.G. Bell, J.C. Cripps & M. O'Hara), Geological Society Engineering Geology Special Publication No. 4, London, pp 517-523.

Siu, K.L. & Wong, K.M. (1985). Concealed marble at Yuen Long. Proceedings of Conference on Geological Aspects of Site Investigation, Geological Society of Hong Kong, Bulletin No. 2, pp 75-88.

Sowers, G.F. (1976a). Foundation bearing in weathered rock. Rock Engineering for Foundations and Slopes. American Society of Civil Engineers, New York, vol. 2, pp 32-42.

Sowers, G.F. (1976b). Settlement in terranes of well-indurated limestone. In Analysis and Design of Building Foundations, (edited by H.Y. Fang), Envo Publishing Co., pp 701-725.

Sowers, G.F. (1979). Introductory Soil Mechanics and Foundations : Geotechnical Engineering. (Fourth edition). Macmillan, New York, 621 p.

Sowers, G.F. (1984). Correction and protection in limestone terrane. Proceedings of the First Multidisciplinary Conference on Sinkholes, Orlando, Florida, pp 373-378.

Tsui, P.C. & Irfan, T.Y. (1990). Complex site geology in marble bedrock, Southwest Yuen Long, Hong Kong. Karst Geology in Hong Kong, (edited by R.L. Langford, R. Shaw & A. Hansen), Geological Society of Hong Kong, Bulletin No. 4, (in press).

Yiu, M. & Tang, K.H. (1990), Case study of pile construction problems in faulted marble bedrock in Tin Shui Wai Area 5, Hong Kong. Proceedings of the Conference on Deep Foundation Practice, Singapore, (in press).

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Table 1 - Geological Succession in the Western New Territories (Langford et al, 1989)

Superficial Deposits (Onshore)			
Age		**Genetic Classification**	**Principal Materials**
QUATERNARY	Holocene	Fill; sanitary fill Alluvium	 Clay, silt, sand and gravel
	Holocene and Pleistocene	Beach deposits Raised beach deposits Debris flow deposits Talus (rockfall deposits)	Sand Sand Silt and sand with cobbles and boulders Boulders
	Pleistocene	Terraced alluvium Debris flow deposits	Clay, silt, sand and gravel Silt and sand with cobbles and boulders
Superficial Deposits (Offshore)			
Age		**Named Divisions**	**Principal Materials**
QUATERNARY	Holocene	Hang Hau Formation Marine Sand	Mainly mud Sand
	Pleistocene	Chek Lap Kok Formation	Clay, silt, sand and gravel

Solid Rocks				
Age		**Named Rock Divisions**		**Principal Rock Types**
MESOZOIC	Upper Cretaceous	Kat O Formation		Sedimentary breccia
	Upper Jurassic	Repulse Bay Volcanic Group	Tai Mo Shan Formation Ap Lei Chau Formation Shing Mun Formation	Coarse ash crystal tuff Fine ash crystal tuff Lithic and crystal tuff, tuff-breccia and tuffite
			Ngau Liu Member Shek Lung Kung Member Yim Tin Tsai Formation Tuen Mun Formation Tsing Shan Formation	Ash crystal tuff Crystal tuff and tuff-breccia Coarse ash crystal tuff Meta-andesite lava Sandstone and conglomerate
PALAEOZOIC	Carboniferous	San Tin Group	Lok Ma Chau Formation Yuen Long Formation	Metasandstone and metasiltstone Marble

Major Intrusive Rocks		
MESOZOIC	Upper Jurassic-Lower Cretaceous	Fine-grained granite Fine to medium-grained granite Medium-grained granite Coarse-grained granite Granodiorite and Dacite
Minor Intrusive Rocks		
TERTIARY	Palaeocene	Andesite Basalt and Gabbro Lamprophyre
MESOZOIC	Upper Jurassic-Lower Cretaceous	Feldsparphyric Rhyolite Quartzphyric Rhyolite Aplite and Fine-grained granite Pegmatite

Table 2 - Lithostratigraphy of the Carboniferous San Tin Group

Lithology				Thickness (m)
San Tin Group	Lok Ma Chau Formation	Tai Shek Mo Member	White to yellowish-grey, metamorphosed fine- to medium-grained sandstone, quartzite and conglomerate, with thin layers of phyllite	> 300
		Mai Po Member	Pale- to dark-grey, metamorphosed fine-grained sandstone, siltstone and carbonaceous siltstone, with thin layers of phyllite and graphite schist	> 500
	Yuen Long Formation	Ma Tin Member	Interbedded marble and siltstone, with thin layers of graphite schist	> 70
			White to grey, fine- to coarse-grained marble, partly dolomitic, with thin layers of phyllite	> 250
		Long Ping Member	Grey to dark grey marble, with disrupted bedding planes and laminae, siliceous horizons	> 300

Table 3 - Unified Mass Weathering/Alteration Classification Scheme for All Rocks in the Tuen Mun - Yuen Long Area

Weathering/Alteration State of Rock Mass				Marble Unit (Yuen Long Formation)			Volcanic Rock Units (Tuen Mun Formation)			Metasedimentary Rocks (Lok Ma Chau Formation)	Minor Intrusions	Major Intrusions
Broad Class	Mass Zone Descriptor	Mass Zone Symbol *	Recognition	White Marble	Grey Marble	Interbedded Marble and Metasiltstone	Tuff Breccia	Tuffaceous Siltstone/ Sandstone	Tuff	Metasandstone, Metasiltstone, Phyllite and Quartzite	Basalt/ Rhyolite	Granite, Grano-diorite
Fresh Rock	Fresh	WI	100% rock	✓	✓	✓ (see Note 1)	✓	✓	✓	✓	✓	✓
Weathered/ Altered Rock	Slightly Weathered/ Altered	WII	100% rock (with discoloration)	X (see Note 2)	X (see Note 2)	✓	✓	✓	✓	✓	✓	✓
	Moderately Weathered/ Altered	WIIIi WIIIii	> 90% rock 50-90% rock	✓ (see Note 3	✓ (see Note 3	✓	✓ (see Note 7)	✓	✓	✓	✓	✓
Sapro-lite	Highly Weathered/ Altered	WIV	0-50% rock	X (see Note 4)	X (see Note 4)	✓ (see Note 6)	✓ (see Note 7)	✓	✓	✓	✓	✓
	Completely Weathered/ Altered	WV	100% soil with structure/ texture	X	X	✓ (see Note 6)	✓	✓	✓	✓	✓	✓
Soil	Residual Soil	WVI	100% soil without structure/ texture	X (see Note 5)	X (see Note 5)	✓ (see Note 6)	✓	✓	✓	✓	✓	✓

Legend :

✓ Present X Not generally present (see notes) * Suffix A is used if rock mass is altered

Notes :

(1) For thick pure marble beds the weathering profile is similar to that of the white and grey marble. Fresh rock not reached at depths up to 100m drilled.

(2) Generally not present in pure marble unless altered/veined by intrusions and mineralization.

(3) Up to 50% dissolved voids may be partially or completely filled with clay residue.

(4) Generally not present due to collapse of mass structure in advanced stages of solution.

(5) Very thin or missing in pure marble.

(6) Metasiltstone beds may be structurally disturbed due to solution of purer marble beds in Zone WV. Significant volume reduction in Zone WVI if largely composed of marble beds.

(7) May contain small voids due to solution of marble clasts.

Table 4 - Unified Material Weathering Classification Scheme for All Rocks in the Tuen Mun - Yuen Long Area

Weathering/Alteration State of Rock Material			Marble Unit (Yuen Long Formation)					Volcanic Rock Units (Tuen Mun Formation)			Metasedimetary Rocks (Lok Ma Chau Formation)	Minor Intrusions	Major Intrusions	Broadly Equivalent Decomposition Grades (GCO, 1988)
					Interbedded									
Broad Class	Grade Descriptor	Material Grade Symbol	White Marble	Grey Marble	Impure Marble	Meta-Siltstone	Marble Affected by Intrusions	Tuff Breccia (Marble-Clast Bearing)	Tuff	Tuffaceous Siltstone/ Sandstone	Metasandstone/ Metasiltstone, Phyllite and Quartzite	Basalt/ Rhyolite	Granite, Grano-diorite	
Fresh Rock	Fresh	1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	I
Decomposed*/ Disintegrated Rock (Weathered Rock)	Slightly ▲ Decomposed/ Disintegrated	2	X (see Note 1)	X (see Note 1)	✓ (see Note 3)	✓	✓	✓	✓	✓	✓	✓	✓	II
	Moderately Decomposed/ Disintegrated	3	X (see Note 1)	X (see Note 1)	✓ (see Note 3)	✓	✓	✓ (see Note 4)	✓	✓	✓	✓	✓	III
	Highly Decomposed/ Disintegrated	4	X	X	✓ (see Note 3)	✓	✓	✓ (see Note 4)	✓	✓	✓	✓	✓	IV
Soil	Completely Decomposed/ Disintegrated	5	X	X	✓ (see Note 3)	✓	✓	✓	✓	✓	✓	✓	✓	V
	Residual Soil	6	✓ (see Note 2)	✓ (see Note 2)	✓	✓	✓	✓	✓	✓	✓	✓	✓	VI

Legend :

✓	Present
X	Not generally present (see notes)
*	The term "Decomposition" includes both solution and chemical alteration of mineral constituents. Suffix (A) is used if rock is altered.
▲	Slightly decomposed rock may be subdivided into slightly discoloured (less than 50% staining of rock material, Grade 2i) and highly discoloured (more than 50% staining of rock material, Grade 2ii). Moderately decomposed rock, except marble, is generally wholly discoloured.

Notes :

(1) In pure carbonate rocks intermediate grades between fresh rock and residual soil do not usually occur or are difficult to distinguish by simple visual means unless tested in the laboratory (i.e. increase in porosity due to solution).
(2) Generally not present unless impure, formed of insoluble residue.
(3) Not present in purer marble members.
(4) May be porous due to solution of marble clasts.
(5) Rock material may show various degrees of disintegration (microfracturing, etc.) with little or no chemical alteration, particularly in tectonically disturbed rocks.

Table 5 - Laboratory Test Results for Tuff Breccia

Rock Type	Sample No.	Borehole No.	Depth (m)	Weathering Grade (see Table 4)	Saturation Moisture Content (%)	Saturated Density (Mg/m³)	Dry Density (Mg/m³)	Effective Porosity (%)	Uniaxial Compressive Strength (MPa)	Modulus of Elasticity		Poisson's Ratio	Point Load Strength(1) (MPa)	Remarks
										Tangent at 50% σ_{ult} (GPa)	Secant at 0-50% σ_{ult} (GPa)			
Tuff Breccia	CTB 11	BD 8A	25.6	2i	0.2	2.84	2.84	0.5	296.4	136.6	80.5	0.536	11.9	
	CTB 2	DT 1	27.8	2i	0.1	2.79	2.78	0.3	281.7	128.2	106.7	0.374	13.0	
	CTB 3	DT 7	16.8	2i	0.1	2.83	2.82	0.3	246.0	75.7	74.1	0.270	11.1	Tuff Band
	CTB 12	BD 8A	25.8	2i	0.3	2.85	2.84	0.8	224.3	63.2	60.6	0.210	9.9	
	CTB 13	BD 9B	33.8	2i	0.2	2.70	2.69	0.5	217.2	51.7	47.6	0.323	11.3	Tuff Band
	CTB 14	BD 9B	34.6	2i	0.1	2.71	2.70	0.3	210.1	50.0	49.6	0.232	10.2	Tuff Band
	CTB 15	BD 9B	34.8	2i	0.2	2.72	2.71	0.5	185.2	50.0	52.0	0.468	9.2	Tuff Band
	CTB 9	BD 3	38.9	2i	0.2	2.84	2.84	0.5	149.7	61.7	44.0	0.284	7.2	
	CTB 10	BD 3	40.3	2i	0.1	2.73	2.73	0.3	90.0 *	78.9	72.6	0.184	11.9	Tuff Band
	CTB 18	BD 11	32.6	2i	0.2	2.70	2.70	0.5	102.2 *	n.d.	n.d.	n.d.	7.7	
	CTB 20	BD 20	32.9	2i	0.0	2.65	2.65	0.0	127.7 *	73.7	74.3	0.203	8.8	Tuff Band
	CTB 4	DT 7	17.6	2ii	0.3	2.98	2.98	0.8	193.2	76.7	66.6	0.220	8.3	
	CTB 5	DT 7	19.7	2ii	0.3	2.89	2.89	0.7	193.2	69.2	61.5	0.231	8.0	
	CTB 1	DT 1	26.5	2ii	0.3	3.03	3.02	0.8	173.8	75.0	73.6	0.242	6.9	
	CTB 6	BD 1	36.1	2ii	0.2	2.97	2.97	0.5	170.0	80.3	82.5	0.250	8.7	
	CTB 7	BD 1	41.2	2ii	0.3	2.94	2.94	0.7	156.6	59.7	45.0	0.279	7.3	
	CTB 8	BD 2	31.8	2ii	0.2	2.97	2.97	0.5	119.6 *	75.0	63.6	0.475	8.4	Tuff Band
	CTB 17	BD 11	32.3	2ii	0.2	2.72	2.71	0.5	71.3 *	54.7	45.7	0.219	5.9	
	CTB 19	BD 12	30.8	2ii	0.4	2.62	2.61	1.0	56.6 *	n.d.	n.d.	n.d.	6.1	Tuff Band
	CTB 16	BD 11	31.2	2ii	0.1	2.72	2.72	0.3	84.2 *	59.7	56.9	0.306	5.4	
	CTB 22	BD 14	31.5	2ii	0.1	2.90	2.90	0.3	139.2	76.9	74.8	0.279	5.6	
Tuff Breccia (honey-combed)	CTB 24	BD 1	38.2	3	1.4	2.65	2.62	3.6	152.6	31.9	27.1	0.383	5.2	Tuff Band
	CTB 25	BD 9B	23.8	3	1.5	2.70	2.66	4.0	147.6	37.4	29.3	0.271	n.d.	
	CTB 27	BD 9B	24.7	3	2.0	2.59	2.54	5.2	69.4	32.8	28.2	0.180	2.6	
	CTB 23	BD 1	33.0	3	2.8	2.54	2.47	7.0	68.6	29.7	26.4	0.119	2.4	
	CTB 26	BD 9B	24.1	3	5.3	2.37	2.25	12.0	26.1	17.0	17.9	0.108	1.7	
	CTB 21	BD 14	27.6	3	2.6	2.56	2.49	6.6	22.1	n.d.	n.d.	n.d.	0.8	

Legend :

n.d. Not determined

* Failed prematurely along pre-existing crack / vein

Note : (1) Average of 5 to 15 results on specimens adjacent to core section tested in uniaxial compression.

Table 6 - Ranges of Laboratory Test Values for Tuff Breccia

Rock Type	Weathering Grade (see Table 4)	Saturation Moisture Content (%)	Saturated Density (Mg/m^3)	Dry Density (Mg/m^3)	Effective Porosity (%)	Uniaxial Compressive Strength (MPa)	Modulus of Elasticity: Tangent at 50% σ_{ult} (GPa)	Modulus of Elasticity: Secant at 0 - 50% σ_{ult} (GPa)	Poisson's Ratio	Point Load Strength (MPa)	Remarks
Tuff Breccia	1	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	Variable lithology with tuff bands and marble-clast rich layers
	2i	0.0 - 0.3 (0.0 - 0.2)	2.65 - 2.85 (2.65 - 2.83)	2.65 - 2.84 (2.65 - 2.82)	0.0 - 0.5 (0.0 - 0.3)	150 - 296 (185 - 246)	50 - 137 (50 - 76)	44 - 107 (50 - 74)	0.18 - 0.54	7.2 - 13.0 (8.8 - 11.1)	
	2ii	0.1 - 0.4	2.62 - 3.03	2.61 - 3.02	0.3 - 1.0	139 - 193	55 - 80	45 - 83	0.22 - 0.48	5.4 - 8.7	
	2	0.0 - 0.4	2.62 - 3.03	2.61 - 3.02	0.0 - 1.0	139 - 296	50 - 137	44 - 107	0.18 - 0.54	5.4 - 13.0	
	3	1.4 - 5.3	2.37 - 2.70	2.25 - 2.66	3.6 - 12.0	22 - 152	17 - 37	18 - 29	0.11 - 0.38	0.8 - 5.2	Honeycombed texture when rich in marble clasts
	4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	

Legend :

n.d. Not determined

Note : Numbers in brackets are for pure tuff members.

Table 7 - Laboratory Test Results for Marble

Rock Type	Sample No.	Borehole No.	Depth (m)	Weathering Grade (see Table 4)	Saturation Moisture Content (%)	Saturated Density (Mg/m³)	Dry Density (Mg/m³)	Effective Porosity (%)	Uniaxial Compressive Strength (MPa)	Modulus of Elasticity: Tangent at 50% σ_{ult} (GPa)	Modulus of Elasticity: Secant at 0 - 50% σ_{ult} (GPa)	Poisson's Ratio	Point Load Strength (1) (MPa)	Remarks
Grey Marble	M21	BD50	55.4	1	0.1	2.70	2.70	0.2	125.6	69.8	69.8	0.313	4.0	
	M22	BD54	44.8	1	0.1	2.81	2.81	0.2	137.5	93.0	82.8	0.488	4.6	
	M23	BD54	45.2	1	0.1	2.85	2.85	0.3	111.9	78.1	68.2	0.383	4.3	
	M 9	BD47	59.7	1	0.1	2.71	2.71	0.3	89.1	52.1	40.5	0.375	3.6	
	M 8	BD47	56.5	1	0.1	2.71	2.70	0.3	81.2	50.0	39.4	0.300	3.4	
	M10	BD47	59.9	1	0.2	2.69	2.69	0.5	64.6	52.2	43.1	0.254	3.4	
	M11	BD47	64.6	1	0.1	2.71	2.71	0.3	74.0	43.5	29.4	0.466	3.1	
	M 6	BD47	48.9	2	0.2	3.10	3.09	0.7	122.4	111.1	117.7	0.203	6.1	With granitic veins
	M 3	BD47	39.6	2	0.3	2.87	2.86	1.0	120.7	66.7	65.8	0.278	4.8	
	M 5	BD47	47.5	2	0.2	2.98	2.98	0.5	83.2	82.1	81.6	0.336	4.1	
	M 4	BD47	45.4	2	0.5	2.81	2.80	1.3	72.0	46.5	35.4	0.346	4.6	
	M 1	BD47	34.5	3	1.2	2.60	2.57	3.1	47.3	46.5	46.4	0.217	n.d.	With granitic veins
	M 2	BD47	34.7	3	1.3	2.93	2.89	3.8	70.0	53.7	53.6	0.208	n.d.	
	M 7	BD47	49.2	3	1.1	3.08	3.05	3.3	58.4 *	71.4	68.7	0.100	n.d.	
White Marble	M18	BD50	51.9	1	0.1	2.76	2.76	0.2	90.5	64.9	56.6	0.286	4.1	
	M19	BD50	52.0	1	0.1	2.75	2.74	0.2	121.5	66.7	65.3	0.292	5.1	
	M20	BD50	53.3	1	0.1	2.79	2.78	0.4	115.1	83.3	85.9	0.258	5.4	
	M24	BD55	47.3	1	0.1	2.70	2.69	0.3	87.9	64.5	54.9	0.323	2.8	
	M25	BD55	48.2	1	0.1	2.68	2.68	0.4	86.3	66.7	56.8	0.347	3.4	
Banded Impure Marble	M27	BD53	70.8	2	0.2	2.71	2.70	0.4	64.0	46.0	28.0	0.230	1.7	
	M28	BD53	73.2	2	0.5	2.79	2.77	1.4	51.4	33.7	22.3	0.416	2.0	
	M29	BD53	74.3	2	0.3	2.80	2.80	0.8	65.6	33.9	24.9	n.d.	2.7	
	M26	BD53	30.7	2	0.1	2.74	2.74	0.4	38.5	53.3	55.8	0.293	n.d.	
Silicified Grey Marble	M15	BD40	57.5	1	0.1	3.09	3.09	0.2	188.2	103.8	112.0	0.274	6.8	
	M16	BD40	59.9	1	0.3	3.24	3.23	1.0	145.7	90.9	101.2	0.227	7.5	
	M14	BD40	50.6	1	0.2	3.11	3.11	0.7	121.0	85.1	93.8	0.160	6.6	
	M12	BD40	49.7	2	0.6	3.10	3.08	2.0	72.9 *	70.0	62.8	0.240	6.1	
	M13	BD40	50.2	2	0.7	3.23	3.21	2.2	60.9 *	87.9	98.2	n.d.	6.6	
	M17	BD40	60.1	2	1.3	3.17	3.13	4.0	52.9 *	38.0	32.7	0.170	n.d.	

Legend :

n.d. Not determined

* Failed prematurely along pre-existing crack/vein

Note : (1) Average of 5 to 15 results on specimens adjacent to core section tested in uniaxial compression.

Table 8 - Ranges of Laboratory Test Values for Marble

Rock Type	Weathering Grade (see Table 4)	Saturation Moisture Content (%)	Saturated Density (Mg/m^3)	Dry Density (Mg/m^3)	Effective Porosity (%)	Uniaxial Compressive Strength (MPa)	Modulus of Elasticity: Tangent at 50% σ_{ult} (GPa)	Modulus of Elasticity: Secant at 0 - 50% σ_{ult} (GPa)	Poisson's Ratio	Point Load Strength (MPa)	No. of Tests on Cores	Remarks
Grey Marble	1	0.0 - 0.2	2.69 - 2.85	2.69 - 2.85	0.2 - 0.5	65 - 138	44 - 93	29 - 83	0.31 - 0.49	3.1 - 4.6	7	
	2	0.2 - 0.5	2.81 - 3.10	2.80 - 3.09	0.7 - 1.3	72 - 122	46 - 111	35 - 118	0.20 - 0.35	4.1 - 6.1	4	With granitic veins
	3	1.1 - 1.3	2.60 - 3.08	2.57 - 3.05	3.1 - 3.8	47 - 70	47 - 71	46 - 69	0.10 - 0.22	n.d.	3	With granitic veins
	Range 1 - 3	0.0 - 1.3	2.60 - 3.10	2.57 - 3.09	0.2 - 3.8	47 - 138	44 - 111	29 - 118	0.10 - 0.49	3.1 - 6.1	14	
White Marble	1	0.0 - 0.1	2.68 - 2.79	2.68 - 2.78	0.2 - 0.4	86 - 122	65 - 83	55 - 86	0.26 - 0.35	2.8 - 5.4	5	Limited occurrence in project area
Banded Impure Marble	2	0.1 - 0.5	2.71 - 2.80	2.70 - 2.80	0.4 - 1.4	39 - 66	34 - 53	22 - 56	0.23 - 0.42	1.7 - 2.7	3	Generally impure and interbedded with metasiltstones
Silicified Marble (Grey Marble)	1	0.1 - 0.3	3.09 - 3.24	3.09 - 3.23	0.2 - 1.0	121 - 188	85 - 104	94 - 112	0.16 - 0.27	6.6 - 7.5	3	Limited occurrence
	2	0.6 - 1.3	3.10 - 3.23	3.08 - 3.21	2.0 - 4.0	53* - 73*	38 - 88	33 - 98	0.17 - 0.24	6.1 - 6.6	3	

Legend :

n.d. Not determined

* Failed prematurely along pre-existing crack / vein

Table 9 - Classification of Rock Units in Terms of Point Load Strength Values (MPa)

Rock Type		Material Weathering Grade				
		Fresh 1	Slightly Decomposed / Disintegrated 2i 2ii	Moderately Decomposed / Disintegrated 3	Highly Decomposed / Disintegrated 4	Completely Decomposed / Disintegrated 5
Basic Dykes	Basalt	(Over 8.0)	9.0 - 4.0	5.0 - 0.3	Less than 0.5	Not determined
Mai Po Formation	Metasiltstone and Metasandstone	(Over 5.5)	(Over 3.5)	3.5 - 0.3	Less than 0.5	Not determined
Yuen Long Formation	Banded Impure Marble	(Over 4.0)	4.0 - 1.5	2.0 - 0.3	Less than 0.5	Not determined
	Metasiltstone	(Over 5.5)	5.5(?) - 2.0	2.5 - 0.3	Less than 0.5	Not determined
	Grey Marble	5.5 - 3.0	← Not generally present →			
	Grey Marble (Silicified / with granitic veins)	9.5(?) - 6.5	7.0 - 3.5	(4.0 - 0.3)	Less than 0.5	Not determined
	White Marble	6.0 - 3.0	← Not present →			
Tuen Mun Formation	Tuff Breccia	(Over 8.0)	14.0-7.0 11-4.5	7.0 - 0.3	Less than 0.5	Not determined

Note : Numbers in brackets are based on limited test results or tests on more weathered samples.

Table 10 - Classification of Rock Units in Terms of RQD, Fracture Intensity and Rock Mass Factor

Lithological Unit	Mass Weathering Zone	Fracture Intensity, per m	RQD (%)	Rock Mass Factor (2)	Remarks
Tuff Breccia of Tuen Mun Formation	Fresh Slightly Weathered Moderately Weathered Highly Weathered	0.5 - 3 1 - 5 3 - 15 Over 10	90 - 100 75 - 100 20 - 80 0 - 25	0.8 - 1.0 0.5 - 1.0 0.2 - 0.6 Less than 0.2	Not present at depths drilled. May contain small solution features if marble-clast bearing.
White and Grey Marble of Yuen Long Formation	Fresh / Slightly Weathered Moderately Weathered (Dissolved) Highly Weathered (Dissolved)	0.2 - 3 1 - 7	80 - 100 30 - 100 Less than 50	0.8 - 1.0 (see Note 1) (see Note 1)	 May contain up to 50 % by volume solution features (may be filled). Not generally present.
Interbedded Impure Marble and Metasiltstone of Yuen Long Formation	Fresh Slightly Weathered Moderately Weathered Highly Weathered	1 - 12 1 - 12 2 - 15 Over 12	50 - 100 50 - 100 10 - 90 0 - 50	0.3 - 1.0 0.2 - 1.0 0.2 - 0.6 Less than 0.2	Not encountered at depths drilled. RQD and fracture intensity depend on the thickness of metasiltstone layers; usually marble layers have higher RQD; may be structurally disturbed if significant solution is present in pure marble layers.
Metasiltstone and Metasandstones of Mai Po Member	Fresh Slightly Weathered Moderately Weathered Highly Weathered	3 - 15 3 - 15 8 - 25 Over 15	10 - 100 10 - 100 0 - 50 0 - 10	0.3 - 0.8 0.2 - 0.8 Less than 0.2 Less than 0.2	Very closely spaced foliation planes; higher values for non-foliated rocks.
Basic Dykes	Fresh to Highly Weathered	Limited occurrence in project area			

Notes : (1) Rock mass factors may not be applicable if the rock contains voids or thick compressible layers.
(2) See Table 13.

Table 11 - Presumptive Allowable Bearing Stress (MPa) for Rock Specified by Various Building Codes and Authorities

Reference	Massive Crystalline Rocks in Sound Condition (Granite, Basalt, Gneiss)	Foliated Metamorphic Rocks in Sound Condition (Slate, Schist)	Sedimentary Rocks in Sound Condition	Badly Fractured Rocks, or Broken Rocks, or Partially Weathered Rocks except Argillaceous Rocks	Heavily Shattered or Weathered Rocks	Remarks
NAVFAC, USA 1982	6 - 10	3 - 4	1.5 - 2.5	0.8 - 1.2		Increase by 10% for each 300mm embedment
Canadian Geotechnical Society 1985	10	3	1 - 4	1.0	To be assessed by examination in situ	
National Building Code, USA 1967	10	4	1.5			
Uniform Building Code, USA 1964	0.2 q_u	0.2 q_u	0.2 q_u	0.2 q_u		
Los Angeles 1970	1.0	0.4	0.3			Earthquake area
British Standards Institution, BS 8004 1986	10	3	2 - 4	To be assessed after inspection	To be assessed after inspection	May need alteration upwards or downwards
US Bureau of Reclamation 1965	10.7	3.8		1.1		
Dallas 1968	0.2 q_u	0.2 q_u	0.2 q_u	0.2 q_u		Increase by 1/3 if the foundation is relatively dry
New York City 1970	6	6	2 - 4	0.8		Increase by 10% for each 300mm embedment
Building Construction Regulations, Hong Kong * 1985	5	1 - 3			To be assessed after inspection	
Sowers 1979	> 10 (RQD = 90%)	1.5 - 4 (RQD = 50%)		0.5 - 1.2 (SPT > 50)		
Weathering/Alteration State	Fresh to Slightly Weathered			Moderately Weathered	Highly to Completely Weathered	
Discontinuity Spacing	Widely to Very Widely	Medium to Closely	Closely to Medium	Closely to Very Closely	Very Closely	

Legend:

q_u Uniaxial compressive strength (UCS) of intact rock sample

* Building Construction Regulations (Hong Kong Government, 1985): these are currently under revision

Table 12 - RQD and Allowable Contact Pressure on Jointed Rock (Peck et al, 1974)

RQD (%)	q_a (MPa)
100	30
90	20
75	13
50	7
25	3
0	1
Note : If tabulated value of q_a exceeds unconfined compressive strength q_u of intact samples of the rock, take $q_a = q_u$.	

Table 13 - Rock Mass Quality Classification Based on Rock Mass Factor, Discontinuity Spacing and RQD (Based on Deere et al, 1969; Coon & Merritt, 1970 and Hobbs, 1975)

Rock Mass Quality Classification	RQD (%)	Discontinuity Spacing, per m	Rock Mass Factor, j
Very poor	0 - 25	Over 15	Less than 0.2
Poor	25 - 50	15 - 8	Less than 0.2
Fair	50 - 75	8 - 5	0.2 - 0.5
Good	75 - 90	5 - 1	0.5 - 0.8
Excellent	90 - 100	Less than 1	0.8 - 1.0

FIGURES

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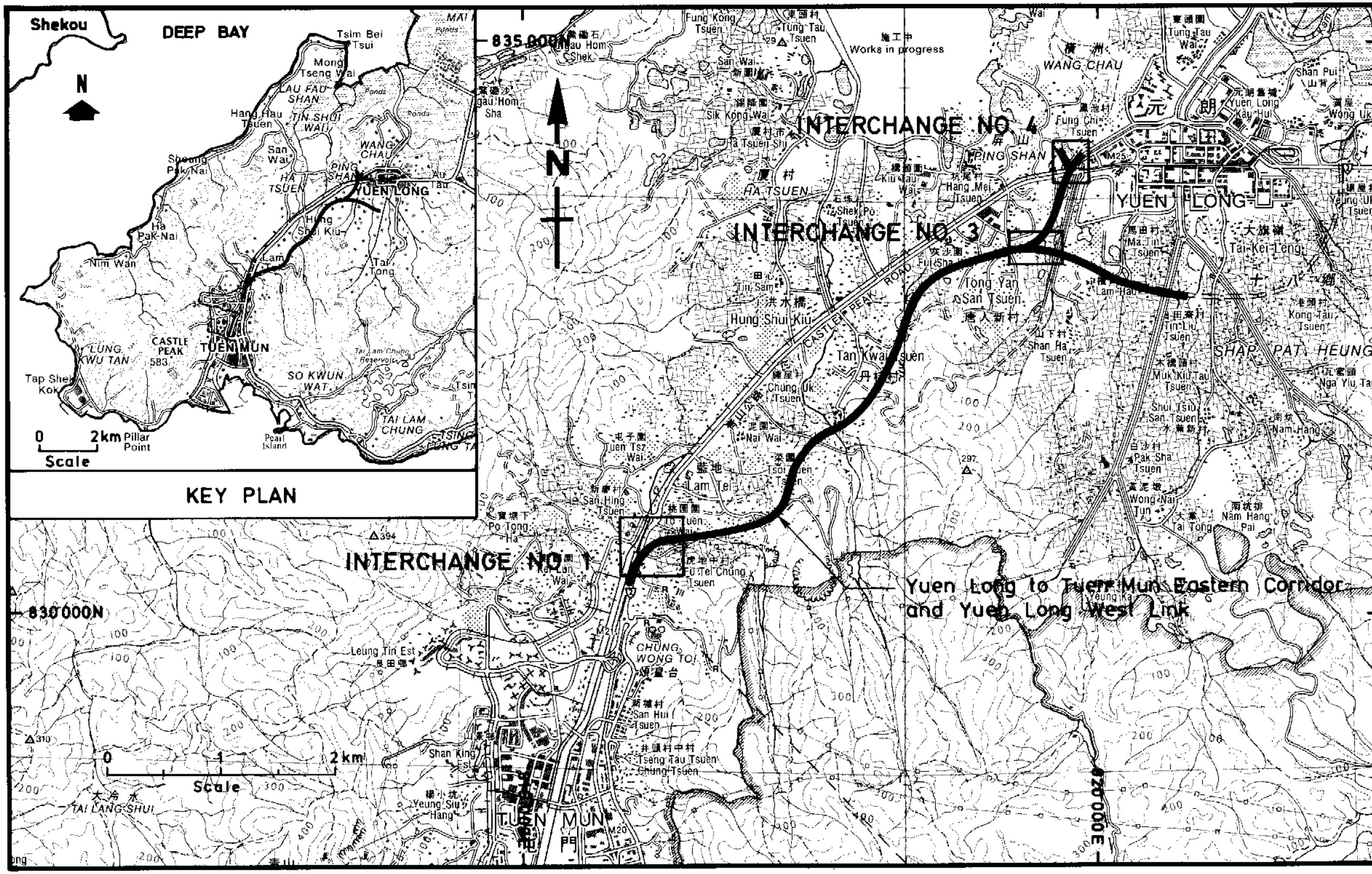


Figure 1 - Location Plan of the Yuen Long to Tuen Mun Eastern Corridor

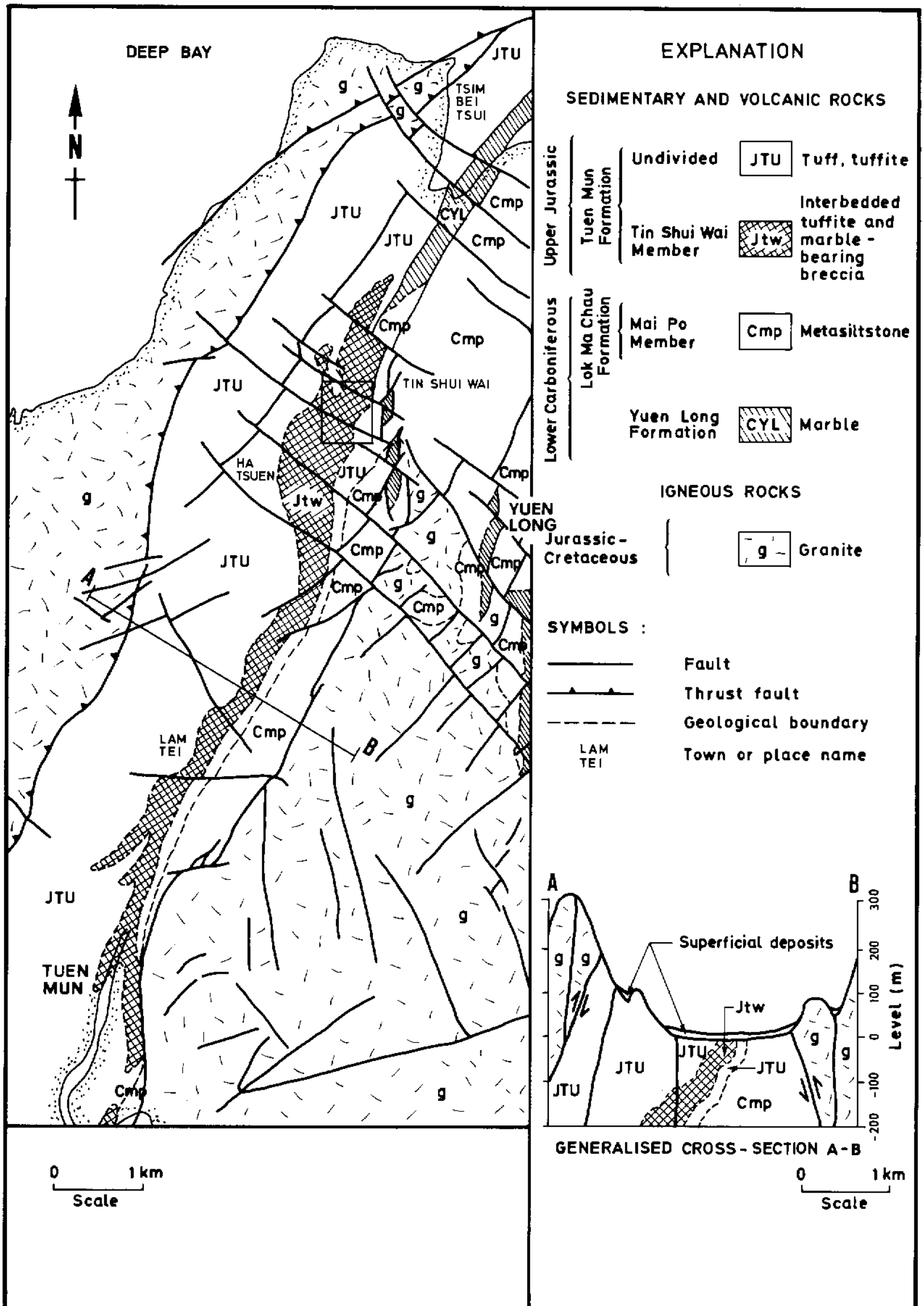


Figure 2 - Geological Map of Part of Designated Area (Darigo, 1989)

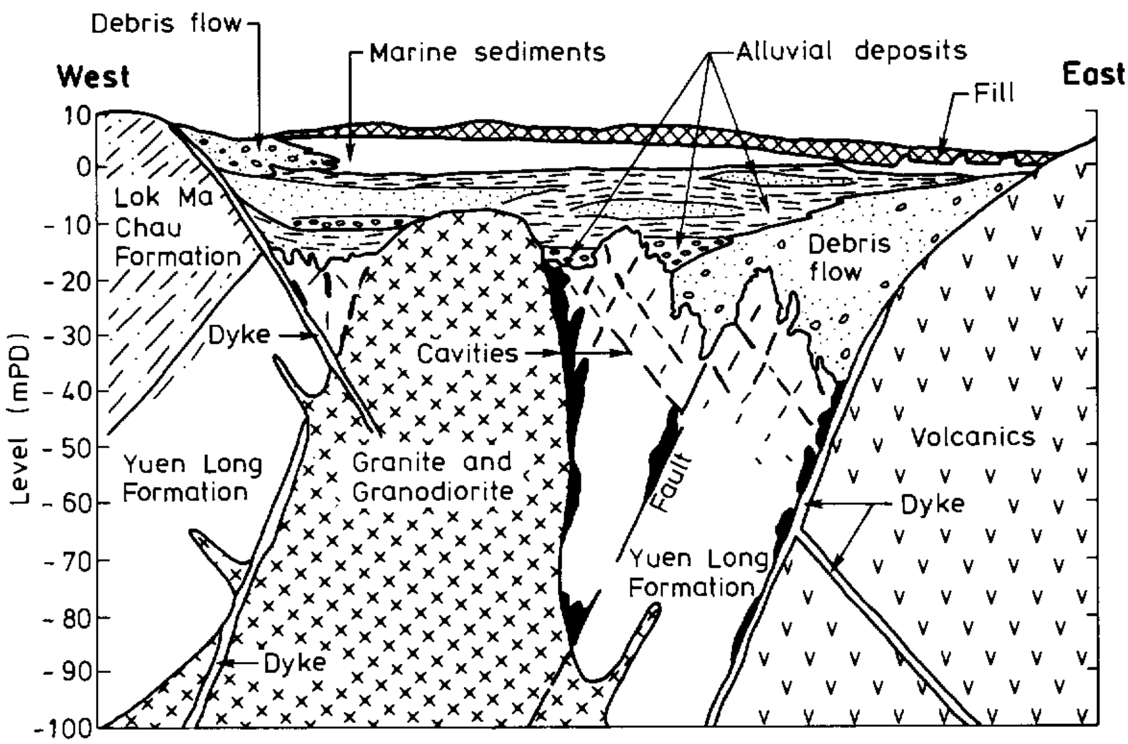


Figure 3 - Generalized Section of the Strata in the Yuen Long Area
(Frost, 1989)

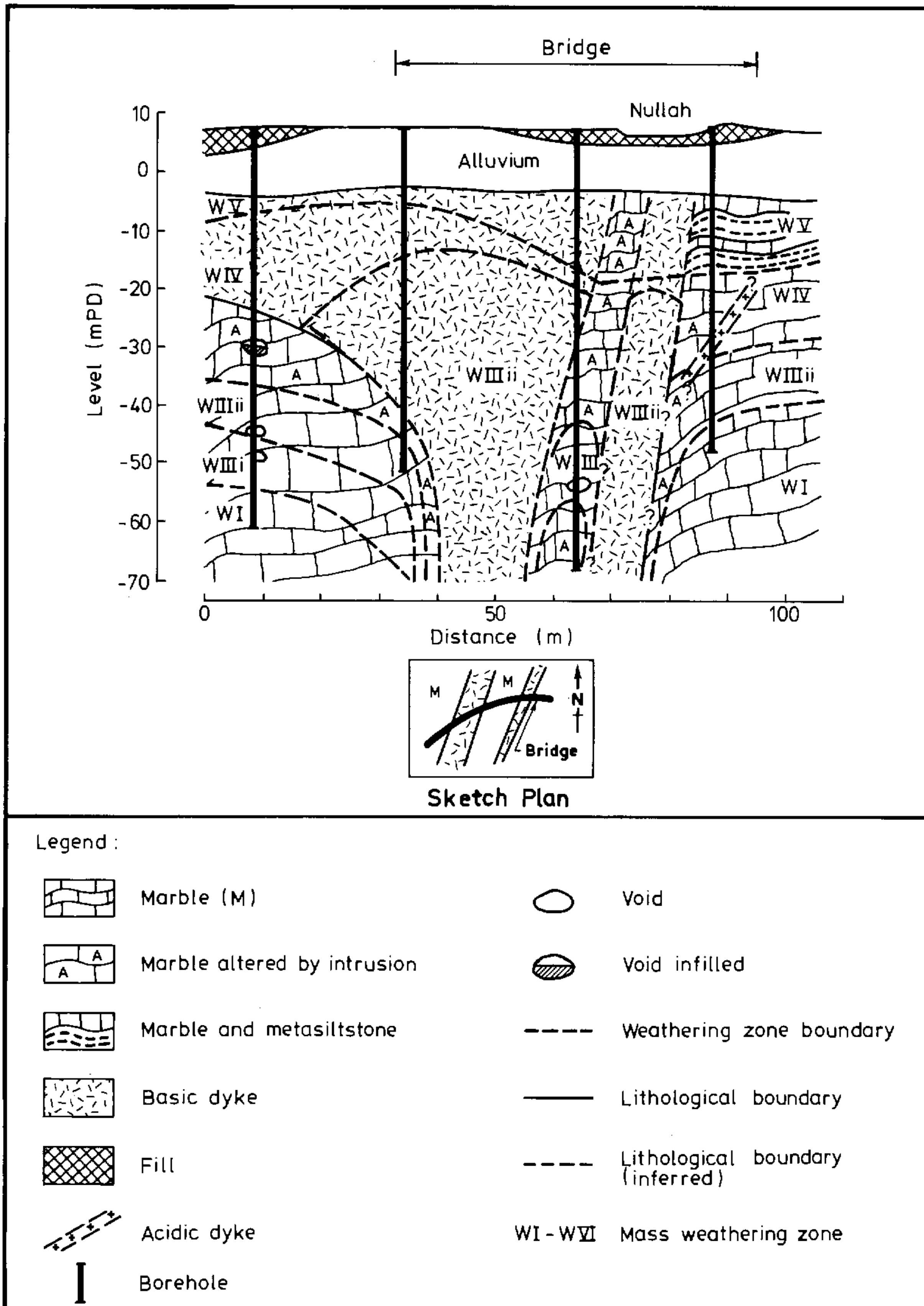


Figure 4 - Complex Foundation Conditions in Marble Intruded by Dykes at Interchange No. 3

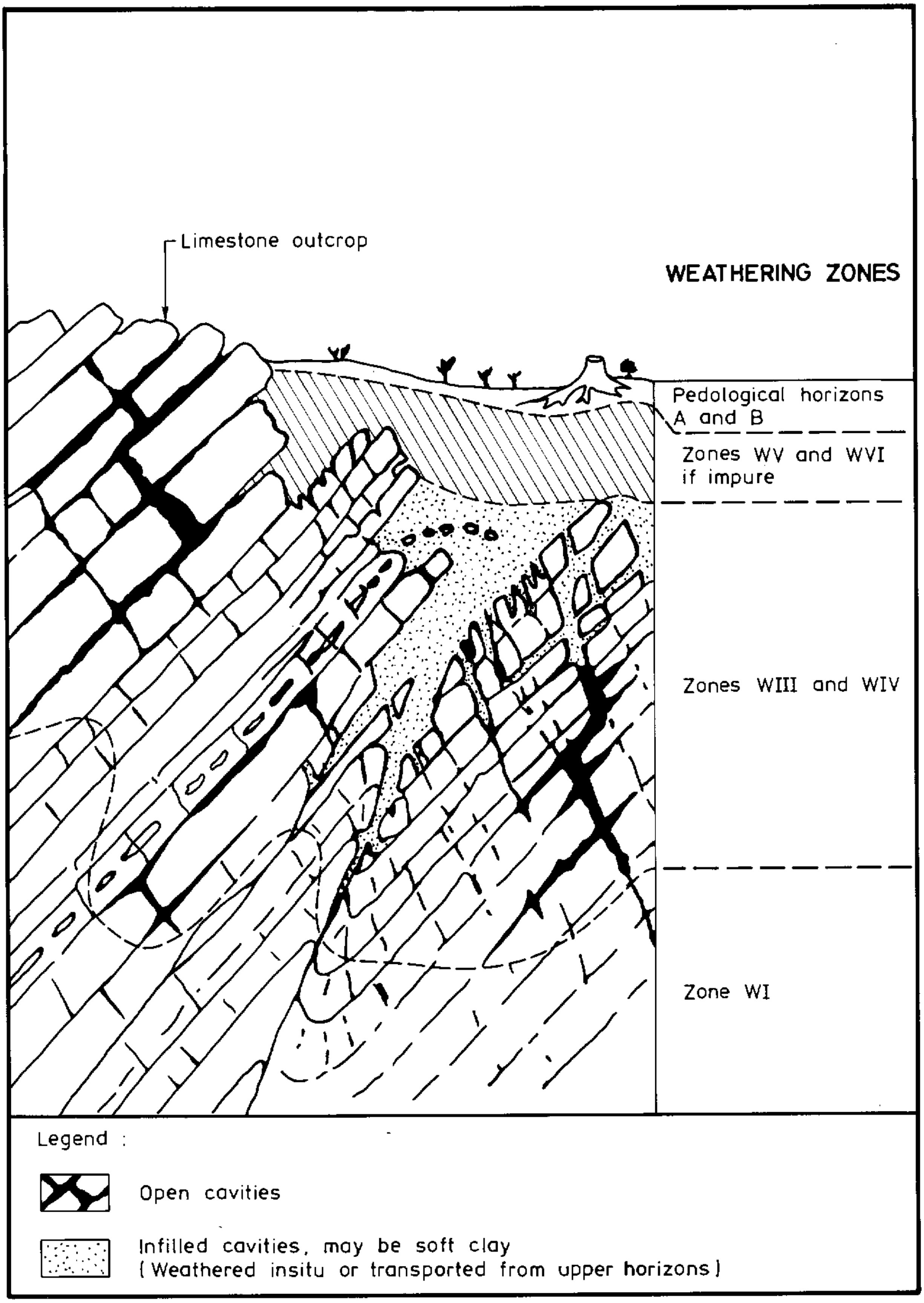


Figure 5 - A Typical Weathering Profile in Carbonate Rocks
(Deere & Patton, 1971 and Dearman, 1981)

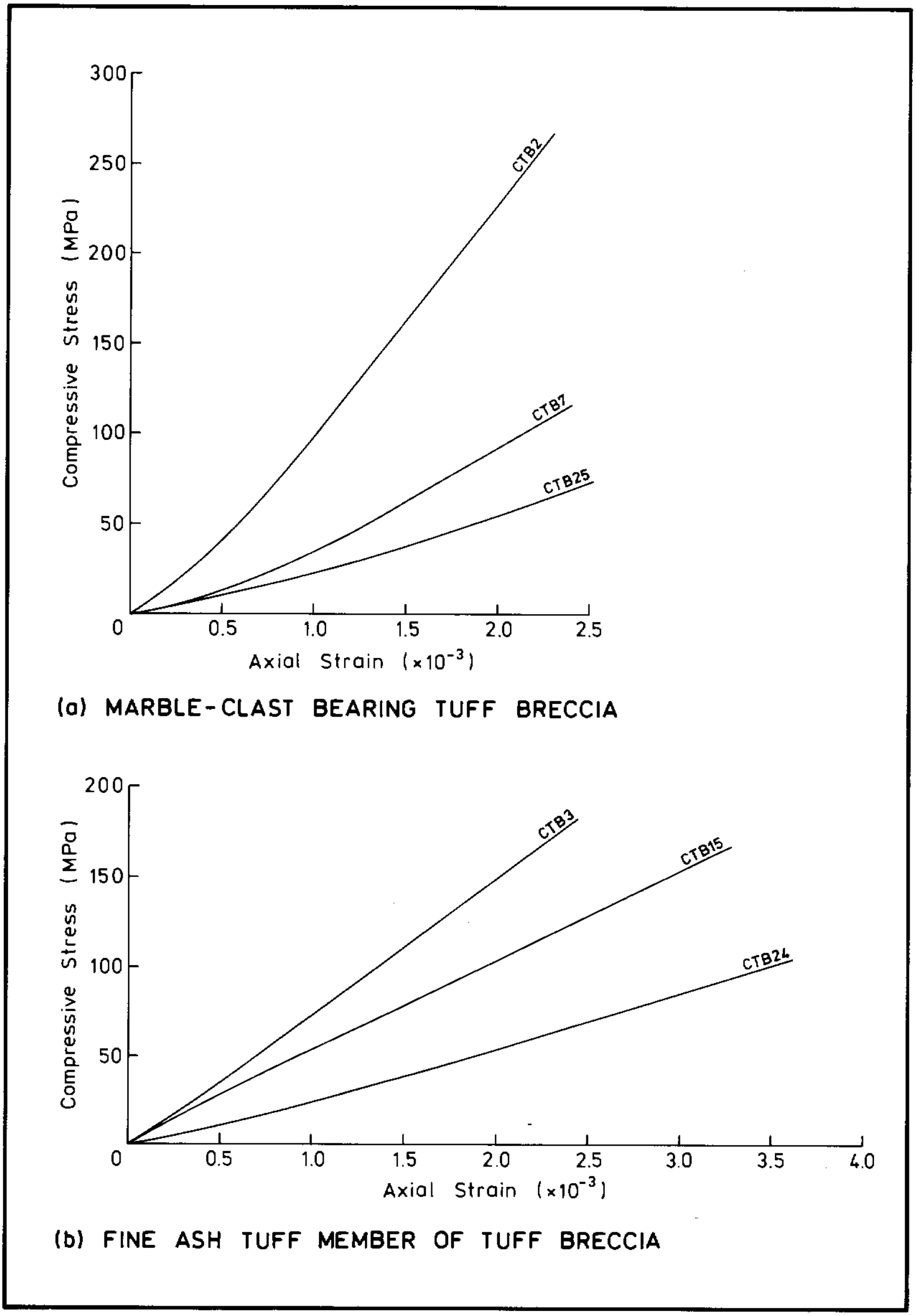


Figure 6 - Stress-Strain Behaviour of Tuff Breccia

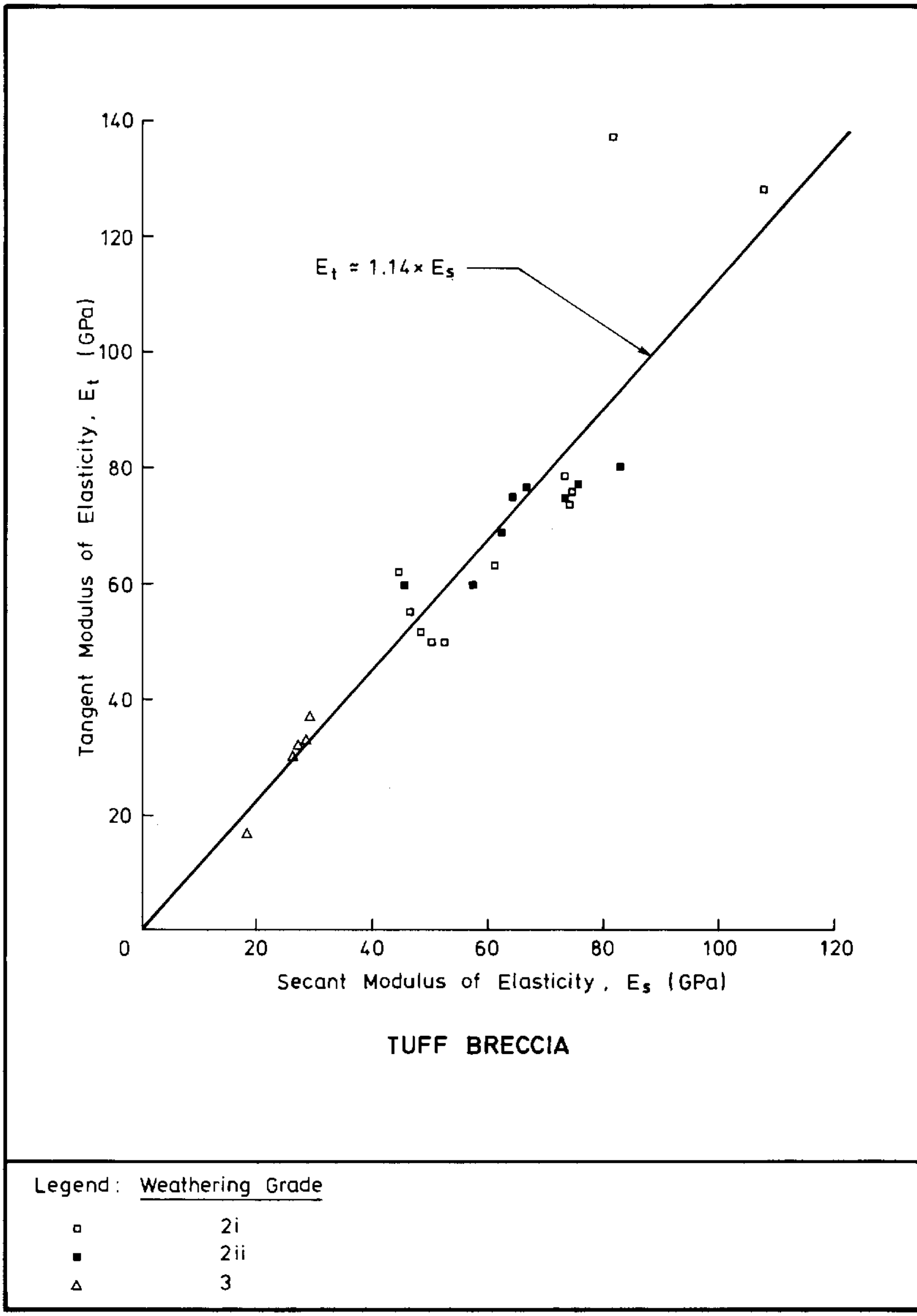
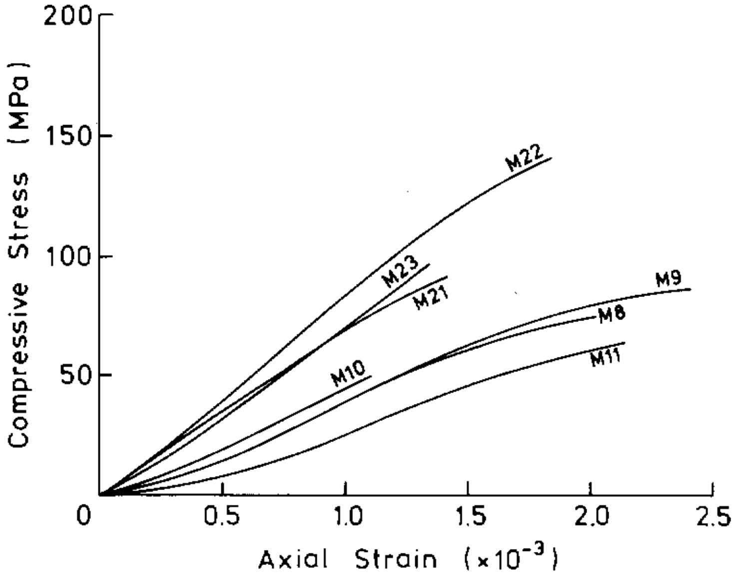
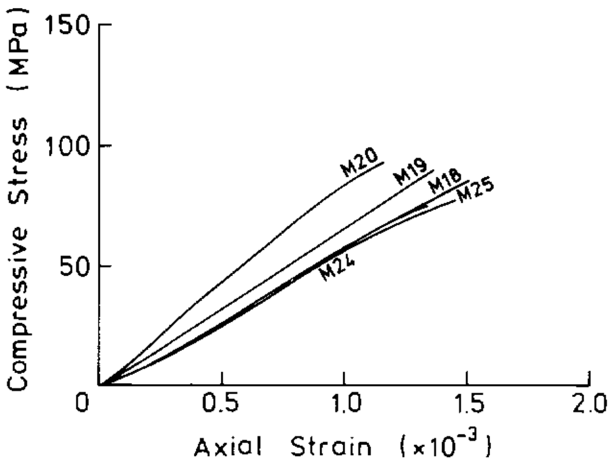


Figure 7 - Relationship Between Tangent Young's Modulus and Secant Modulus for Tuff Breccia

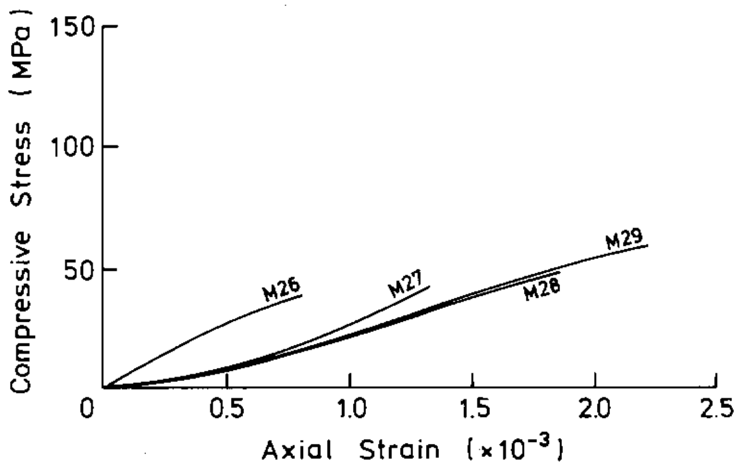


(a) GREY MARBLE

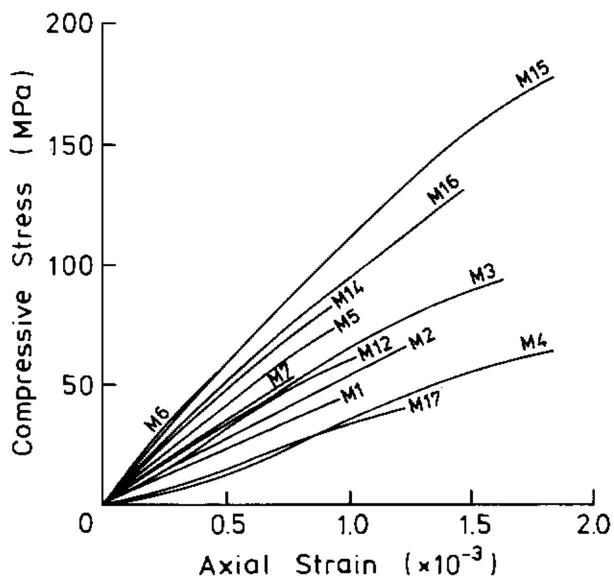


(b) WHITE MARBLE

Figure 8 - Stress-Strain Behaviour of Pure Marble



(a) BANDED IMPURE MARBLE



(b) GREY MARBLE WITH GRANITIC VEINS/SILICIFIED MARBLE

Figure 9 - Stress-Strain Behaviour of Banded Impure Marble and Marble Affected by Intrusions

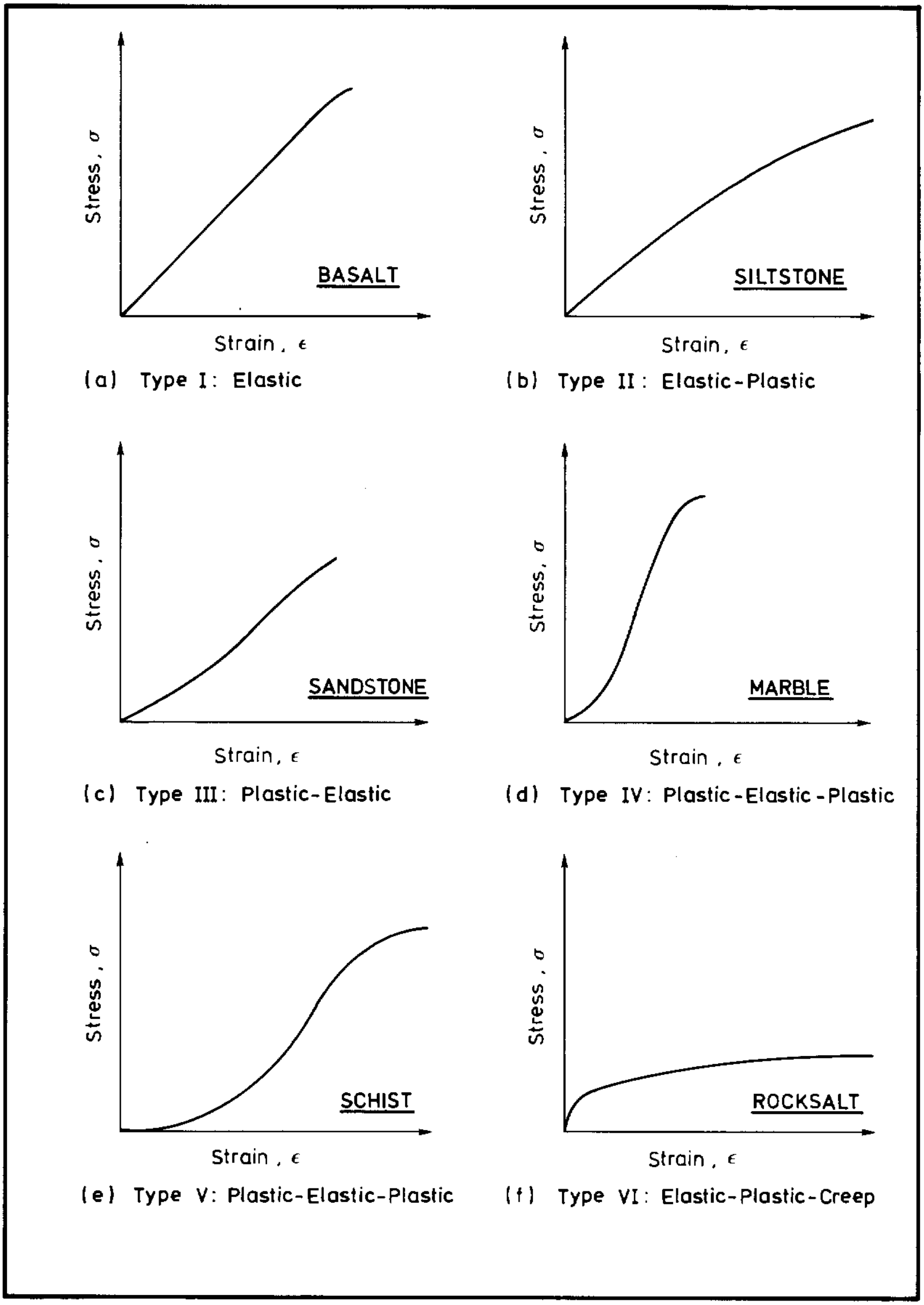
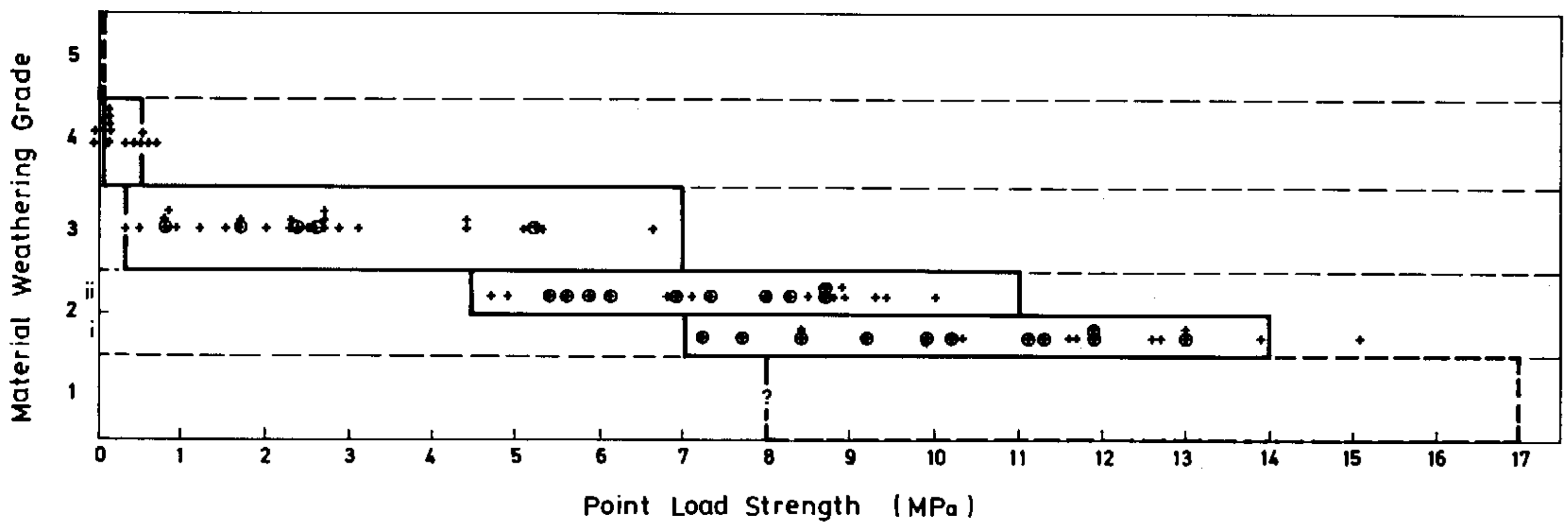


Figure 10 - Typical Stress-Strain Curves for Rock in Uniaxial Compression to Failure (Based on Deere & Miller, 1966)



TUFF BRECCIA

Legend :

⊕ Average of 5 to 15 results on specimens adjacent to core sections tested in uniaxial compression

+ Average of 5 to 15 results on core specimens

Figure 11 - Ranges of Point Load Strength Values for Tuff Breccia

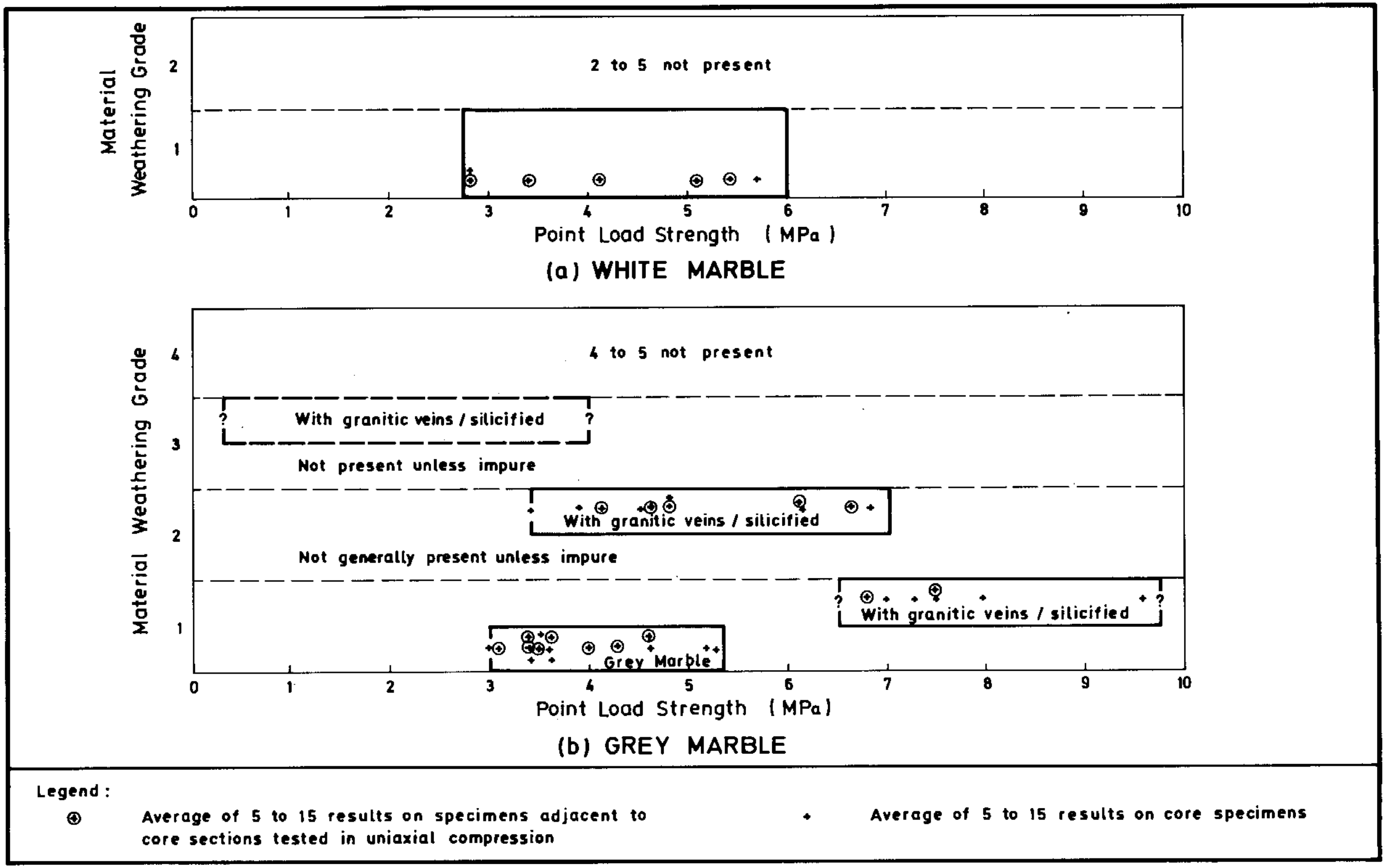


Figure 12 - Ranges of Point Load Strength Values for White and Grey Marble

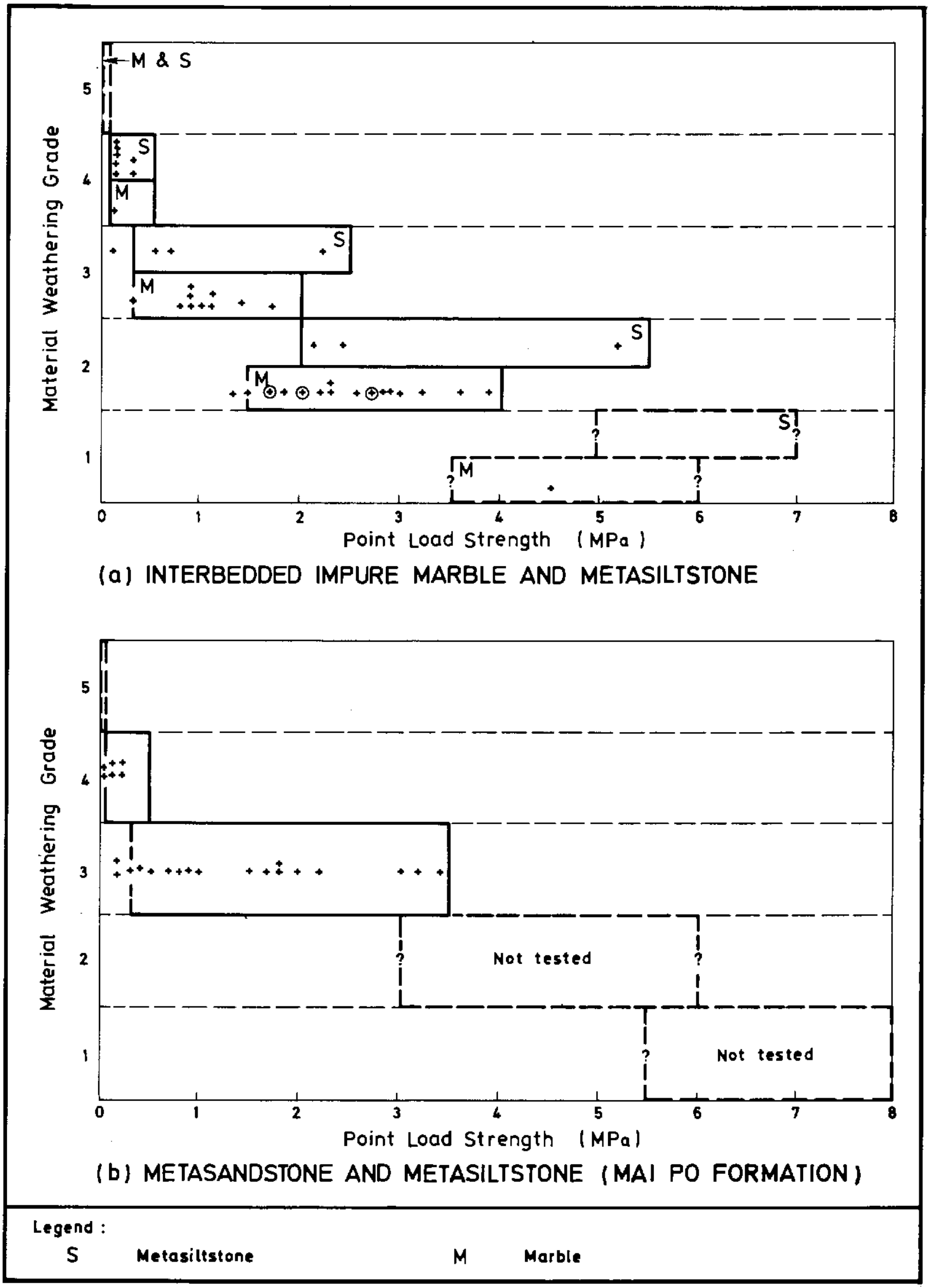
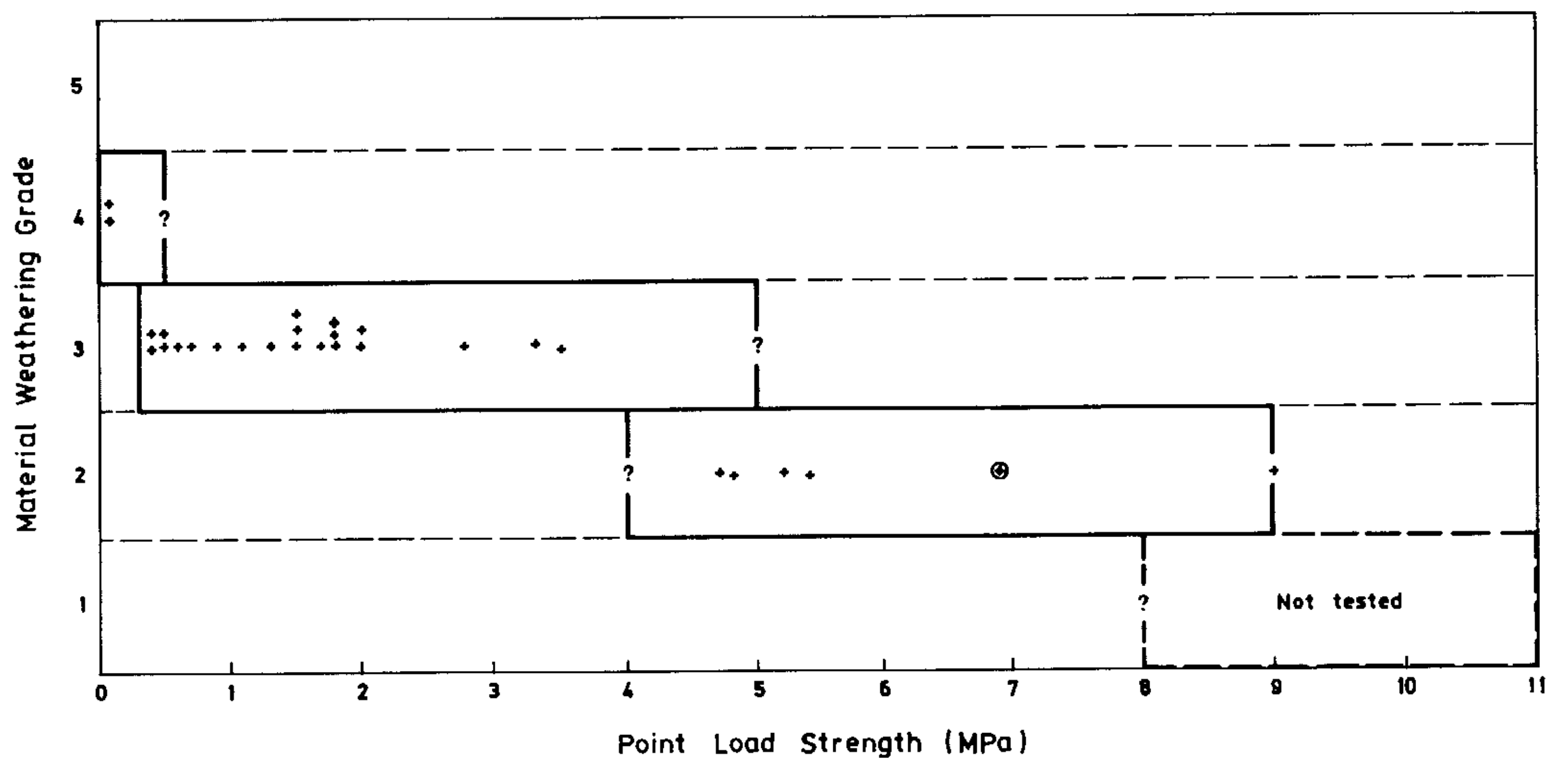


Figure 13 - Ranges of Point Load Strength Values for Banded Impure Marble and Metasiltstone (Yuen Long Formation), and Metasandstone and Metasiltstone (Lok Ma Chau Formation)



BASALT

Legend:

⊕ Average of 5 to 15 results on specimens adjacent to core sections tested in uniaxial compression

\+ Average of 5 to 15 results on core specimens

Figure 14 - Ranges of Point Load Strength Values for Basalt

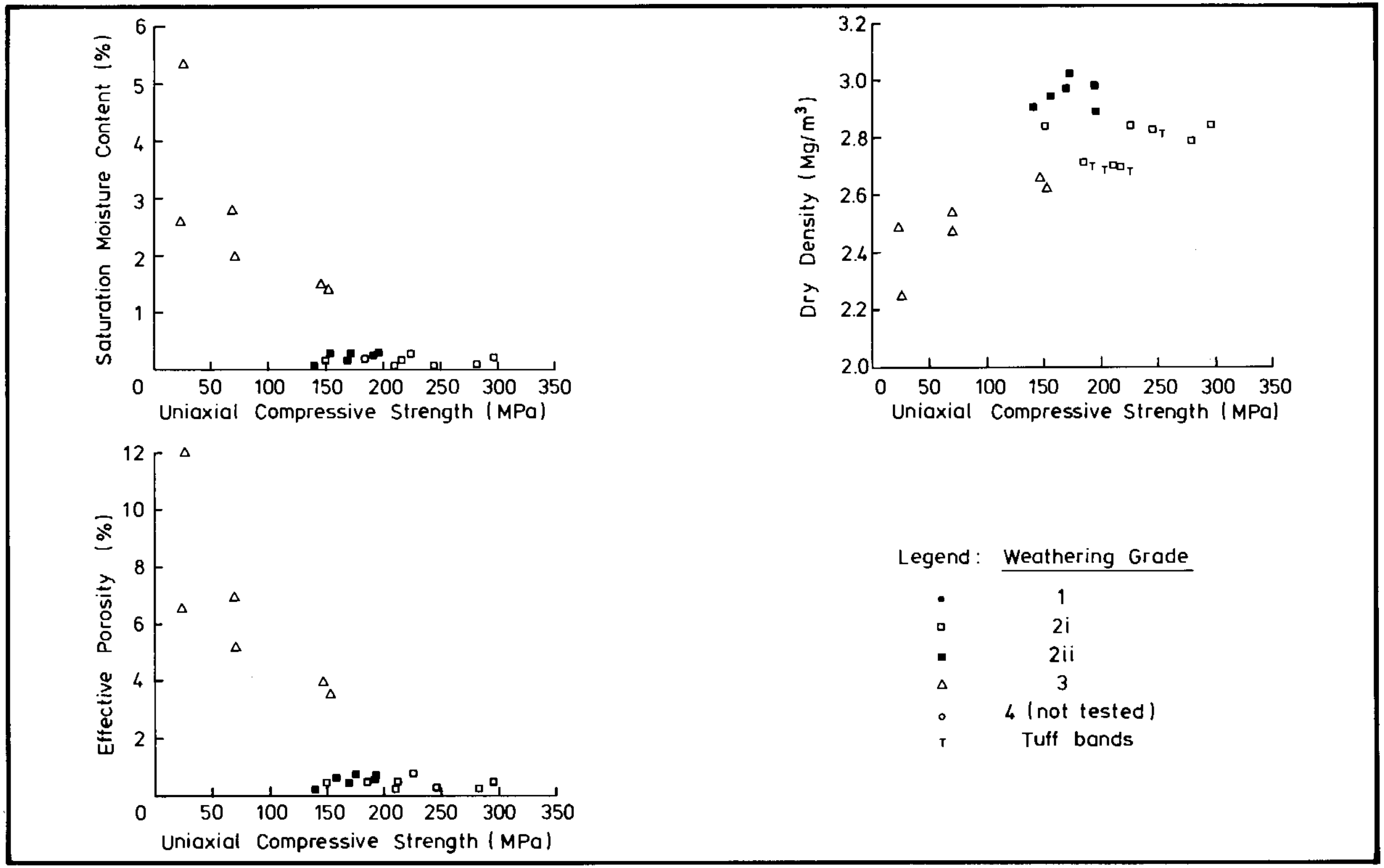


Figure 15 - Relationships Between Index Properties and Uniaxial Compressive Strength for Tuff Breccia

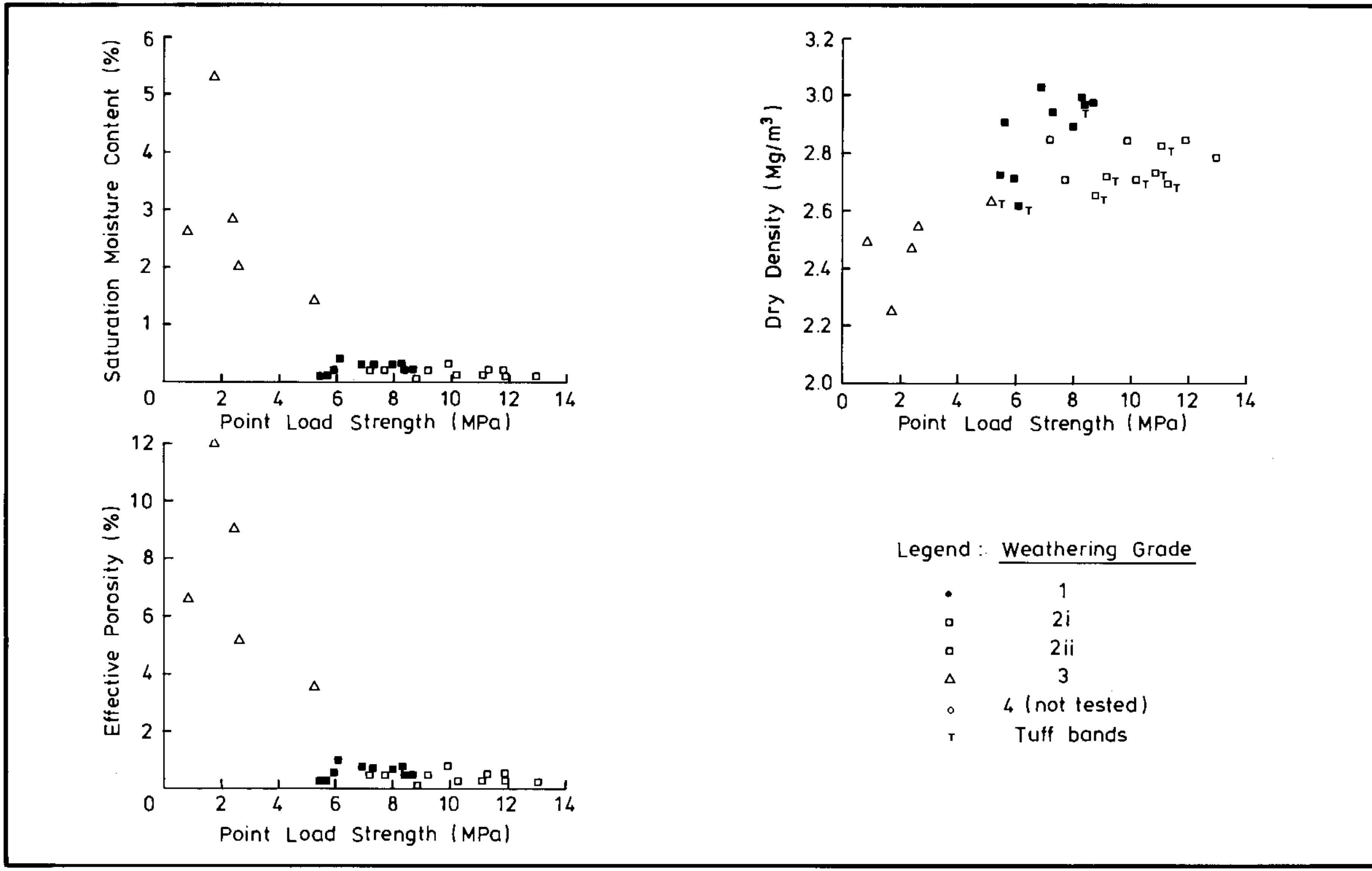


Figure 16 - Relationships Between Index Properties and Point Load Strength for Tuff Breccia

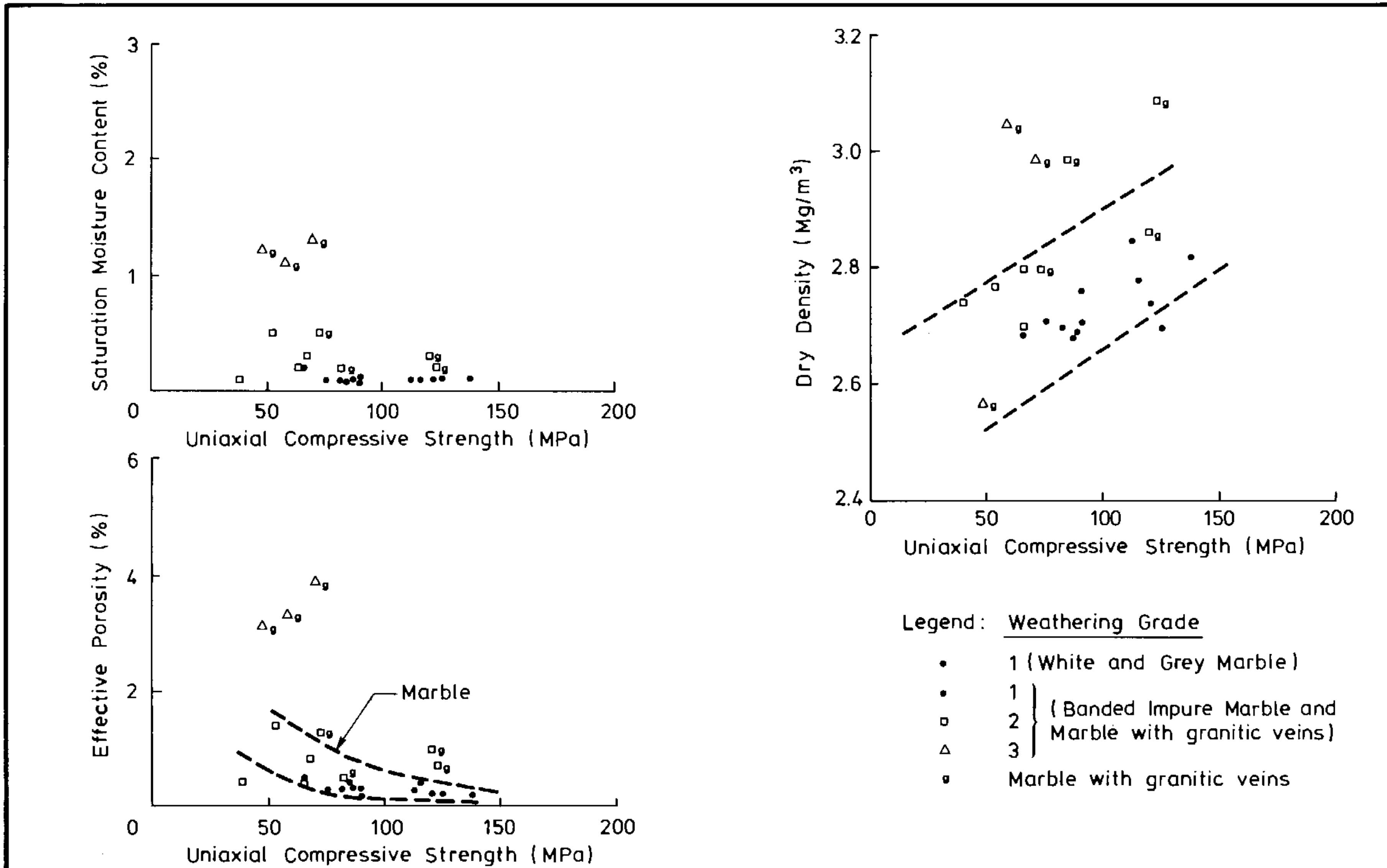


Figure 17 - Relationships Between Index Properties and Uniaxial Compressive Strength for Marble

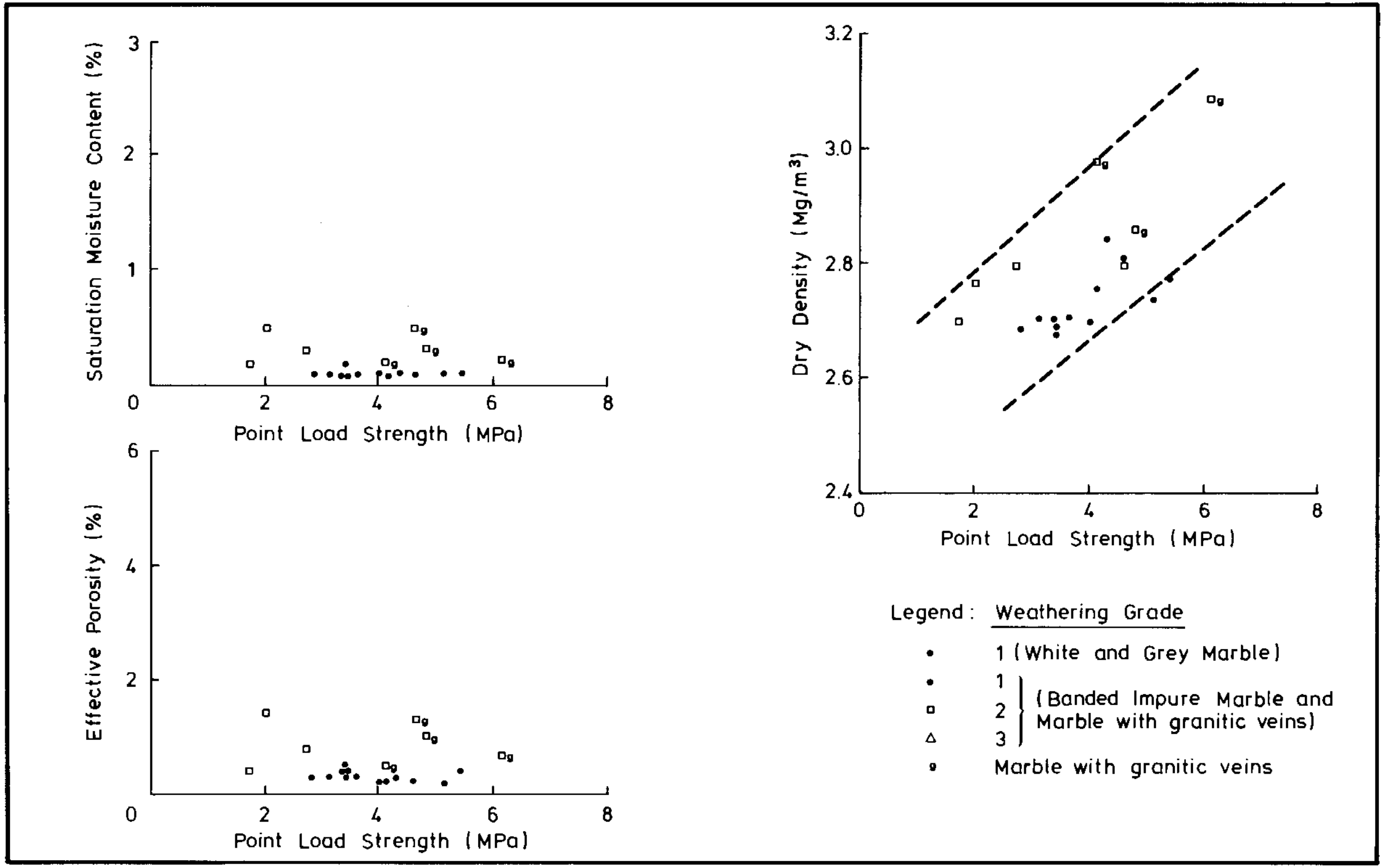


Figure 18 - Relationships Between Index Properties and Point Load Strength for Marble

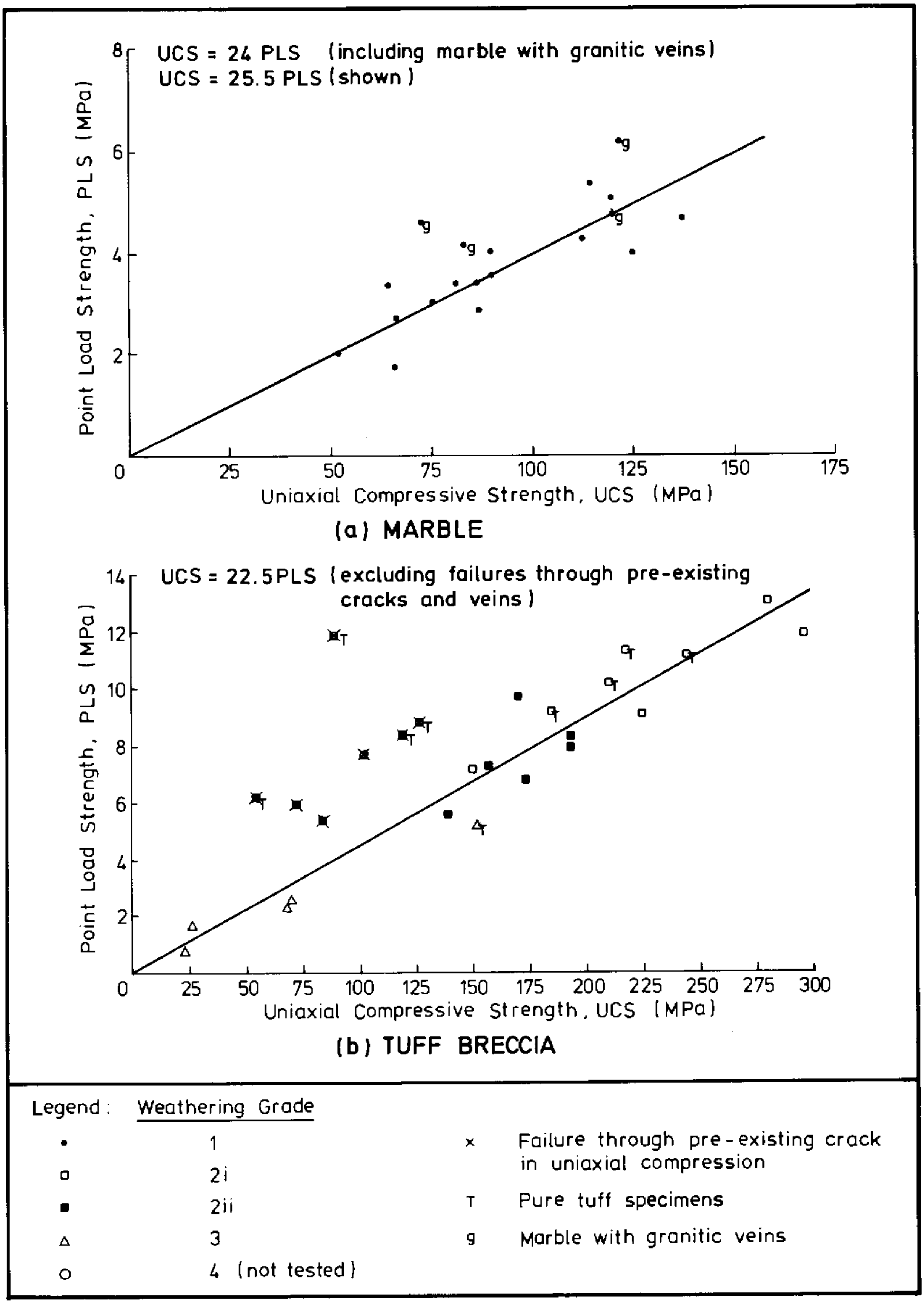


Figure 19 - Relationships Between Uniaxial Compressive Strength and Point Load Strength for Marble and Tuff Breccia

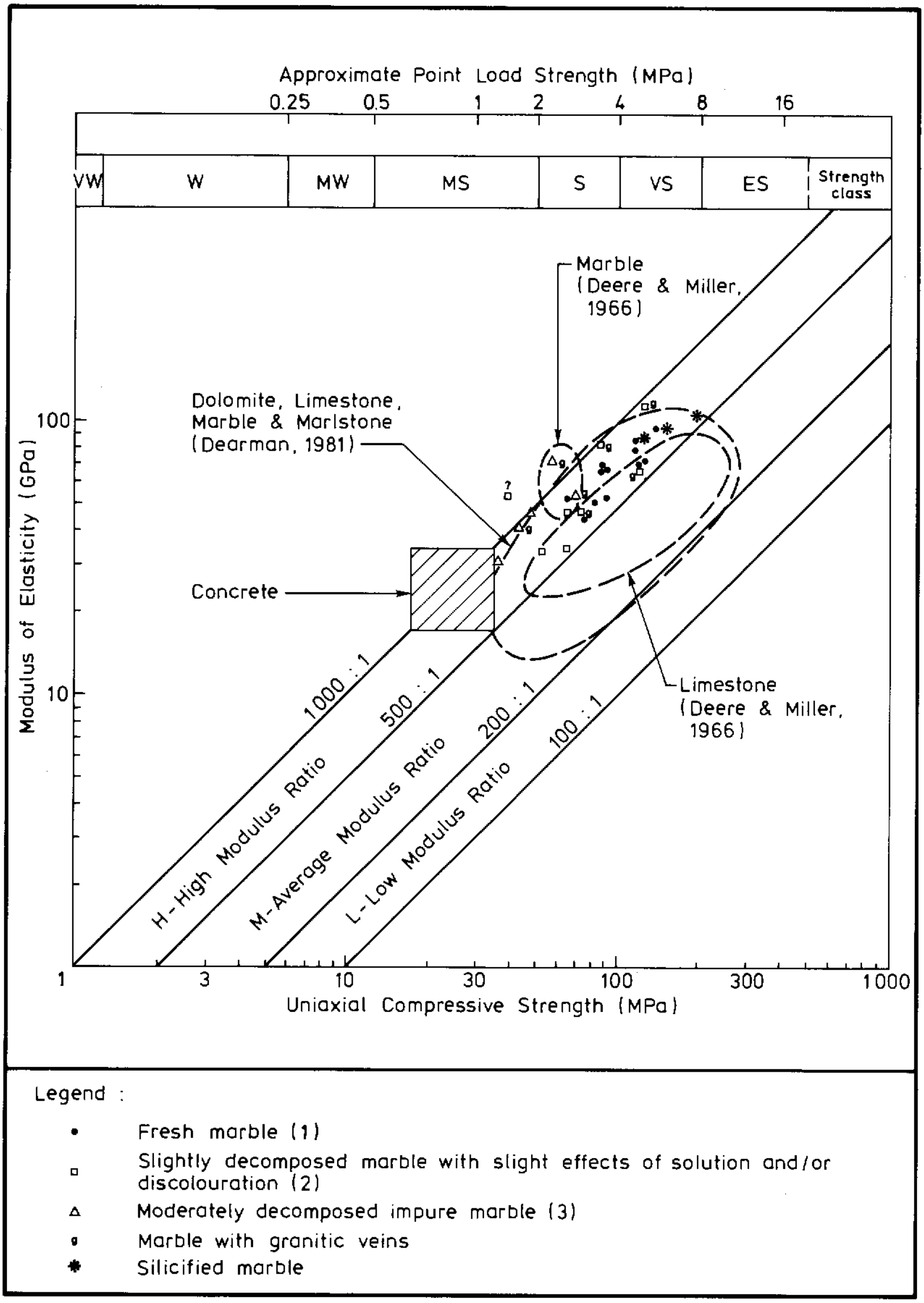
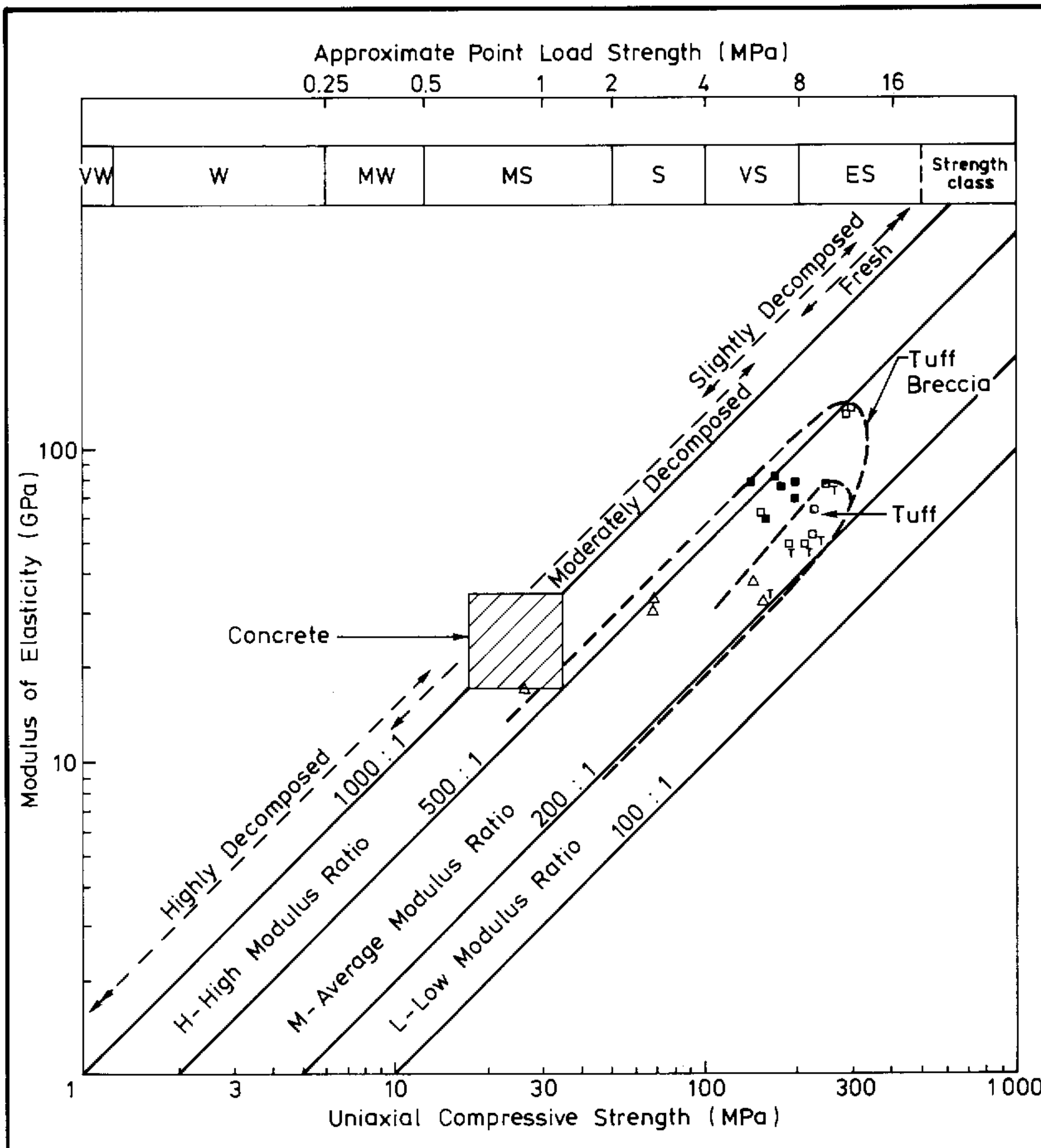


Figure 20 - Engineering Classification of Marble in Terms of Elastic Modulus and Uniaxial Compressive Strength



Legend : Weathering Grade

- • 1 (not tested)
- □ 2i
- ■ 2ii
- △ 3
- o 4 (not tested)
- т Pure tuff bands

Note : Failures through pre-existing cracks and veins are excluded.

Figure 21 - Engineering Classification of Tuff Breccia in Terms of Elastic Modulus and Uniaxial Compressive Strength

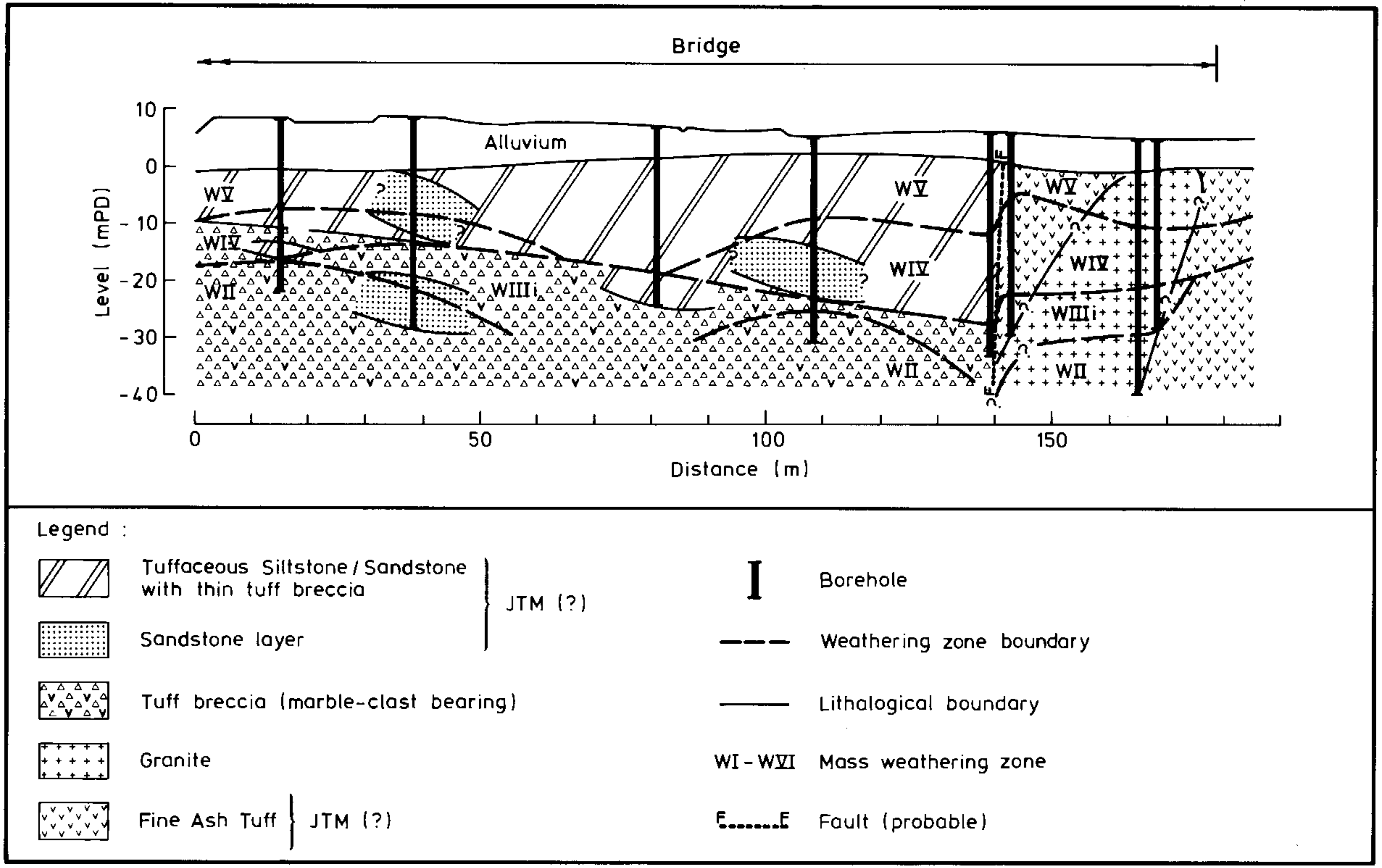


Figure 22 - Weathering Profile in Volcanic Rock Units at Interchange No. 1

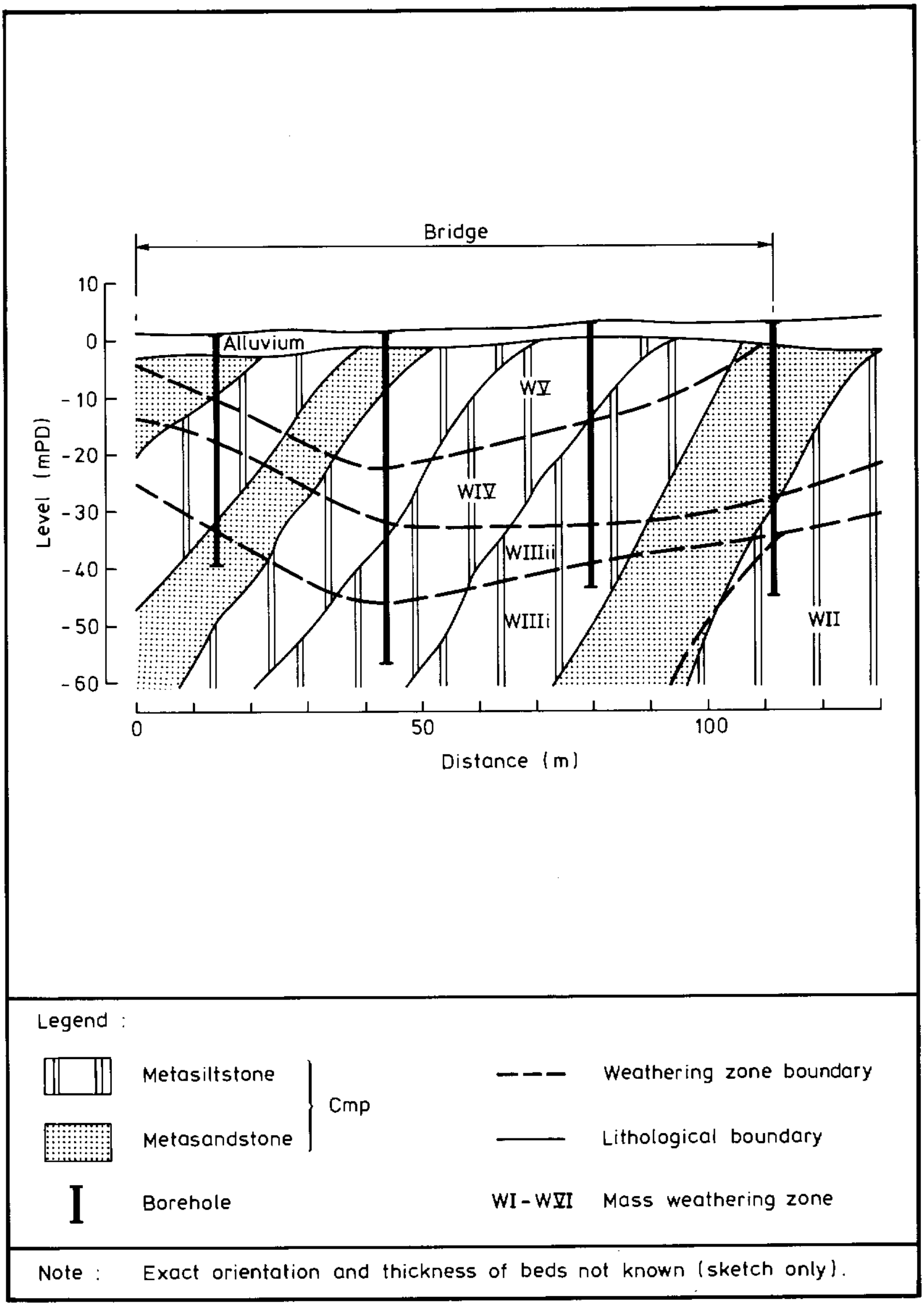


Figure 23 - Weathering Profile in Metasedimentary Rocks
at Interchange No. 4

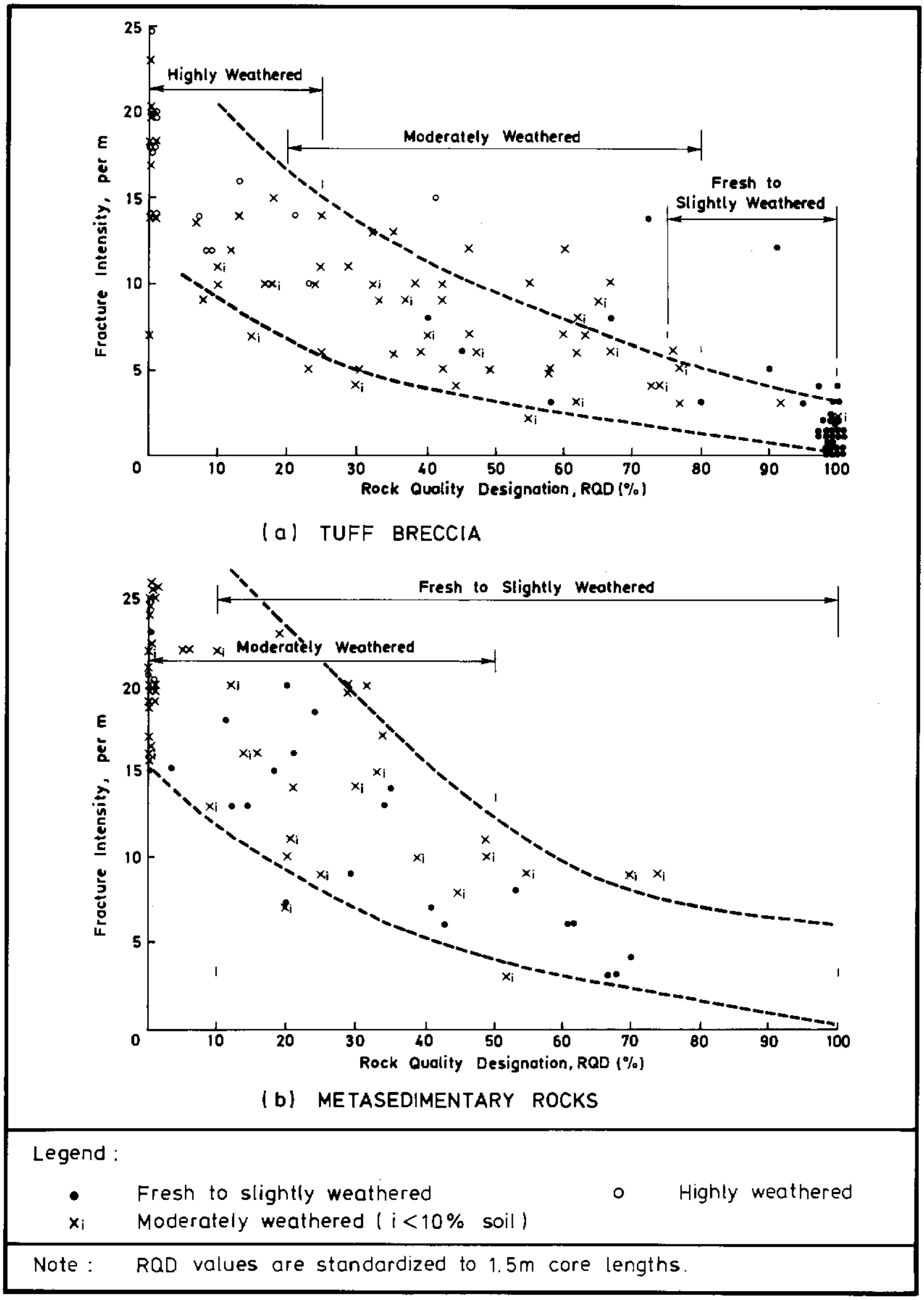
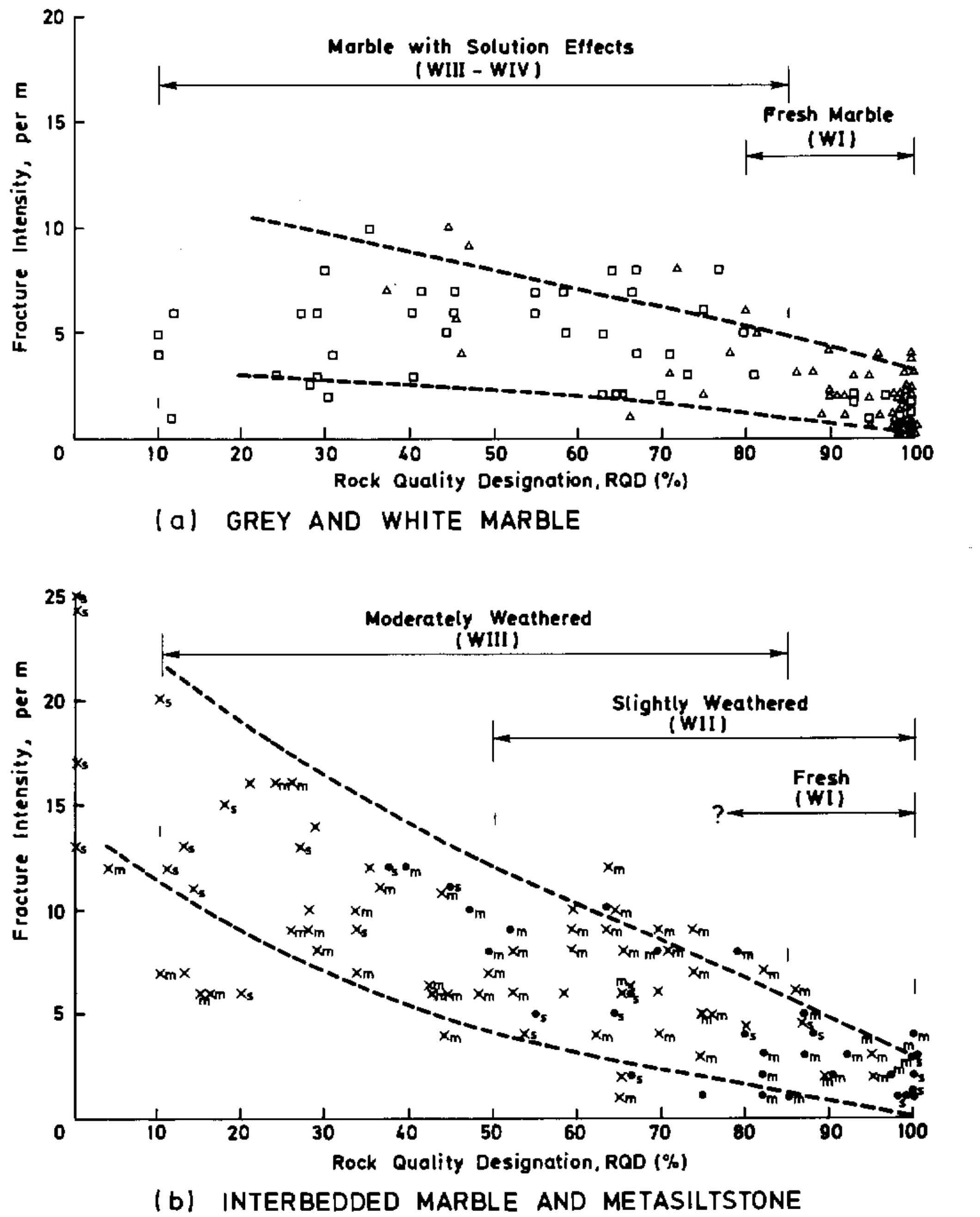


Figure 24 - Fracture Intensity Versus RQD for Tuff Breccia (Tuen Mun Formation) and Metasedimentary Rocks (Lok Ma Chau Formation)



Legend :

△	Fresh marble	□	Marble with solution effects
•	Fresh/Slightly weathered	x	Moderately weathered
m	Marble	s	Metasiltstone

Note : RQD values are standardized to 1.5m core lengths.

Figure 25 - Fracture Intensity Versus RQD for Grey and White Marble and Interbedded Marble and Metasiltstone Subunits (Yuen Long Formation)

PLATES

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Plate 1 - Oblique Aerial Photograph Showing the Northwest New Territories and the Proposed Yuen Long to Tuen Mun Eastern Corridor

Borehole No. BD 47

Borehole No. BD 47

Test Specimens :

M 1 (34.5 - 34.7 m); M 2 (34.7 - 34.9 m); M 3 (39.6 - 39.8 m);
M 4 (45.4 - 45.8 m); M 5 (47.5 - 47.7 m); M 6 (48.9 - 49.2 m);
M 7 (49.2 - 49.4 m)

Completely to highly decomposed basalt dyke at 11.7 - 29.0 m, completely decomposed altered marble (by basic and acidic dyke intrusions) at 29.0 - 34.4 m, marble with granitic veins at 34.4 - 35.05 m, completely decomposed altered fault / dyke at 35.05 - 39.3 m, slightly to completely discoloured grey marble with granitic veins at 39.3 - 52.9 m, slightly discoloured to fresh grey marble over 52.9 m. Possible void (no core recovery) at 45.8 - 46.9 m, highly to completely decomposed (altered) marble at 41.2 - 42.3 m, 43.4 - 45.4 m and 49.45 - 52.9 m.

Plate 2 - Grey Marble with Granitic Veins (Yuen Long Formation)

Borehole No. BD 47

Borehole No. BD 47

Test Specimens :

M 8 (56.5 - 56.65 m); M 9 (56.65 - 56.8 m); M 10 (59.8 - 60.0 m); M 11 (64.6 - 64.8 m)

Solution effects and staining along joints. Colour changes to dark grey at 65.2 m. Infilled cavities at 56.9, 58.15 and 60.0 m.

Plate 3 - Grey Marble (Yuen Long Formation)

Borehole No. BD 54

Borehole No. BD 54

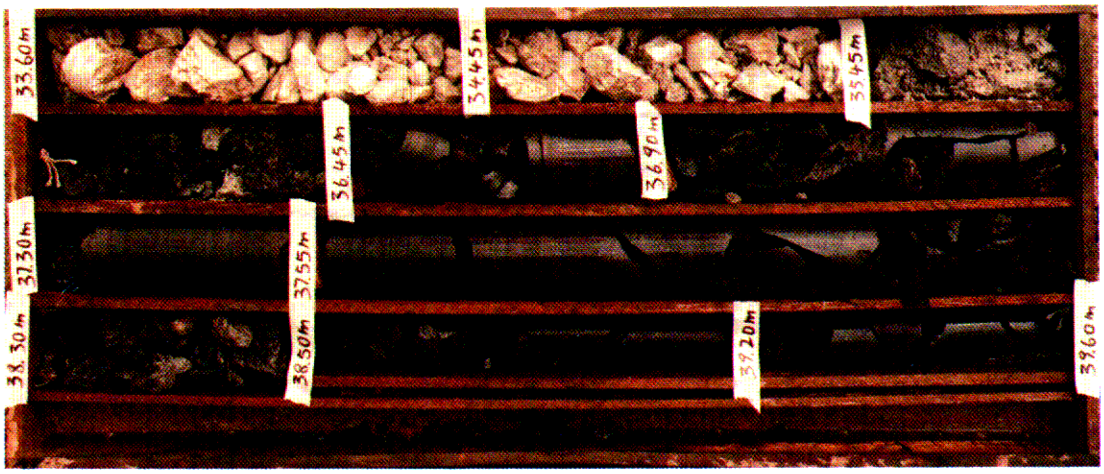
Test Specimens :

M22 (44.6 - 44.8 m) ; **M23** (45.2 - 45.4 m)

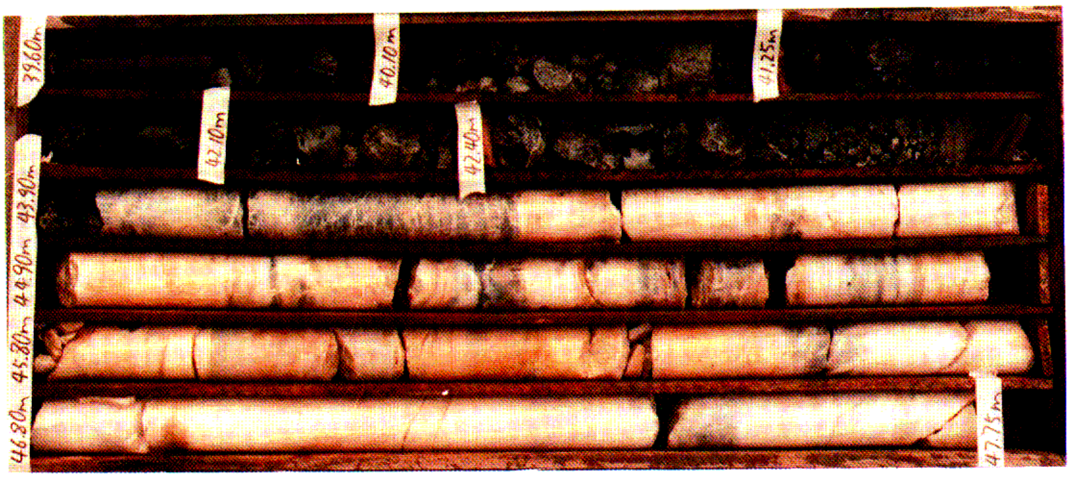
Alluvium 0 - 12 m, completely weathered metasiltstone and impure marble zone 12 - 18 m (SPT < 60), highly weathered metasiltstone and impure marble zone 18 - 30 m (SPT > 60), moderately weathered impure marble with metasiltstone zone 30 - 40 m, slightly weathered impure marble zone 40 - 43 m and fresh grey marble, over 43 m.
Jar samples : highly decomposed impure marble and metasiltstone.

Plate 4 - Impure Marble Interbedded with Phyllite, and Grey Marble (Uppermost Part of the Ma Tin Member, Yuen Long Formation)

Borehole No. BD 55



Borehole No. BD 55



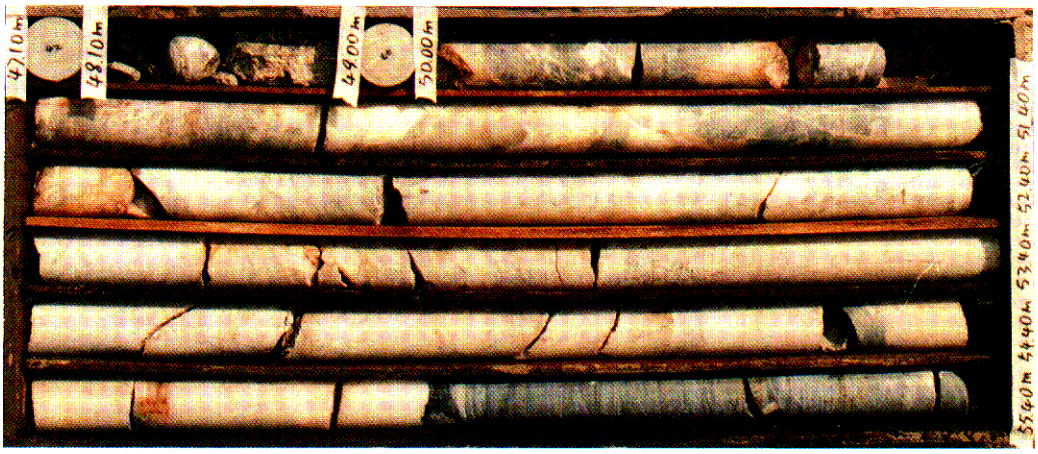
Test Specimens :

M 24 (47.3 - 47.6 m)

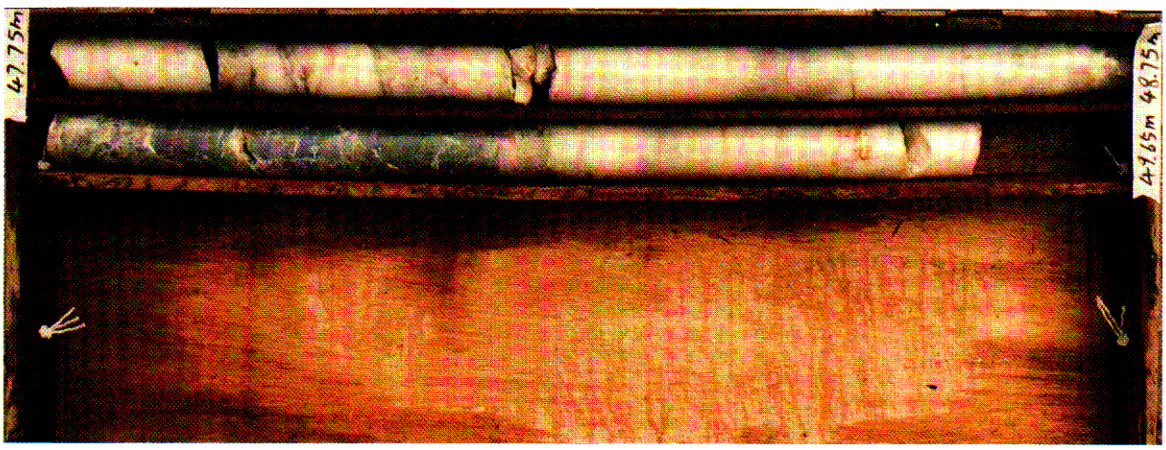
Highly to completely decomposed/altered (by dyke intrusion) marble at 33.6 - 35.6 m and 40.1 - 44.0 m, basalt dyke at 35.65 - 40.0 m, white marble with slight solution effects and grey marble bands at 44.0 - 47.75 m.

Plate 5 - White Marble Altered by Basalt Dyke Intrusion

Borehole No. BD 50A



Borehole No. BD 55



Test Specimens :

M18 (51.8 - 52.0 m); **M19** (52.0 - 52.2 m); **M20** (53.3 - 53.5 m), Borehole **BD 50** ; **M25** (48.2 - 48.4 m), Borehole **BD 55**

Plate 6 - White and Grey Marble (Ma Tin Member, Yuen Long Formation)

Borehole No. BD 53

Borehole No. BD 53

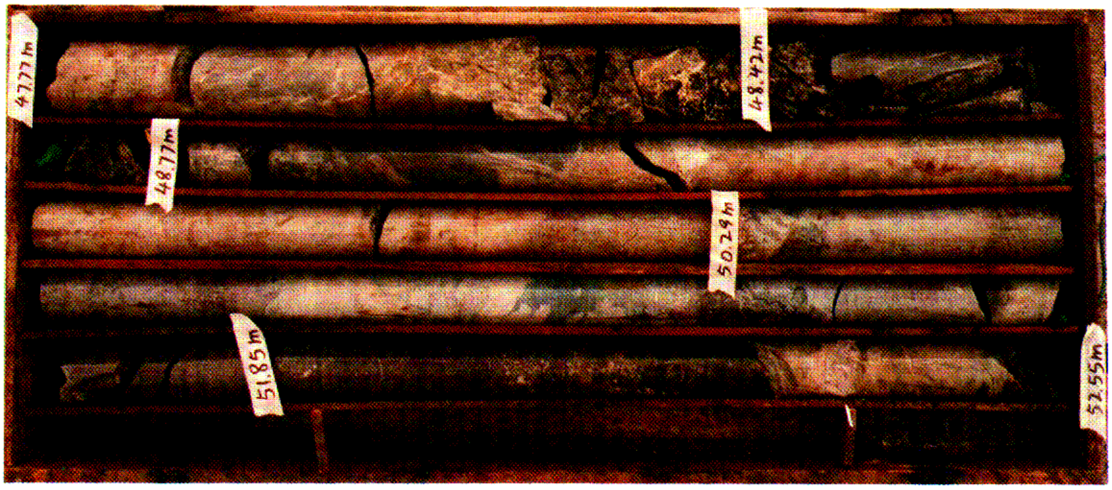
Test Specimens :

M 26 (30.6 - 30.9 m). Other test specimens **M 27** (70.8 - 71.0 m), **M 28** (73.2 - 73.4 m) and **M 29** (74.3 - 74.5 m) are not shown.

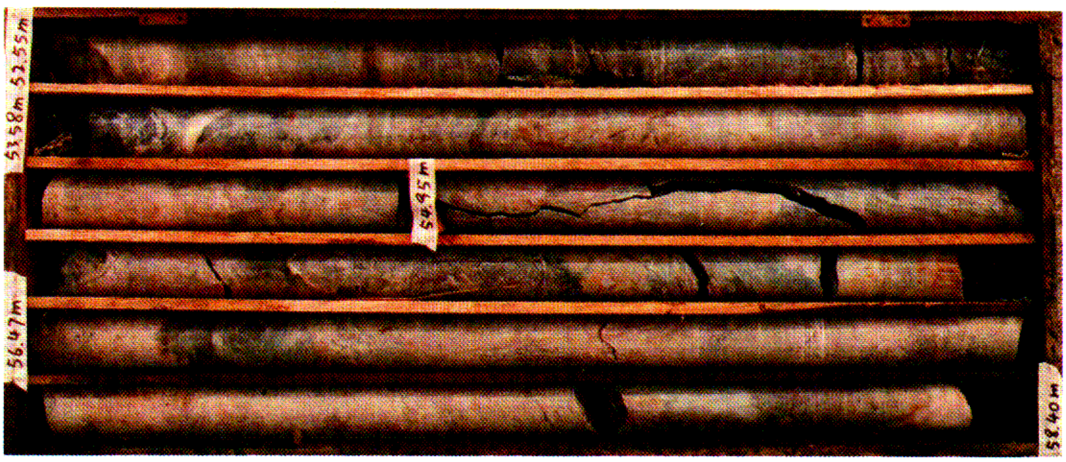
Moderately to highly decomposed impure marble at 30.9 - 31.6 m.
Metasiltstone at 37.4 - 39.3 m.

Plate 7 - Banded Impure Marble with Metasiltstone (Uppermost Part of the Ma Tin Member, Yuen Long Formation)

Borehole No. BD 40



Borehole No. BD 40

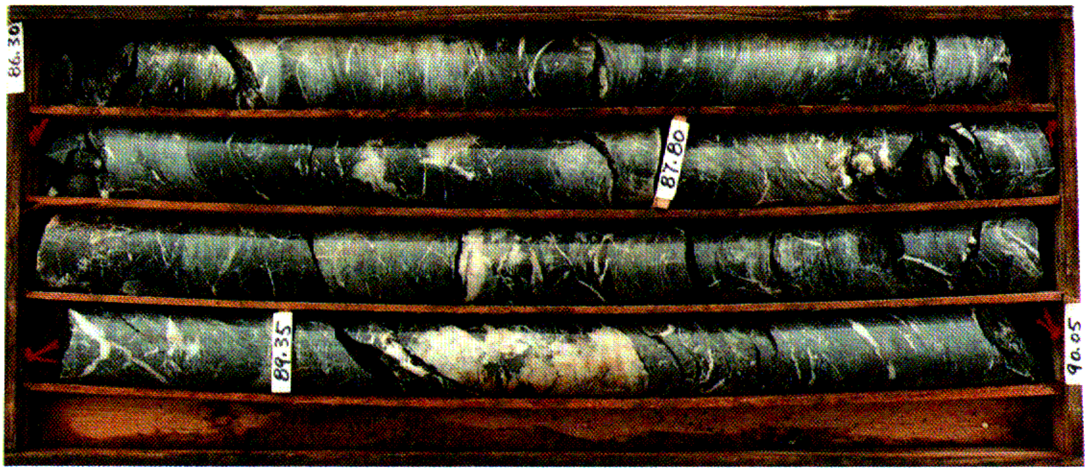


Test Specimens :

M12 (49.7 - 49.9 m); **M13** (50.15 - 50.3 m); **M14** (50.6 - 50.8 m); **M15** (57.5 - 57.7 m). Other test specimens **M16** (59.9 - 60.1 m) and **M17** (60.2 - 60.4 m) are not shown.

Plate 8 - Silicified Grey Marble

Borehole No. BGS 2 (Hong Kong Geological Survey Borehole).



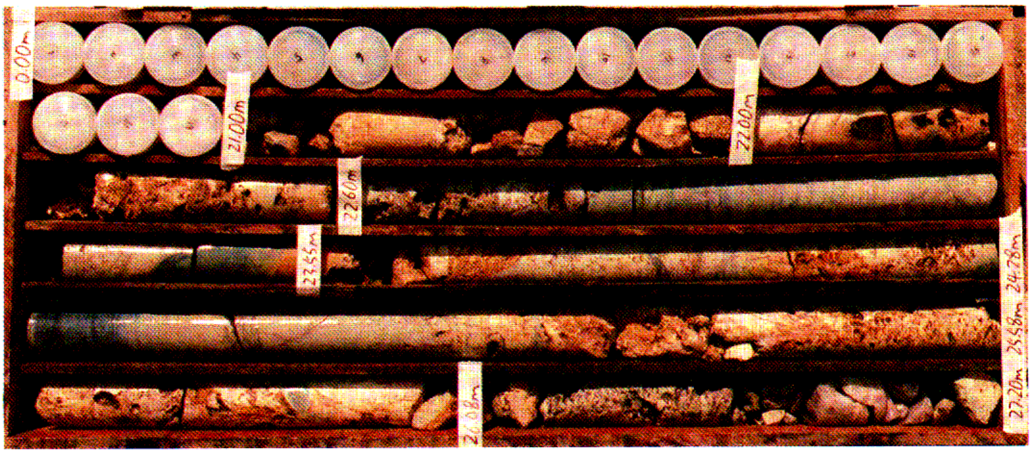
Borehole No. BGS 2 (Hong Kong Geological Survey Borehole).

Test Specimens :

Not tested.

Plate 9 - Dark Grey to Black Marble (Long Ping Member, Yuen Long Formation)

Borehole No. BD 9 B



Borehole No. BD 9 B

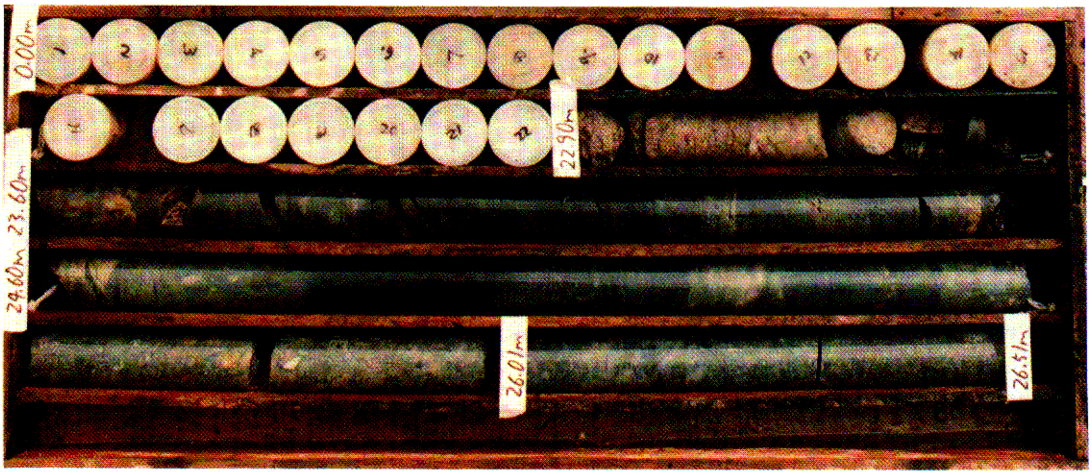
Test Specimens :

CTB 13 (33.8 - 34.0 m); CTB 14 (34.6 - 34.8m); CTB 15 (34.8 - 35.0m);
CTB 25 (23.8 - 24.0 m); CTB 26 (24.1 - 24.3m); CTB 27 (24.6 - 24.8m)

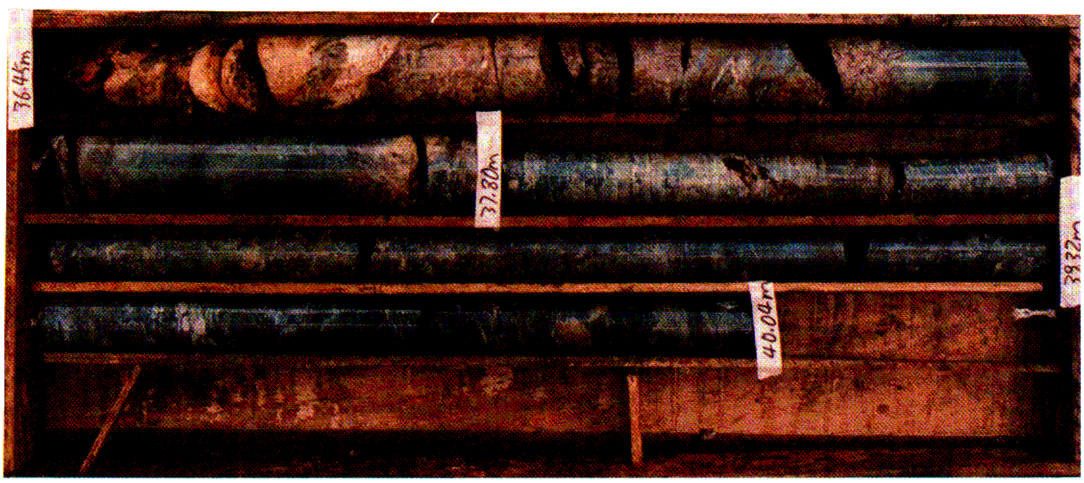
Honeycombed (with solution voids) moderately to highly decomposed tuff breccia at 21.0 - 22.8m, 23.6 - 24.3m and 24.6 - 27.2m, slightly decomposed tuff breccia at 22.8 - 23.6m and 24.3 - 24.6m, slightly decomposed to fresh tuff bands (with marble clasts) at 33.6 - 35.9m.

Plate 10 - Tuff Breccia with Marble Clasts (Tuen Mun Formation)

Borehole No. BD 8A



Borehole No. BD 3



Test Specimens :

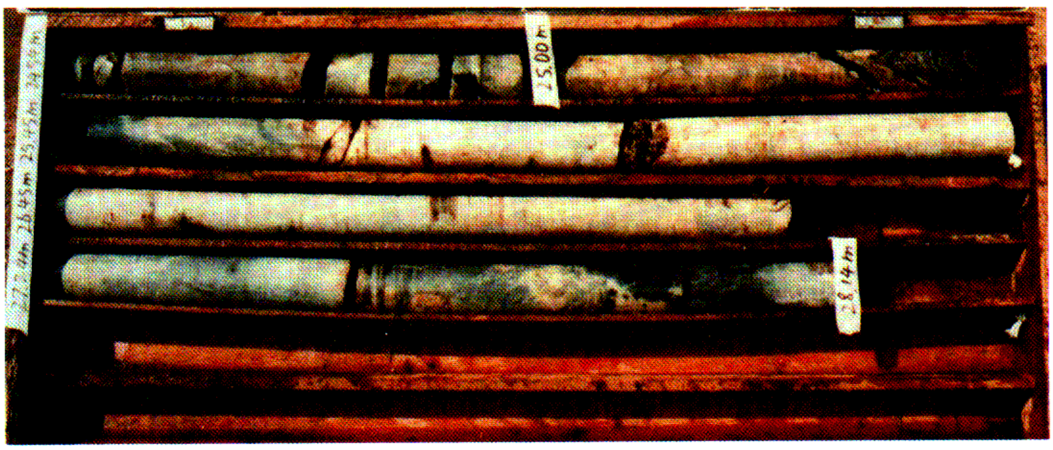
CTB11 (25.6 - 25.8 m); CTB12 (25.8 - 26.0 m), Borehole **BD 8A**;
CTB 9 (38.8 - 40.0 m), Borehole **BD 3**

Slightly decomposed (slightly to highly discoloured) tuff breccia at 37.4 - 40.0 m, and moderately decomposed (completely discoloured and with minor solution holes) tuff breccia at 36.45 - 37.4 m in borehole BD 3. Slightly decomposed marble clast-bearing tuff breccia at 23.8 - 26.5 m, pure tuff band at 24.9 m, in borehole BD8A.

Plate 11 - Tuff Breccia with Marble Clasts (Tuen Mun Formation)

Borehole No. DT 7

Borehole No. DT 1



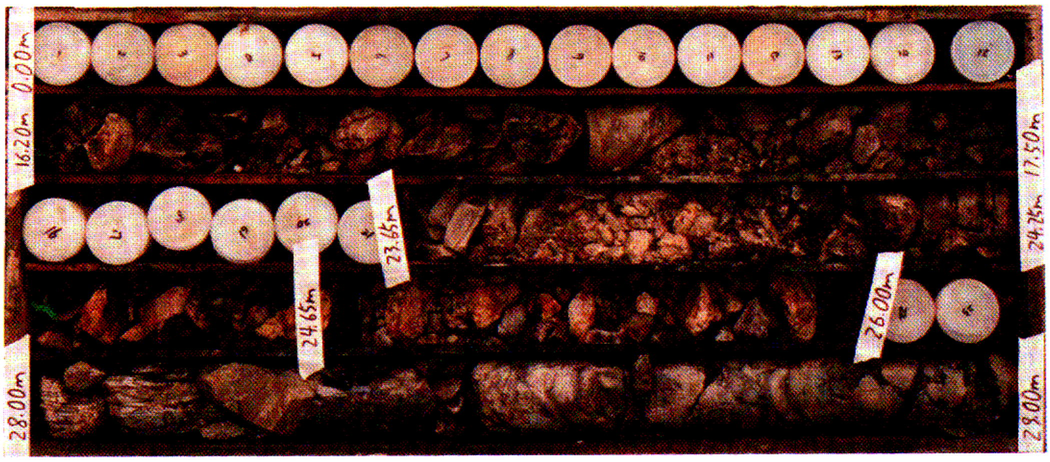
Test Specimens :

CTB1 (26. 5 - 26. 8m); **CTB2** (27.8 - 28. 1 m), Borehole **DT1**;
CTB3 (16. 8 - 17. 0m); **CTB4** (17. 6 - 17. 75m), Borehole **DT7**

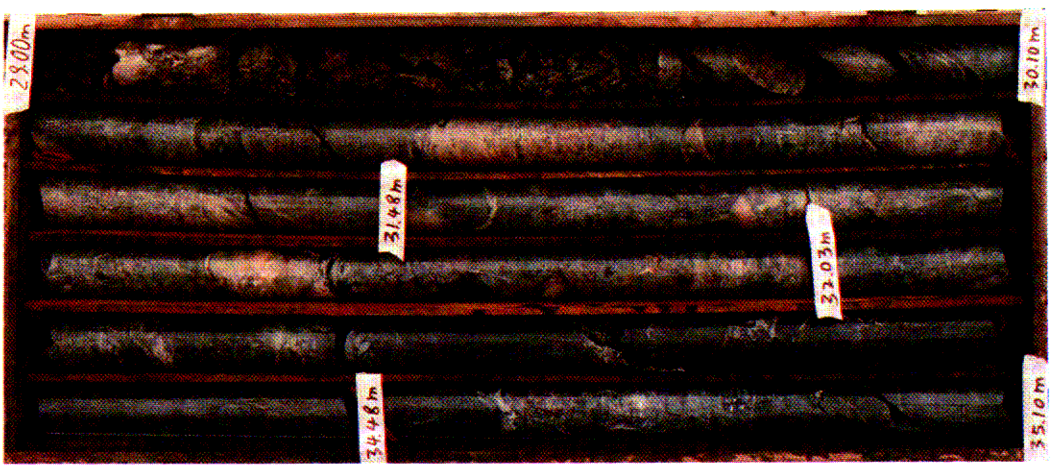
Slightly decomposed (slightly to highly discoloured) tuff breccia at 15. 8 - 18.58m in Borehole DT 7, moderately decomposed (completely discoloured) tuff breccia at 25. 7 - 27. 25m in Borehole DT1.

Plate 12 - Tuff Breccia with Marble Clasts (Tuen Mun Formation)

Borehole No. BD 11



Borehole No. BD 11



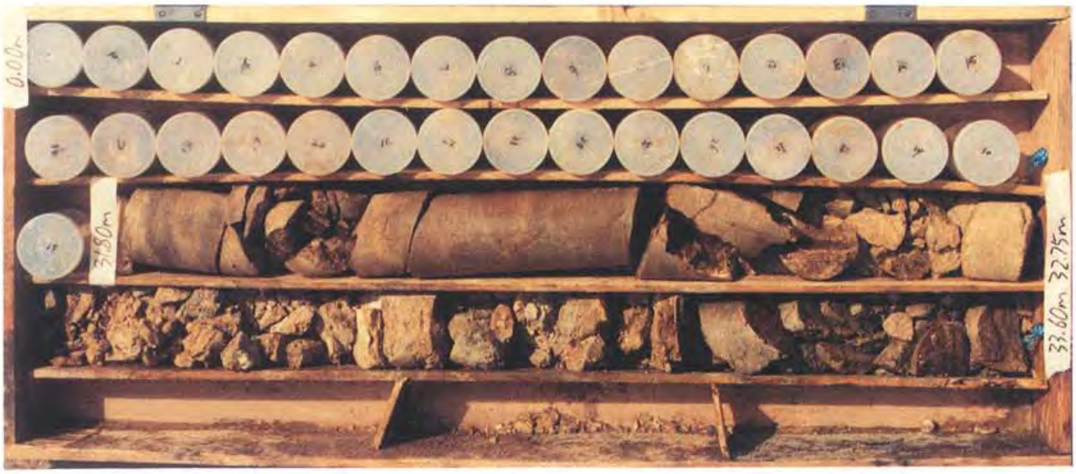
Test Specimens :

CTB16 (31.2 - 31. 35 m); **CTB17** (32. 3 - 32.6 m); **CTB18** (32. 6 - 32.9 m)

Siltstone 16. 2 - 17. 5 m, sandstone 17. 5 - 28. 0 m, tuff breccia 28.0 - 35.1 m.

Plate 13 - Sandstone, Siltstone and Tuff Breccia (Tuen Mun Formation)

Borehole No. BD 59



Borehole No. BD 59

Test Specimens :

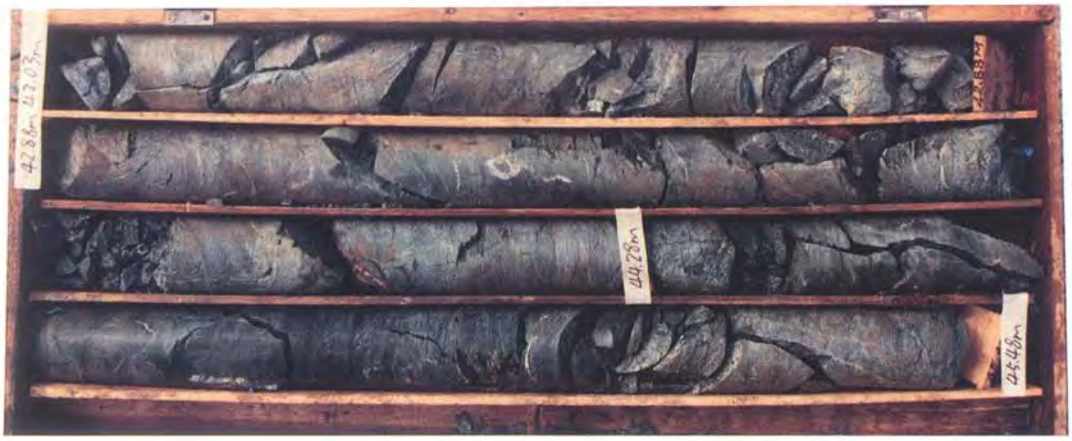
Not tested.

Alluvium 0 - 5 m, completely weathered metasiltstone zone 5 - 11m, highly weathered metasandstone with metasiltstone zone (SPT >60) 10 - 31.8 m, moderately weathered metasandstone zone 31.8 - 37.2m.

Plate 14 - Metasandstone and Metasiltstone (Lok Ma Chau Formation)

Borehole No. BD 59

Borehole No. BD 59



Test Specimens :

Not tested.

Slightly weathered metasandstone zone 37.2 - 44.4 m,
fresh metasandstone zone over 44.4 m.

Plate 15 - Metasandstone and Metasiltstone (Lok Ma Chau Formation)