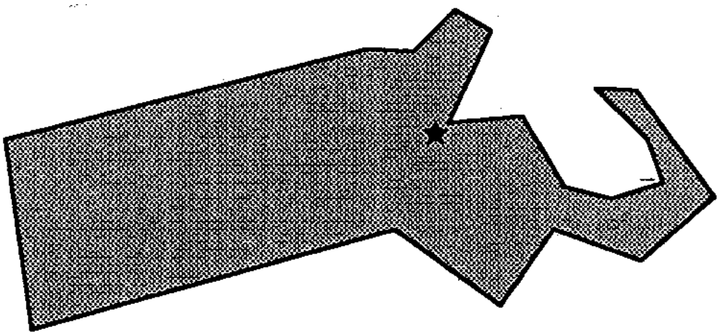
GEOLOGICAL BACKGROUND AND ENGINEERING PARAMETERS OF BOSTON BLUE CLAY



PETER J CONNORS

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CONTENTS

INTRODUCTION

- -Boston Blue Clay, (BBC), is a marine clay existing in one of the layers of the complex Boston soil profile. This report investigates:

1. The history of Boston geology, detailing the environmental and man made conditions leading to the final composition exhibited by the present clay layer.
2. The engineering parameters of BBC including index classification, strength parameters, stress history, and compressibility.
3. The effects of stress history, anisotropy, and thixotropy of BBC on its engineering parameters.

GEOLOGY OF THE BOSTON BASIN

The Boston Basin lies in a valley off the eastern border of the Appalachian Orogenic belt. This zone is a fault-bounded structural and topographic basin containing a wide variety of strata having highly irregular stratigraphic and structural relations formed from a piece of North west Africa that clung to North America during late Precambrian and early Paleozoic collision between Paleo-North American and Paleo-African Plates. Earthquake activity and other indications of crustal movement show it to still be a tectonically active region (Barosh et al., 1989).

The subsurface composition, stratigraphy, and topography of sedimentary and volcanic rock, as well as the variety of overburden soils were formed from a combination of widespread volcanic activity, earthquakes, erosion, glacation, climate and weather ,and man-made filling, see figures 1 and 2 (Barosh et al., 1989) and figure 3 (Aldrich, 1970). 3,600 to 500 million years ago, during Precambrian, Cambrian, and Ordovician periods, volcanic activity created complexes of rock on either side of the Boston Basin (Barosh et al.,1989). Also in these periods, faulting of the basin by earthquaking and tectonic movements structurally deformed the basin. In later periods, about 14,000 years ago, the Pleistocene and Holocene Eras, successive advances and retreats of glacial ice followed by extreme variations of climate and sea level eroded the bedrock and deposited the overlying soils (Barosh et al., 1989), (Aldrich, 1970).

Upon the final melting and retreating of the Wisconsin ice sheet, land rebounding from the mass of ice and a rise in sea level formed the soil conditions and topography of the soils subsequent to man made filling of the Boston Basin. Little geologic change has affected the area since the filling of the basin by man (Barosh et al., 1989). The fill, gotten from points of higher elevation and surrounding areas, was placed to make way for the expanding population of the Boston area, see figure 3.

STRATIGRAPHY OF THE SOILS OF THE BOSTON BASIN

The complexity of the soil profiles typical to the Boston area is demonstrated in figures 4 and 5, (Aldrich, 1970) and (Johnson, 1989) respectively. Figure 4 shows the boring logs of three actual sites and figure 5 displays the three most likely encountered boring logs of the area. While the extreme bottom layer of the profile apparently contains sound bedrock, the aspects of the bedrock is becoming increasingly important with the construction of major high-rise buildings on deep foundations (Aldrich, 1970). The 2000 to 4000 foot stratum of bedrock is divisible into of two layers. The lower layer is referred as Roxbury Conglomerate. The upper layer, Cambridge Slate, also known as Argillite, is composed of fine-grained clayey rocks, slaty in places, derived from siltstone, claystone, or shale. The untouched Argillite is a hard material bluish to brownish gray in color, whereas weathering or hydrothermal alteration has changed the material to a light gray kaolin (Aldrich, 1970), (Johnson, 1989). In many areas the argillite is highly weathered or altered to the degree that the material can be readily crumbled between the fingers (Johnson, 1989). To the foundation engineer the presence of the altered argillite and the occurrence of the clay seams within an otherwise hard indurated rock, present an important condition to be explored for any major building project (Aldrich, 1970).

The overburden soils of natural and manmade deposits consist of glacial till, BBC, sand and gravel outwash, organic soils, sand and gravel fill, and manmade fill. The glacial till is a compact unsorted non-stratified mixture of rock fragments and minerals. Unweathered, the till is blue-gray, while the weathered till is a rusty buff color. Pockets and layers of pervious stratum of sand and gravel are located in the till.

Mantling the till is a complex layer of a marine clay. The marine clay, BBC, is a deposit of sediments transported by streams of melted glaciers during the Pleistocene age. The sediments settled out of the glacial waters in the quiet marine Boston Basin. The clay deposit consists of two distinct layers equaling a total thickness of 50 to 125 feet. The upper layer has a yellowish or brownish crust of clay that experienced severe weathering and desiccation. The lower layer, blue-gray to drab olive-green color, has a medium to soft consistency. Located throughout the clay are discontinuous layers and lenses of sand, rocks, and isolated pockets of granular soil and occasional boulders. The sand layers have enabled the clay to obtain a higher degree of permeability in the horizontal direction (Morrison, 1984), (Johnson, 1989). Sand, peat, and silt cover the layers of clay, which overlie glacial till and bedrock.

Following the readvance of glacial ice, a well stratified, very pervious layer of sand and fine gravel deposited above the BBC's weathered crust. The deposit ranges in thickness from 10 to 25 feet. The deposit is recognized as a medium compact to compacted gray, well-graded gravelly sand.

The next soils, organic deposits laid over the Boston Basin before the filling by man, are classified into three distinct layers. First a layer of fresh water peat was deposited above the sand and gravel outwash. This deposit was formed in areas having sluggish drainage. Above this deposit, a layer of organic silt with shells was formed in salt water by tidal action. This layer is gray in color and varies from a non-plastic silt to a plastic clayey silt. The final layer of organic origin, a deposit of salt marsh peat, formed along the shoreline of the rising sea. All three layers of organic deposit have variable thickness in depth.

The final layer of soil, the fill, was deposited in the tidal areas throughout the Boston Basin over the last two centuries. The fill contains sand, gravel, and other miscellaneous material including dredged materials and demolition rubble. The fill was placed in the tidal areas to increase the amount of land for the growing population. A considerable amount of land was gained for this purpose over that period, as indicated in figure 3 (Aldrich, 1970).

ENGINEERING PARAMETERS OF BOSTON BLUE CLAY

Typical engineering parameters for BBC were obtained through survey of literature. The different literature sources include laboratory and in-situ tests reflecting the general parameters describing the illitic marine clay of the northeastern United States known as Boston Blue Clay. A summary of BBC parameters is presented in table 1.

Index Classification

According to Casagrande's plasticity charts, figures 6 and 7, BBC belongs to the CL zone with other glacial clays such as Detroit, Chicago, and Canadian clays. The CL zone classifies BBC as an inorganic clay of medium plasticity. The BBC deposits of this particular study have typical Atterberg Limits that include a Plasticity Index, PI, of 21 and a Liquid Limit, LL of 41. BBC is classified as a medium to very sensitive clay having a Sensitivity, St, of approximately 7±2. The degree of sensitivity is a problem for laboratory testing since considerable breakdown of the clay's fabric occurs during sample recovery. The clay contains a natural water content, Wn, of 30 to 50% with slight variation in depth, see figures 8 and 9. Generally, the clay's saturated unit weight varies from 114 to 120 pcf. Additional values of index classification are listed in the table 1.

Stress-History

The Boston Blue Clay of the North Eastern United States has a unique stress history affecting its engineering behavior. Upon its formation during glacial periods, several occurrences of uplifting exposed the upper layer of the BBC deposit to erosion, desiccation, and leaching, contributing to the clay's stress history. Plots of effective stress and overconsolidation ratio vs. depth, in figures 8 and 9, show both the maximum past pressure and OCR are varying with depth. The OCR in the upper layer decreases from approximately 5 to 6.5 down to 1.5, classifying regions of the upper layer as significantly overconsolidated. Beyond the upper layer, the deeper clay is a normally consolidated clay, unchanging with depth.

The maximum past pressure at the top of the clay layer is significantly higher than the effective stresses at that depth. Figures 8 and 9, show a decrease in magnitude of maximum past pressure from 4 to 2.7 tsf through the first layer. Upon entering the lower normally consolidated layer, the maximum past pressure increases linearly with a slightly higher magnitude than the effective stress. At the bottom of the stratum, a depth of 120 ft, the magnitude of the maximum past pressure appears to be roughly 3.5 tsf, according to figures 8 and 9.

Strength Parameters

The strength parameters of Boston Blue Clay vary considerably over the depth of the clay deposit. Figures 10 and 11, exemplify this showing the scatter of the results through the deposit. The undrained shear strength determined by field vanes, shown in figure 10, exhibits a considerable scatter through the upper layer, but a definite trend of increase in magnitude with depth in the lower layer. Overall the upper layer's undrained shear strength varies between 0.3 and 0.6 tsf, while the lower normally consolidated layer, shows a linear increase from 0.4 tsf at a depth of about 80 ft to 0.6 tsf at the bottom of the stratum, at a depth of about 120 ft.

Figure 11 presents the undrained shear strength determined by laboratory methods in comparison to the values obtained by field tests. A considerable scatter of the values obtained for shear strength over depth of the deposit is observed. Figure 11 also presents a comparison of the field strength and the peak SHANSEP results against the performance of the tests run for determination of the undrained shear strength. The results of the SHANSEP method, both in extension and compression, display a band of magnitude, as it relies on OCR and hence on the maximum past pressure for its analysis.

The coefficient of lateral earth pressure, K, is a parameter dependent on OCR and hence on the depth. The plot of Earth pressure vs. elevation, in figure 12, shows a distinct decrease in magnitude with increasing depth for the estimated range of initial conditions of the clay deposit. In the top of the upper layer were the clay exhibits a higher OCR, K is approximately 1.0, but is decreasing with increasing depth to an asymptote of 0.6. Therefore the anisotropic nature of the clay is shown since isotropic behavior deals with materials having equal qualities in all directions.

The friction angle, although dependent upon the type of test and the OCR of the clay, as suggested by Ladd et al 1977, is found to be between 30° and 37°. An average of 33o is primarily used (Baligh and Vivatrat, 1979).

Other Engineering Parameters, displaying the strength characteristics of the clay, are shown in table 1.

Compressibility

The values obtained for the consolidation parameters, after a comparison with other soils, (see Das, 1990), typify it as a clay. The low coefficient of permeability is in the region of being practically impervious, as defined in Holtz and Kolvac, 1981, and will definitely affect the settlement of the clay layer. Aldrich has noted in a 1970 article that: "widely-spread settlements have occurred in some instances to a very marked extent".

As mentioned in a previous section, the clay contains isolated pockets of sand lenses located throughout the clay. These anomalies are more pervious than the clay and increase the horizontal permeability of the clay, (Morrison, 1984) and (Johnson, 1989), therefore affecting its compressibility. The horizontal permeability is almost 4 times the value of the vertical permeability, as can be seen from the values presented in table 1. The ability of horizontal permeability affecting the rate of consolidation has also been emphasized as a conclusion of three-dimensional loading tests. Ladd has concluded that the accelerated rates of consolidation in the clay is due to lateral drainage, (Ladd et al., 1977). Table 1 displays values of compressibility typical of BBC.

THE EFFECT OF ANISOTROPIC BEHAVIOR ON BBC

A material is termed "Anisotropic" if its' properties differ according to the direction of measurement. One of the reasons there are variations in the Engineering parameters of BBC is due to the soil's combined or cross anisotropy. Combined Anisotropy is the combination of inherent and stress system induced anisotropy. Combined anisotropy is a trait of most in-situ clays since normally consolidated, lightly over-consolidated, and heavily over-consolidated clays usually have horizontal to vertical stress ratios less than or greater than one, a trait of stress system induced anisotropy (from O'Neill, 1985).

Inherent anisotropy is a result of nature, where the depositional environment of the clay causes variation in particle orientation. Particle orientation refers to the orientation (i.e. either horizontal, vertical, or some angle in between) in which the particles settled out during formation. Measurements of clays have shown that the particles tend to become oriented in the horizontal direction during one-dimensional deposition and subsequent loading. The inherent anisotropy existing in the clay's structure therefore, causes variation in parameters including modulus of elasticity, shear strength, and pore pressure response (Ladd et al, 1977).

Stress system induced anisotropy is due to the difference in algebraic increment in shear stress necessary to cause failure as the major principal stress varies from parallel to the direction of depositional axis, (from O'Neill, 1985).

The effects of combined anisotropy are shown in figure 13. The results of the test show the progressive decrease in strength of the specimen as the major principle stress moves from the vertical to the horizontal direction (Ladd et al., 1977). The anisotropic nature of the clay is also displayed in figure 14. The pore pressure parameter A_f has a distinct difference in value at the same OCR depending upon the loading condition.

THE EFFECTS OF STRESS HISTORY ON BBC

The importance of stress history on undrained strength-stress-strain properties is well recognized (Ladd et al., 1977). BBC has a distinct decrease in OCR with depth, hence their is a required understanding of the relationship between OCR and strength-strain-stress properties. Skempton's pore pressure parameter, the strength anisotropy, Ks, and undrained strength ratio are shown in figures 14 and 15, to vary significantly with OCR. Skempton's pore pressure parameter tends to decrease with increased OCR, and the other two parameters tend to increase with OCR.

The stress history of the deposit also affects the dissipation of pore pressure, and hence the degree of consolidation in the clay. According to results gathered by Baligh and Vivatrat in 1979, see figure 16, there is a higher degree of pore pressure dissipation in the upper layers of the clay than at greater depths. The upper layers are significantly overconsolidated with respect to the lower clay layers. Therefore the indication of faster dissipation rates when OCR increases is present.

ENVIRONMENTAL EFFECTS ON BOSTON BLUE CLAY

The engineering behavior of a given clay is determined by the structure the clay has at the time of measurement (Lambe, 1958). The structure of Boston Blue Clay is one of the parameters dependent upon the environment. Any change in the soil-water structure caused by environmental impacts might expand the clay particle's Double-layer water layer. The Double-layer water layer is one of two layers of water surrounding the clay particle, the other being the Adsorbed water layer. The expansion of the Double-layer tends to increase the interparticle repulsion causing an increase in the soil structure, therefore resulting in a decrease in the strength of the soil (Lambe, 1958). It has been suggested that the change in the soil-water structure may be brought about by environmental conditions. The environmental changes can be in the form of an increase in temperature, water content, pH and other factors (Lambe, 1958).

Another effect of the environment on BBC's strength results from the BBC's formation in salty environment. The lesser strength of the clay probably arose because it formed in ponds of water that were salty. As the fine suspended particles settled to the bottom to form the clay, salt was incorporated into the clay. Much later, the salt leached out, weakening the clay (Ladd, 1993).

EFFECTS OF THIXOTROPY ON BBC

Thixotropy is a time dependent reversible process in which materials under constant composition and volume soften when remolded but regain strength with time (Das, 1990). Thixotropy is evident in BBC causing an increase in preconsolidation pressure, undrained shear strength, and decreasing recompression ratio as elapsed storage time of lab test samples lengthens. Comprehensive testing and conclusive results on the effects of Thixotropy are presented in a thesis by O'Neill, 1985.

Test results of fall cone penetration presented in figure 17, demonstrate the thixotropic nature of the clay. After the fabric of the clay is broken down, during remolding and resedimentaiton of the sample, a definite trend of decreasing penetration depth with storage time was obtained The decrease of depth would result from an increase in the stiffness of the clay. Since a correlation between undrained shear strength and penetration depth can be found, (Baligh and Vivatrat, 1979), one can reason there is an increase in strength of the clay after storage time of lab test samples lengthens.

Another parameter affected by Thixotropy during laboratory testing is preconsolidation pressure. From figure 18, it's noted that the preconsolidation pressure has a dramatic increase upon increasing storage time. The increase in preconsolidation pressure results in an increase in OCR. The increase in OCR affects the engineering parameters of the clay, as noted earlier.

The effects of thixotropy on the compressibility of BBC are shown in figure 19. Through the relationship between storage time and recompression ratio, the recompression ratio of BBC is found using two ranges of consolidation stress. The upper range caused disturbance in the clay since the consolidation stress is close to the value of the sample's maximum past pressure. Considering the lower range however, an increase in the stiffness of 40% is observed (O'Neill, 1985).

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Table 1 Engineering Parameters of Boston Blue Clay

LAYER	UPPER	LOWER	GENERAL	REFERENCES
DEPTH	TO 75 FT.	75 TO 120 FT.		
INDEX PROPERTIES				
UNIT WEIGHT, TOTAL (ave)			120 PCF	(after LAMBE AND WHITMAN,1969)
UNIT WEIGHT, SAT	114 TO 120 PCF	113 TO 118 PCF		(JOHNSON, 1989)
UNIT WEIGHT, DRY	81 TO 87 PCF	80 TO 85 PCF		(AFTER JOHNSON, 1989)
VOID RATIO, INITIAL			1.02	(after LAMBE AND WHITMAN,1969)
LIQUID LIMIT	40 TO 55	40 TO 55	41	(JOHNSON, 1989),(Baligh and Vivatrat, 1979)
PLASTIC LIMIT			20	(BALIGH AND VIVATRAT, 1979)
PLASTICITY INDEX	15 TO 30	15 TO 30	21	(JOHNSON, 1989)
LIQUIDITY INDEX			0.8	(after LAMBE AND WHITMAN,1969)
SHRINKAGE LIMIT			6	(after BALIGH AND VIVATRAT, 1979)
WATER CONTENT	30 TO 40	30 TO 50		(JOHNSON, 1989)
SENSITIVITY			7±2	(BALIGH AND VIVATRAT, 1979)
SPECIFIC GRAVITY			2.78	(DAS, 1990)
STRESS HISTORY				
OCR	6.5 TO 1.5	1.5 TO 1.15		(BALIGH AND VIVATRAT, 1979)
MAX PAST PRESSURE	4.0 TO 2.7 TSF	2.7 TO 3.5 TSF		(BALIGH AND VIVATRAT, 1979)
STRENGTH PARAMETERS				
EFFECTIVE FRICTION ANGLE			33°	(BALIGH AND VIVATRAT, 1979)
UNDRAINED SHEAR STRENGTH, (USS)			0.22*σvo	(LADD et al., 1977)
USS, GEONOR FEILD VANE			0.4 TO 0.6 TSF	(BALIGH AND VIVATRAT, 1979)
USS	0.3 TO 0.6 TSF	0.2 TO 0.4 TSF		(JOHNSON, 1989)
ALLOWABLE BEARING PRESSURE	1 TO 2 TSF	0.5 TO 1 TSF		(JOHNSON, 1989)
COMPRESSIVE STRENGTH			0.8 TO 1.2 TSF	(BALIGH AND VIVATRAT, 1979)
POISSIONS			0.28	(WHITTLE et al., 1990)
COEFFICIENT OF EARTH PRESSURE	1.1 TO 0.7	0.7 TO 0.6		(SEE MORRISON,1984)
MODULOUS OF ELASTICITY			100 TO 140 TSF	(DAS, 1990)
CONSOLIDATION PARAMETERS				
COMPRESSION RATIO	.1397 to .2750	.1740 to .7524		(SEE MORRISON, 1984)
COMPRESSION RATIO			.15 TO .25	(JOHNSON, 1989)
RECOMPRESSION RATIO	.01154 to .1225	.0115 to .0344		(after MORRISON, 1984)
RECOMPRESSION RATIO			.02 TO .04	(JOHNSON, 1989)
PERMEABILITY , horizontal (ave)	1.38x10-6 cm/s	4.41x10-8 cm/s		(after MORRISON, 1984)
PERMEABILITY , vertical (ave)	4.069x10-7 cm/s	3.56x10-8 cm/s		(after MORRISON, 1984)
COMPRESSION INDEX			0.35	(DAS, 1990)
SWELL INDEX			0.07	(DAS, 1990)
COEFFICIENT OF CONSOLIDATION, Cv			7.82x10-3 cm^2/sec	(after MORRISON, 1984)
VOL COEFFICIENT OF COMPRESSIBILITY			.0523 cm/kn	(LAMBE AND WHITMAN,1969)

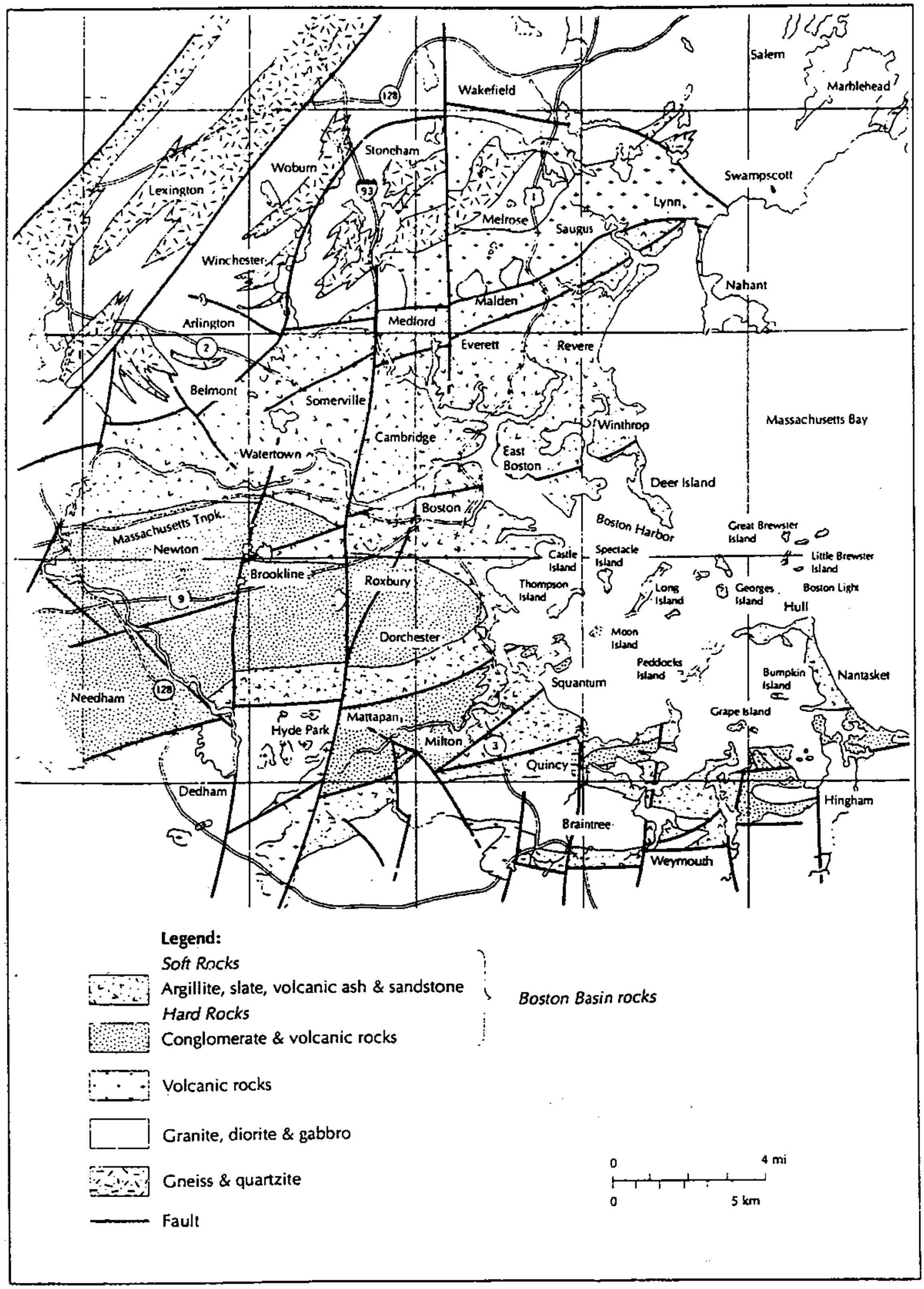


Figure 3-1 Generalized bedrock geologic map of the area surrounding Boston (Barosh et al., 1989).

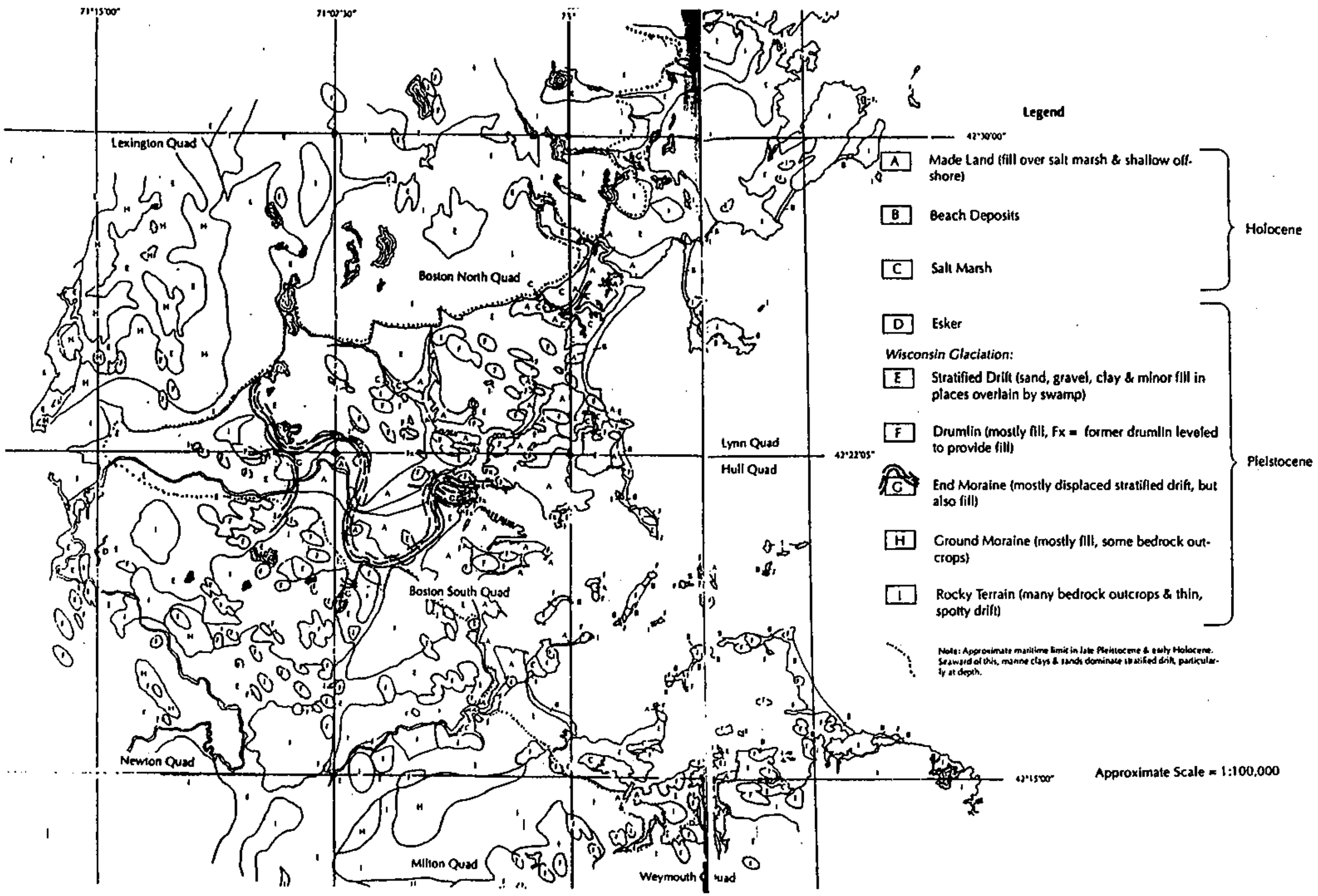


Figure 3-2 Surficial geologic map of the area surrounding Boston (Barosh et al., 1989).

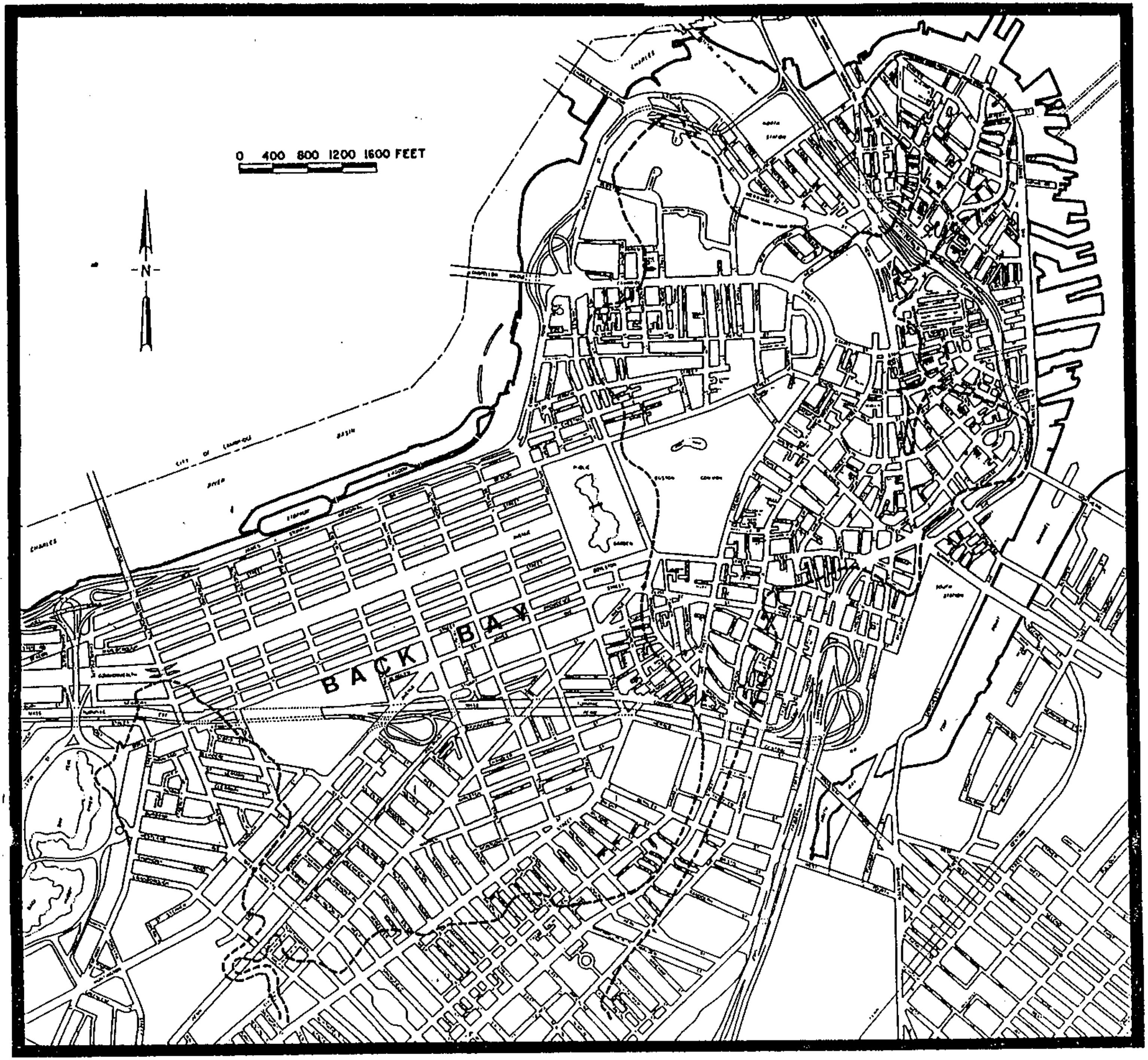


Figure 3-3 Colonial shoreline superimposed on a modern map (Aldrich, 1970).

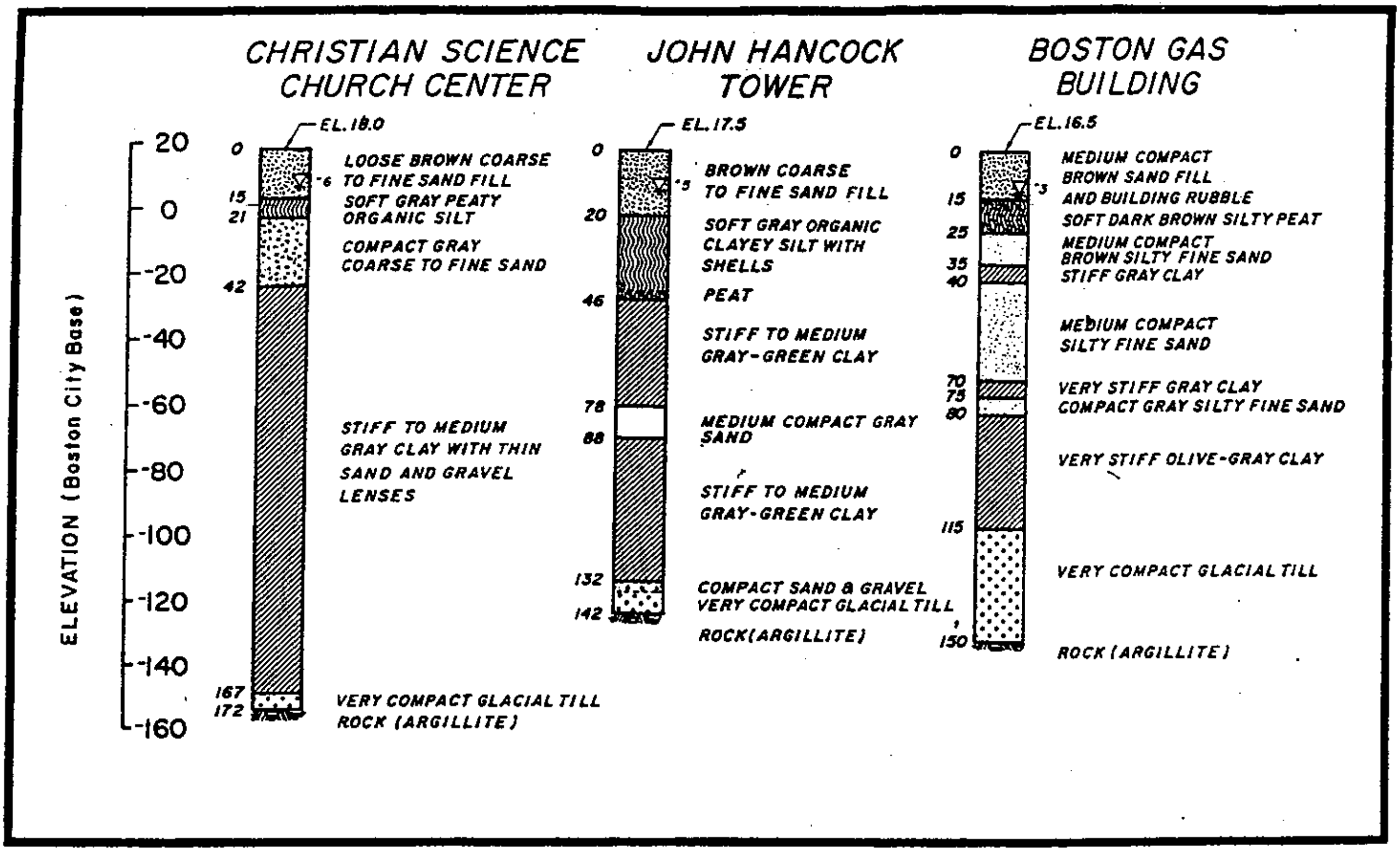
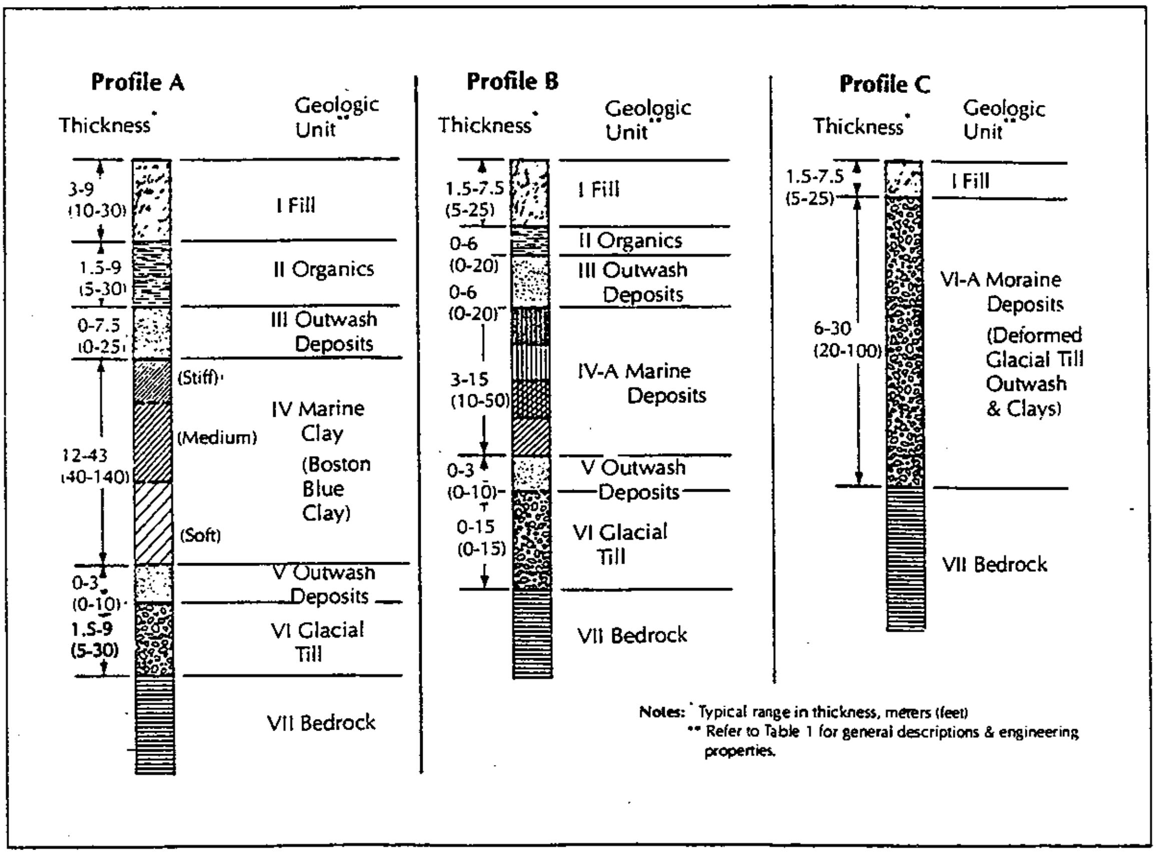


Figure 3-4 Typical soil profiles in Back Bay (Aldrich, 1970).



Notes: * Typical range in thickness, meters (feet)
** Refer to Table 1 for general descriptions & engineering properties.

Figure 3-5 Geologic units encountered in typical major foundations of Boston (Johnson, 1989).

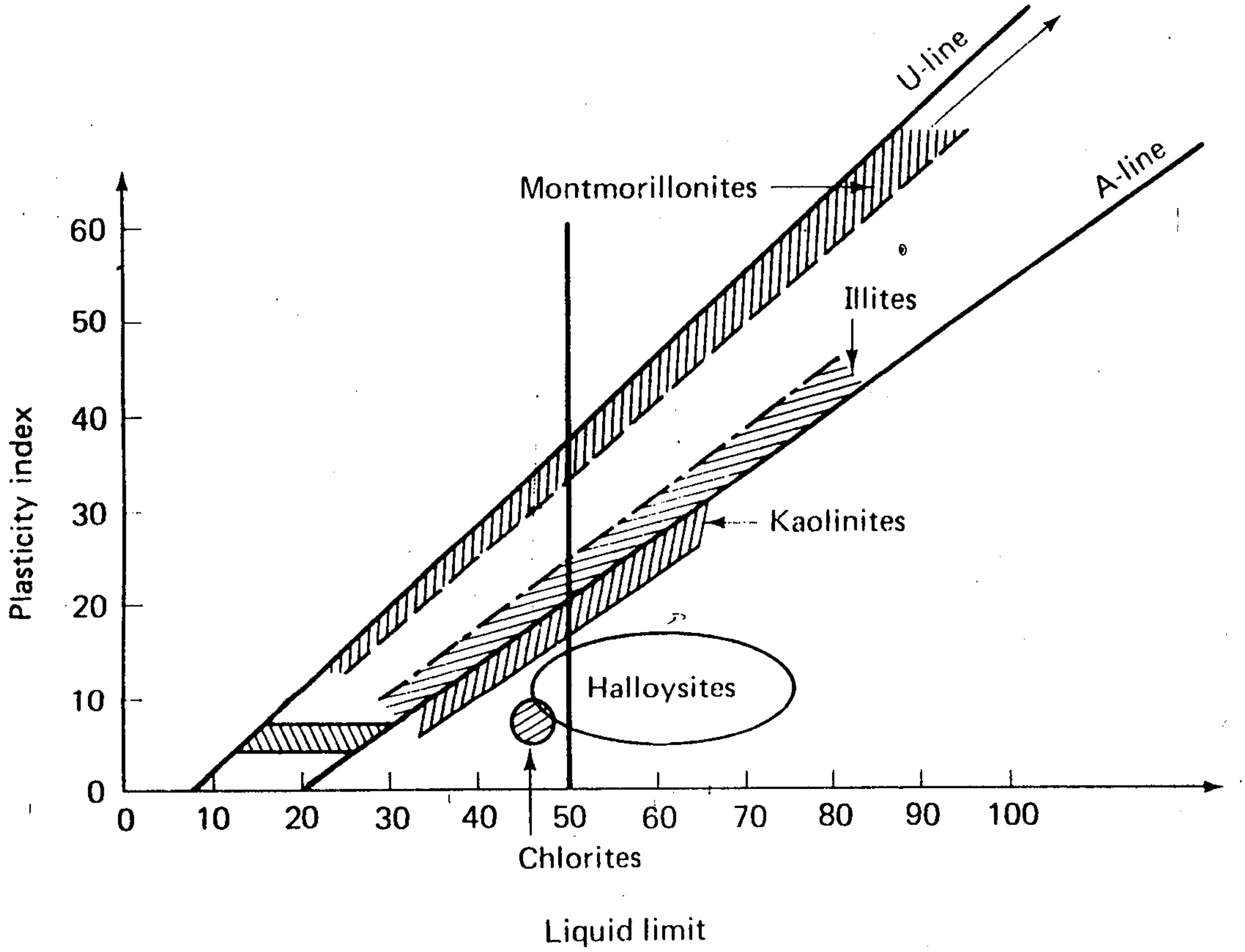


Figure 3-6 Location of common clay minerals of Casagrande's plasticity chart (after Casagrande, 1948, and data in Mitchell, 1976) (Holtz and Kolvac, 1981).

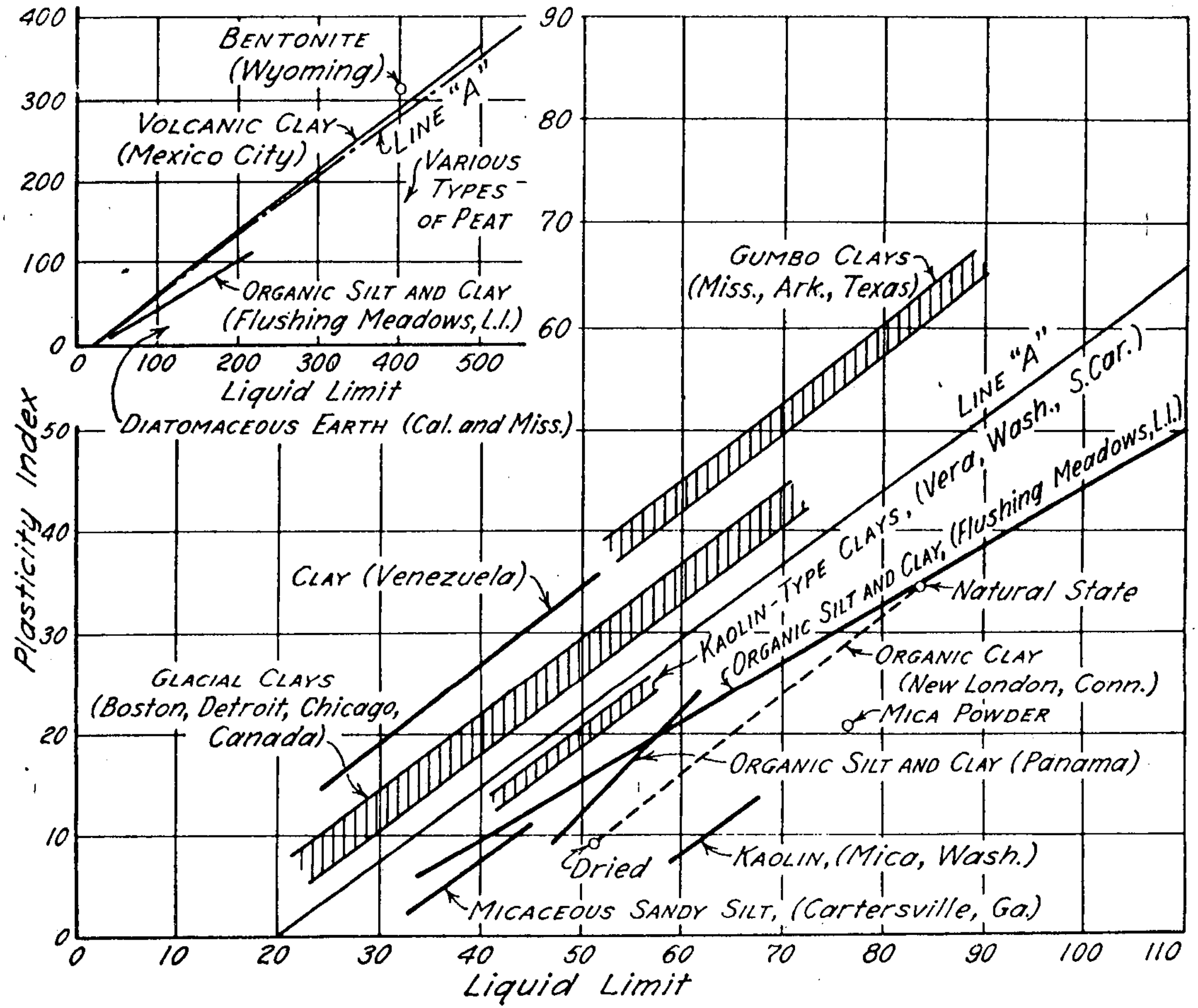


Figure 3-7 Relation between liquid limit and plasticity index for typical soil (after Casagrande, 1932a).

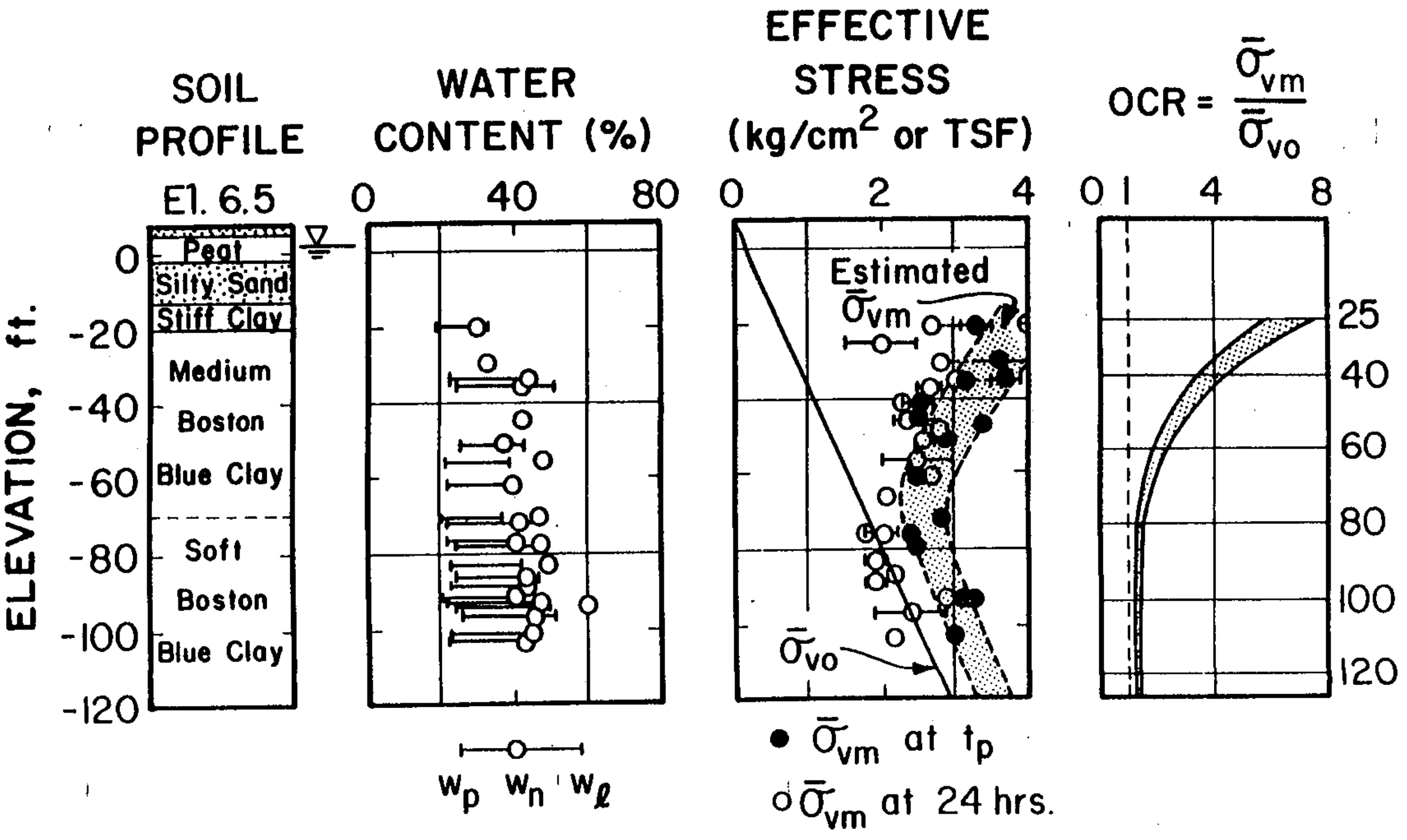


Figure 3-8 Soil profile based of sampling and laboratory testing in BBC (after Baligh and Vivatrat, 1979), (see Morrison, 1984).

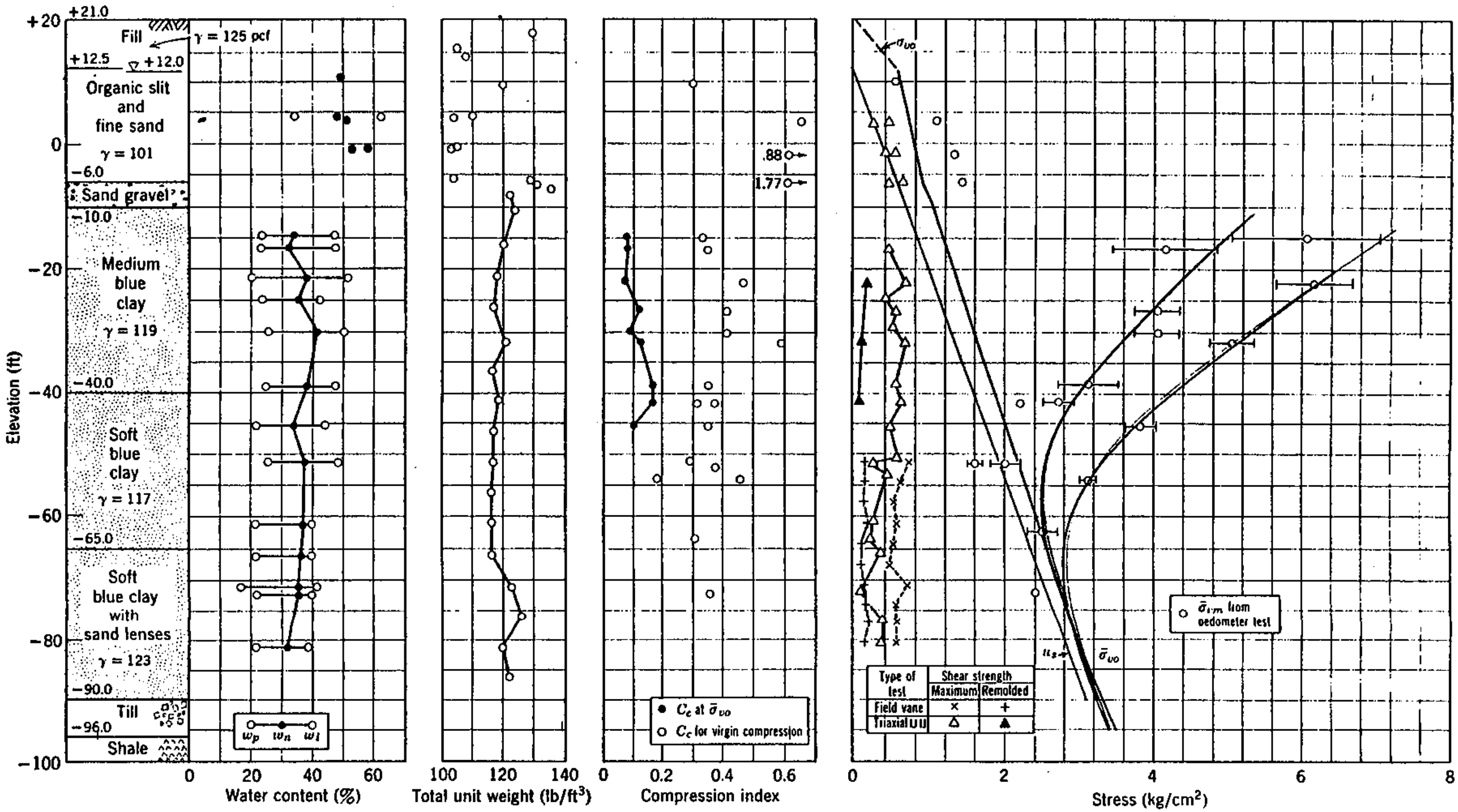


Figure 3-9 Soil profile at MIT Advanced Engineering Center (Lambe and Whitman, 1969).

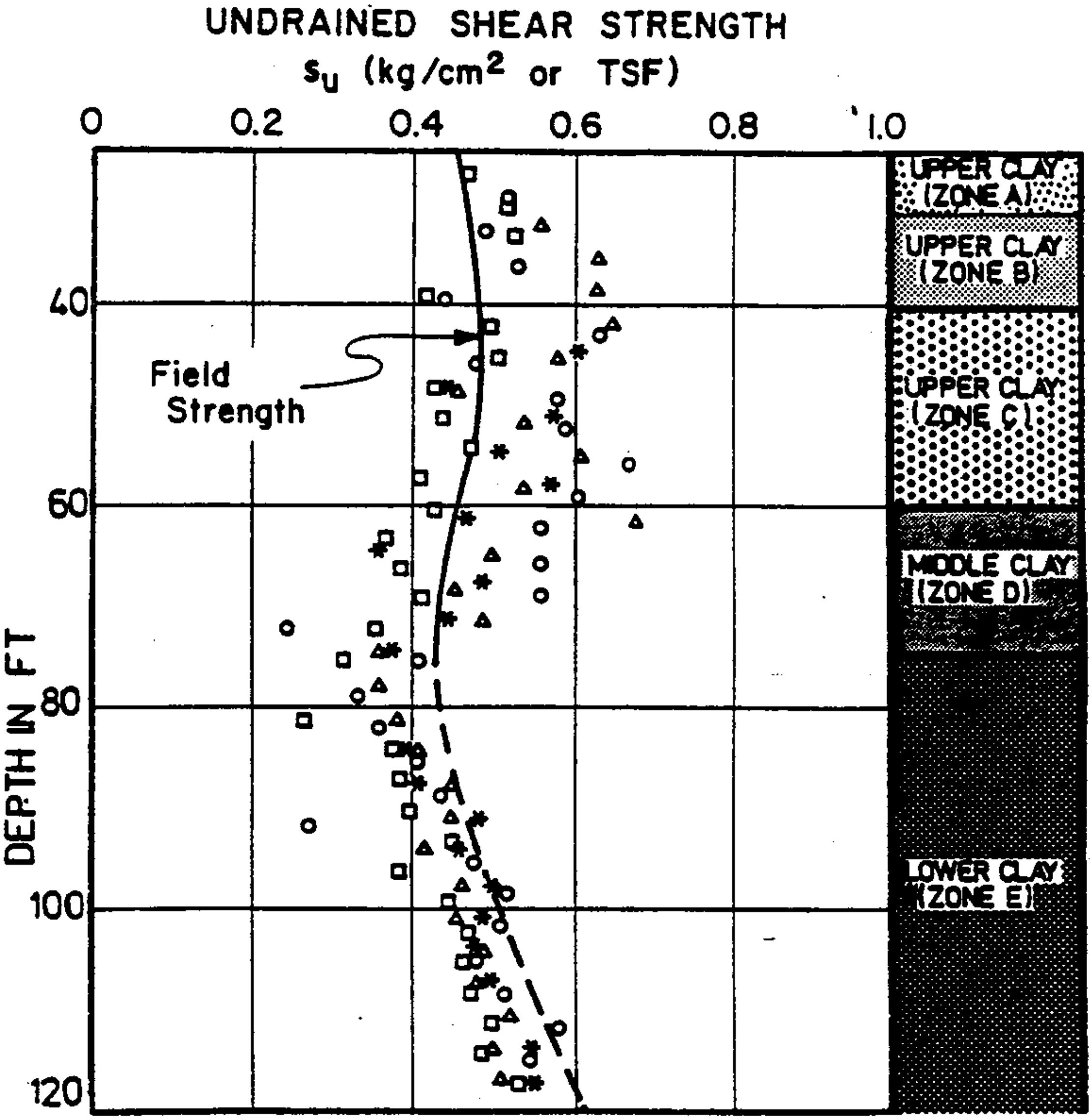


Figure 3-10 Field vane strengths at I-95, Saugus, MA (after Baligh and Vivatrat, 1979)(Morrison, 1984)

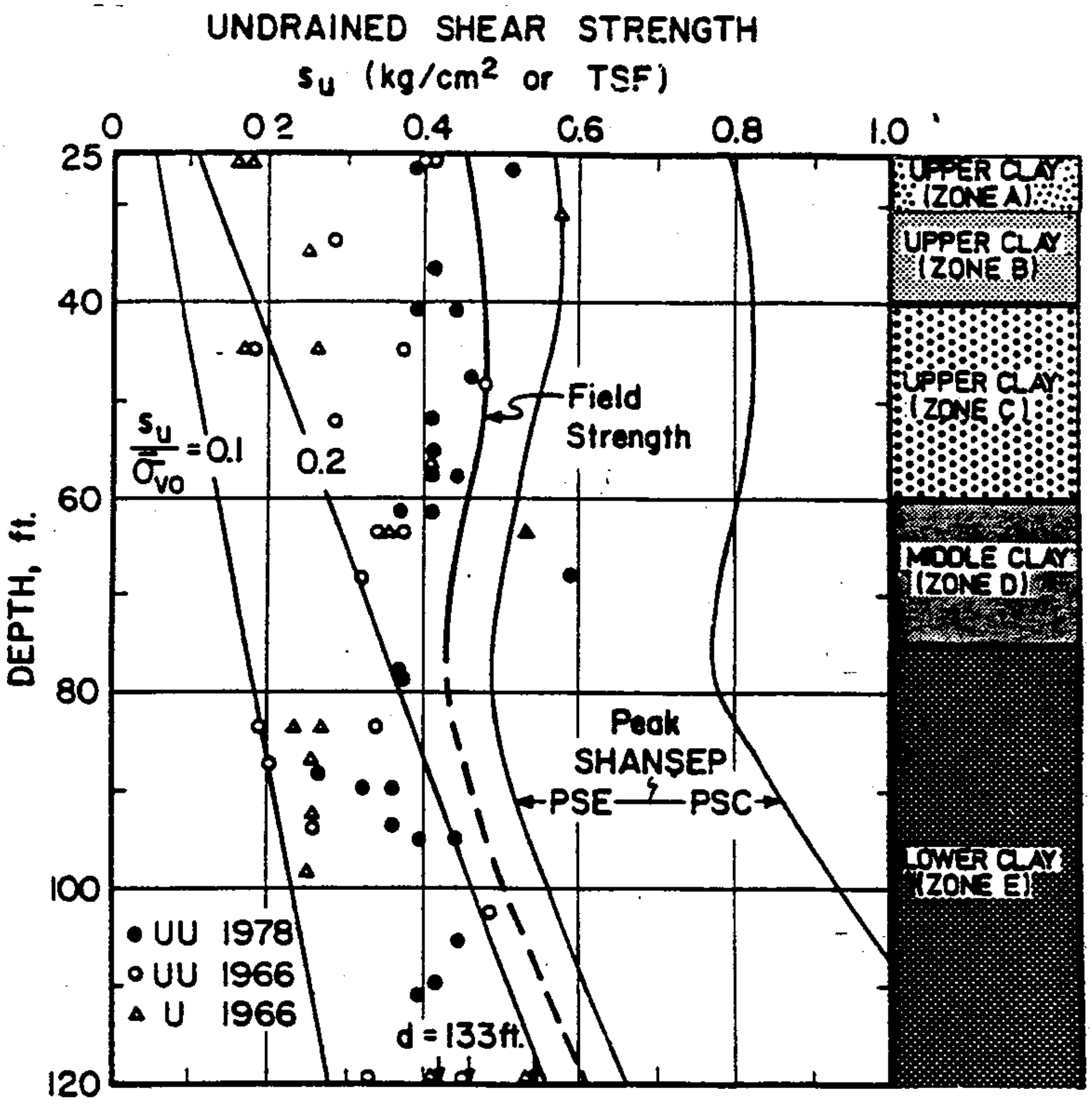
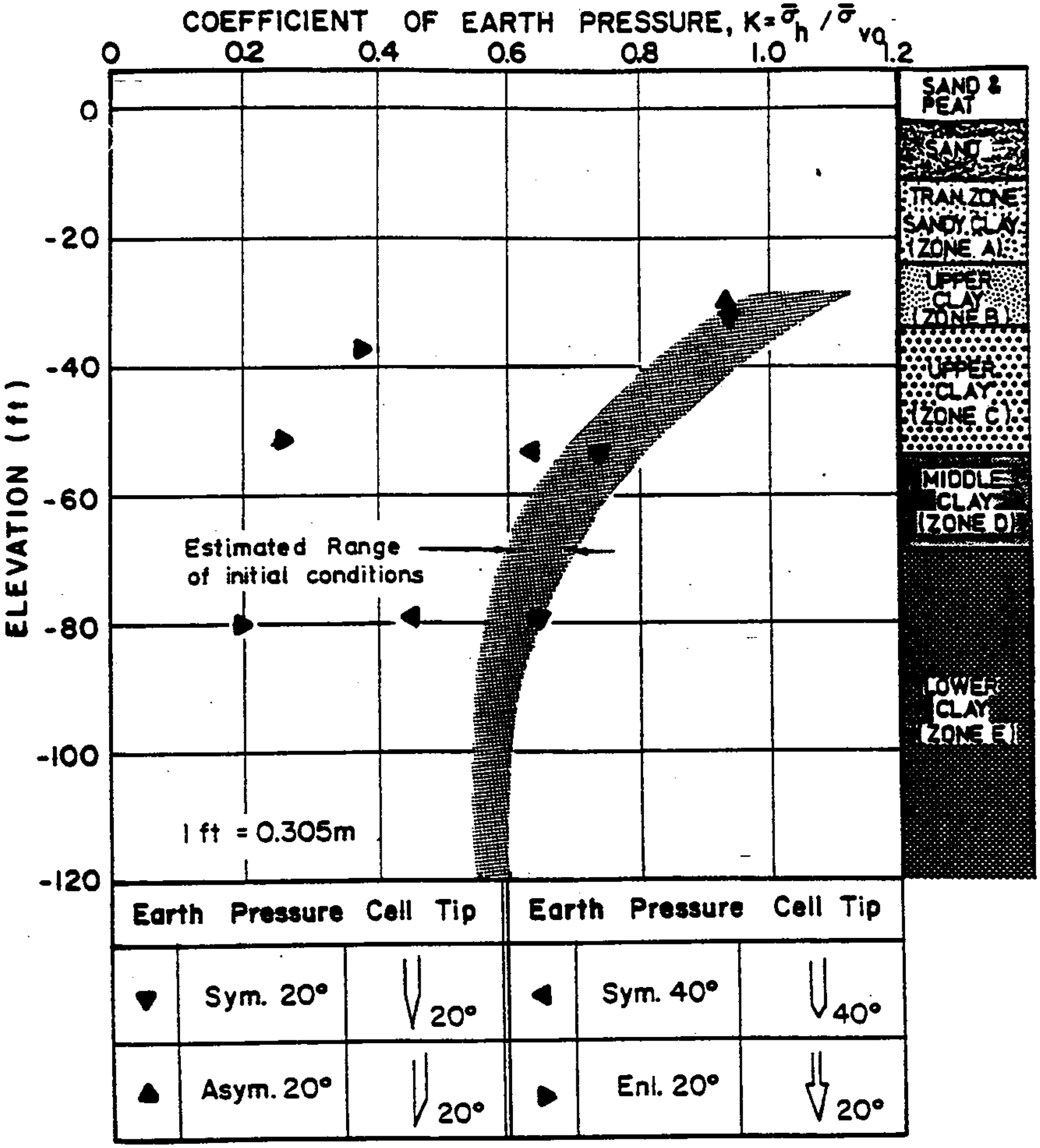
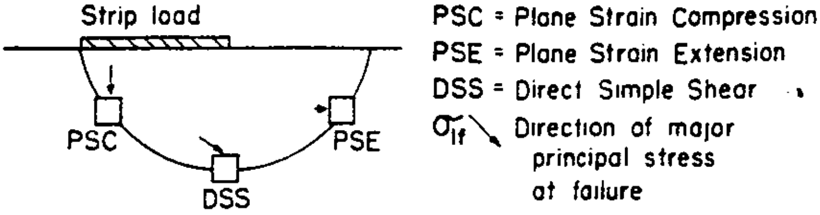


Figure 3-11 Laboratory values of undrained shear strength as a function of depth at Sta. 246, Saugus, Ma. (after Baligh and Vivatrat, 1979) (Morrison, 1984).



Elevation = Depth - 6.5

Figure 3-12 Coefficients of earth pressure at Sta. 246, Saugus, MA (after Ladd et al., 1979)(Morrison, 1984).



(a) STRESS SYSTEMS ALONG A FAILURE SURFACE

SOIL	LL% PI%	C_u/σ'_{vc} PSC $C_u=\tau_{ff}$ (1)	DSS $C_u=\tau_h$ (2)	PSE $C_u=\tau_{ff}$ (1)	REFERENCE
Portsmouth Sensitive Clay	35 15	0.295	0.20	0.13	Ladd & Edgers (1972)
Haney Sensitive Clay	44 18	0.27	—	0.175	Vaid & Campanella (1974)
Boston Blue Clay	41 21	0.30	0.20	0.145	Ladd & Edgers (1972)
AGS·CH Clay	71 40	0.295	0.25	0.18	MIT & Univ. of British Col.
San Francisco Bay Mud	88 45	0.295	0.25	0.23	Duncan & Dunlop (1969)
Conn. Valley Varved Clay	clay 65,39 silt 35,12	0.255	0.165	0.23	Ladd & Edgers (1972)

(1) $\tau_{ff} = 0.5(\sigma_1 - \sigma_3)_f \cos\phi'$ (2) $\tau_h = (\tau_h)_{max}$

(b) ANISOTROPIC STRENGTH DATA FOR NORMALLY CONSOLIDATED CLAYS

Figure 3-13 **Combined undrained strength anisotropy as measured by CK_0U plane strain shear tests (Ladd et al., 1977).**

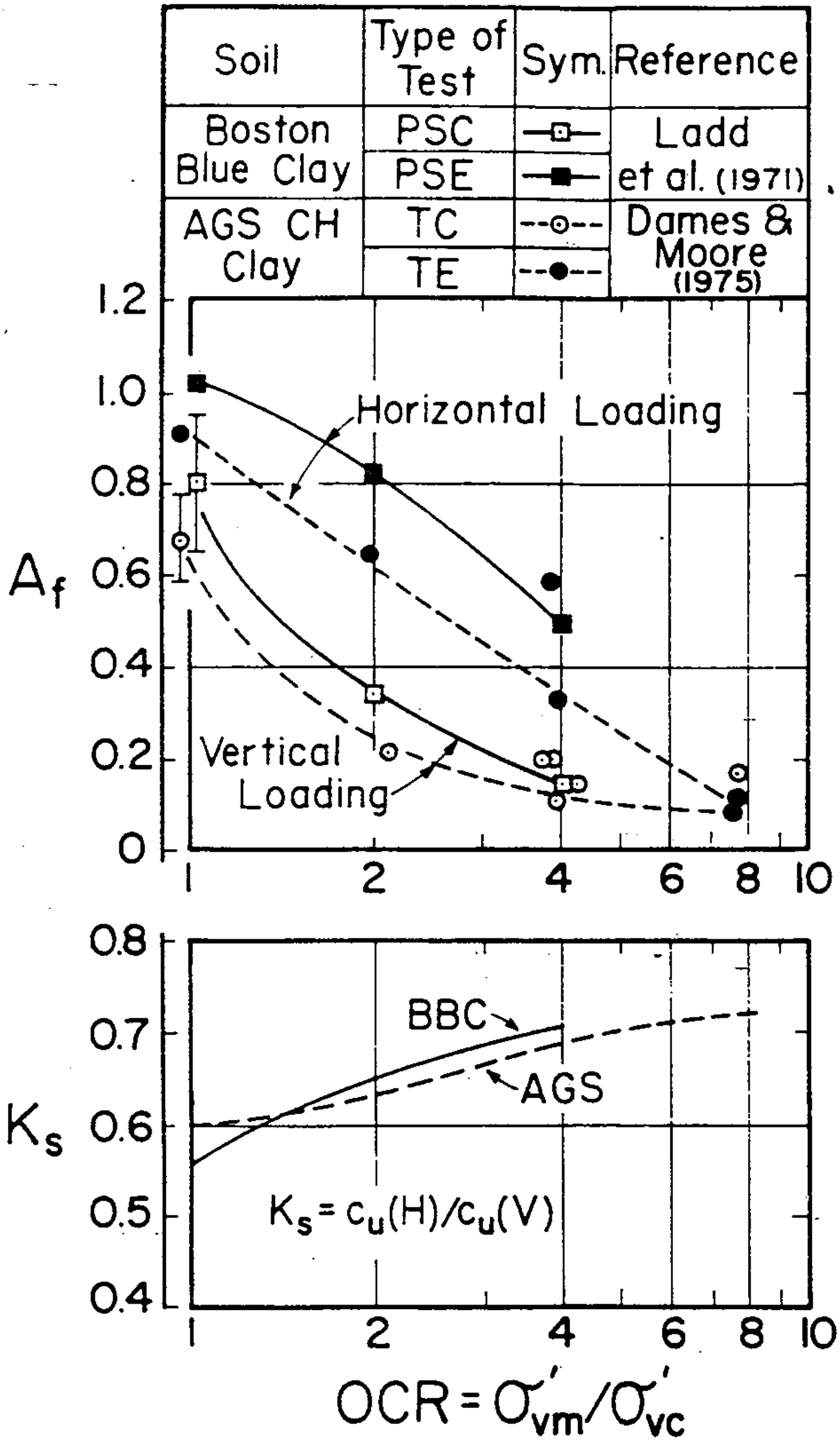


Figure 3-14 Variation in A_f and K_s with OCR from CK_0U tests on two clays (Ladd et al., 1977).

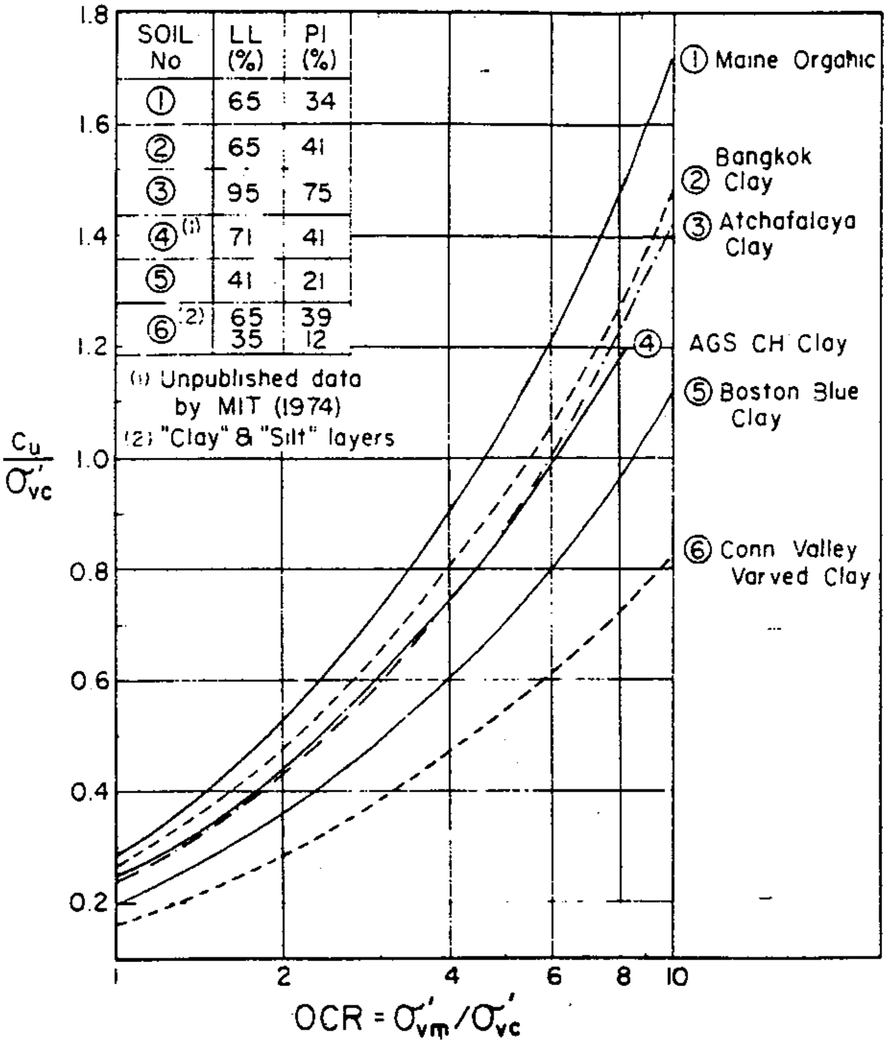


Figure 3-15 Undrained strength ratio vs OCR from CK_0U direct simple shear tests on six clays (Ladd et al., 1977).

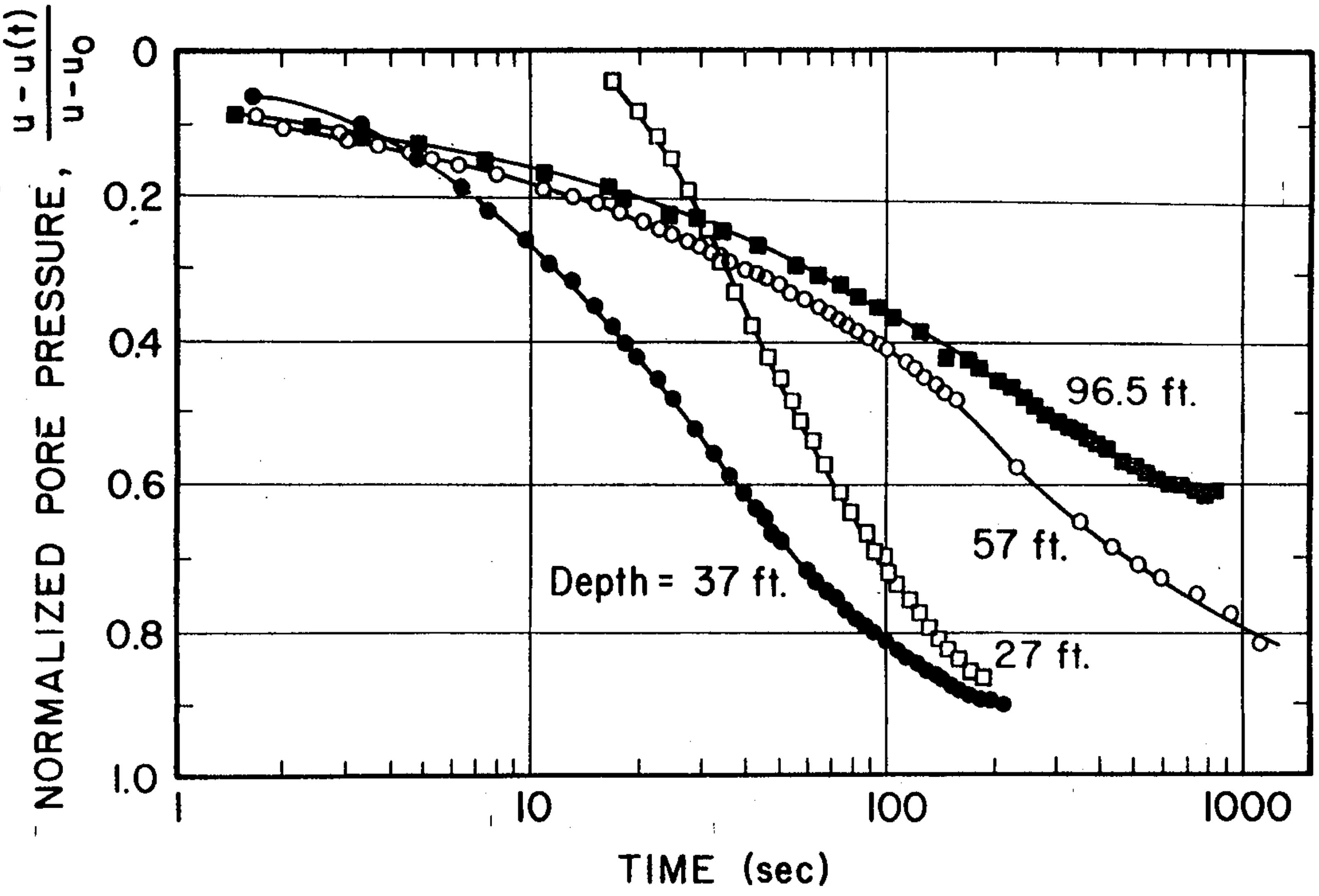


Figure 3-16 Pore Pressure Dissipation at the Tip of an 18° Conical Probe (after Baligh and Vivatrat, 1979).

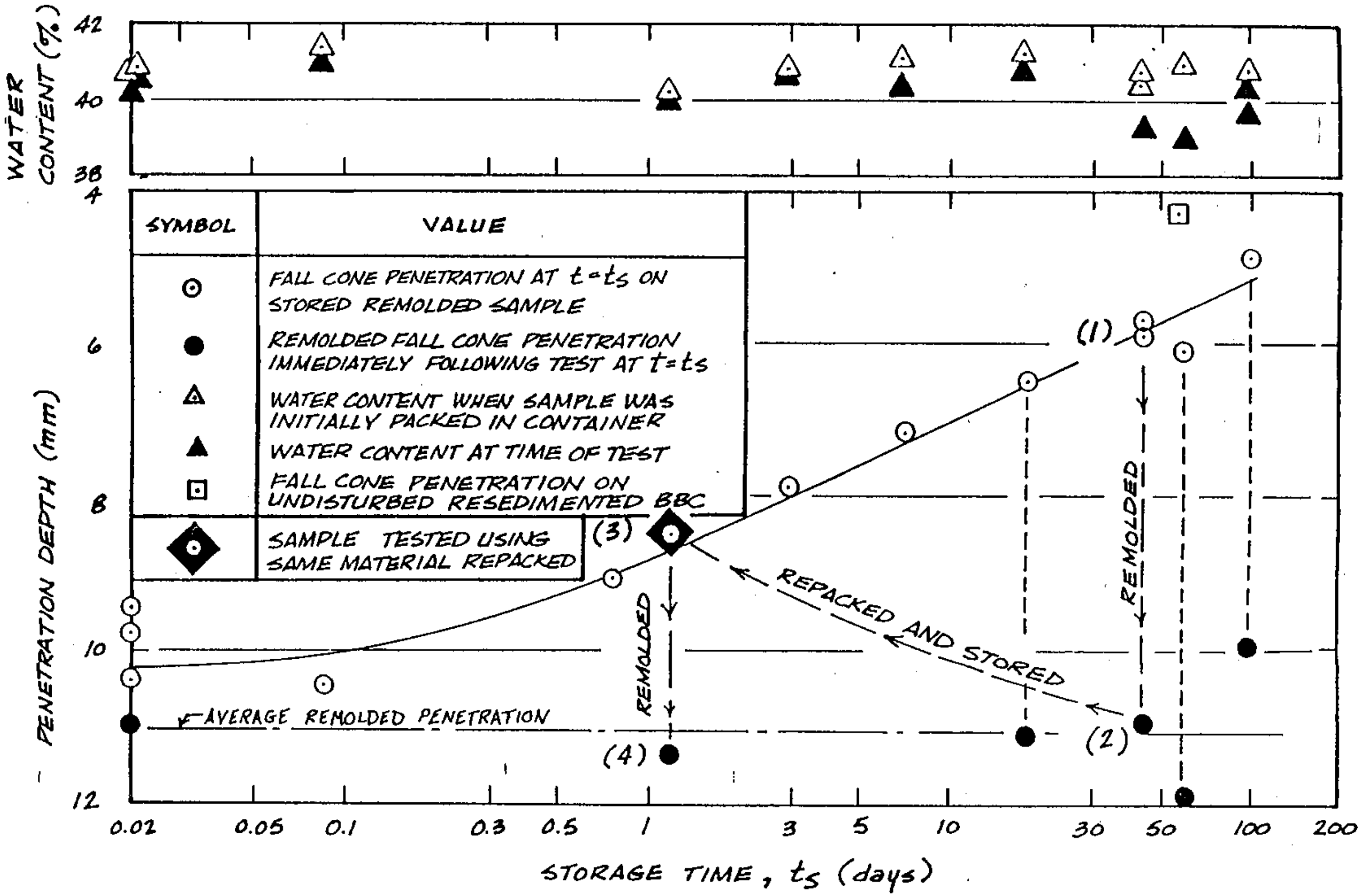


Figure 3-17 Effect of Thixotropy on fall cone penetration depths for remolded resedimented BBC (O'Neill, 1985).

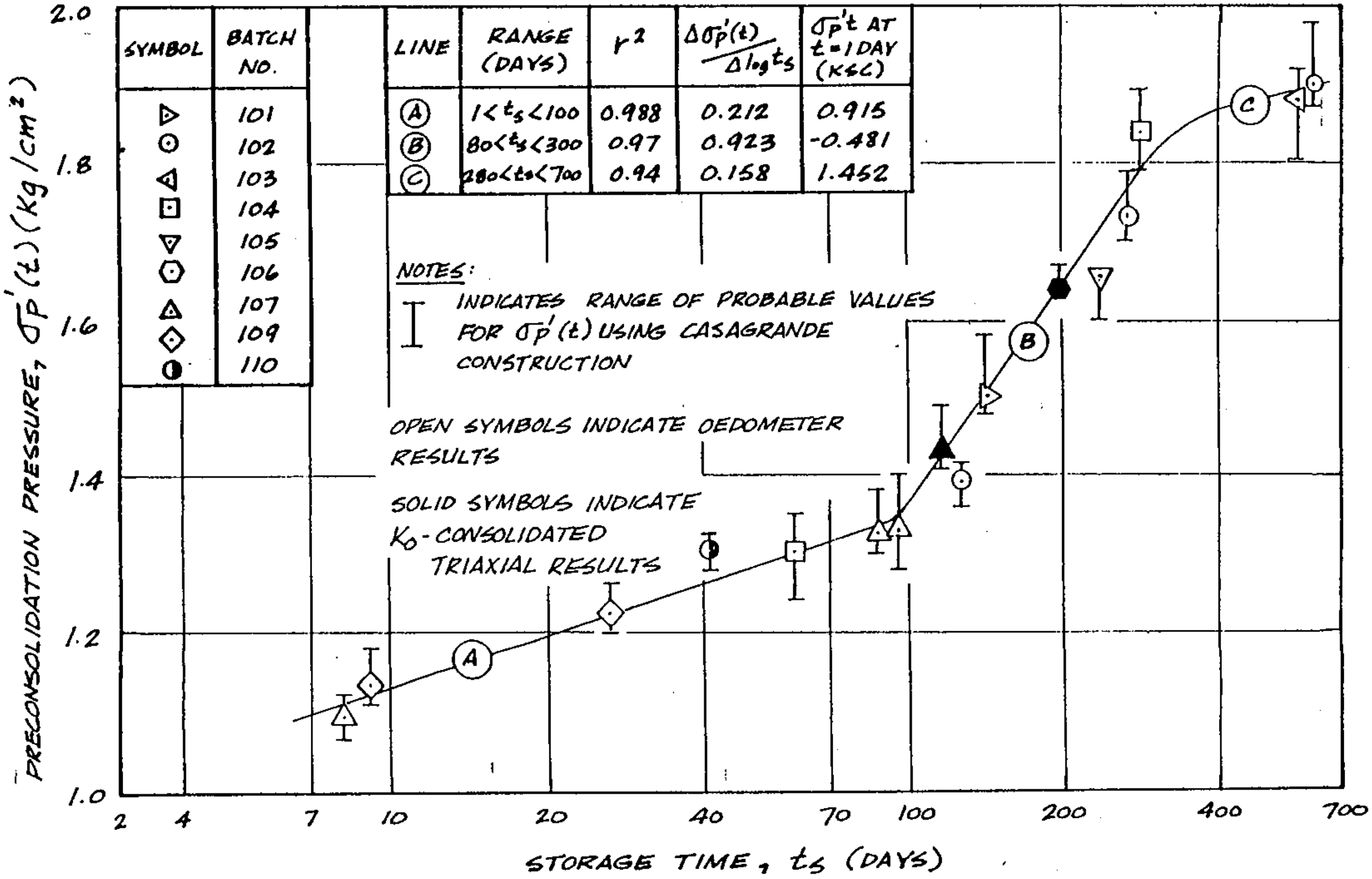


Figure 3-18 Effect of Thixotropy on measured preconsolidation pressure for resedimented BBC (O'Neill, 1985).

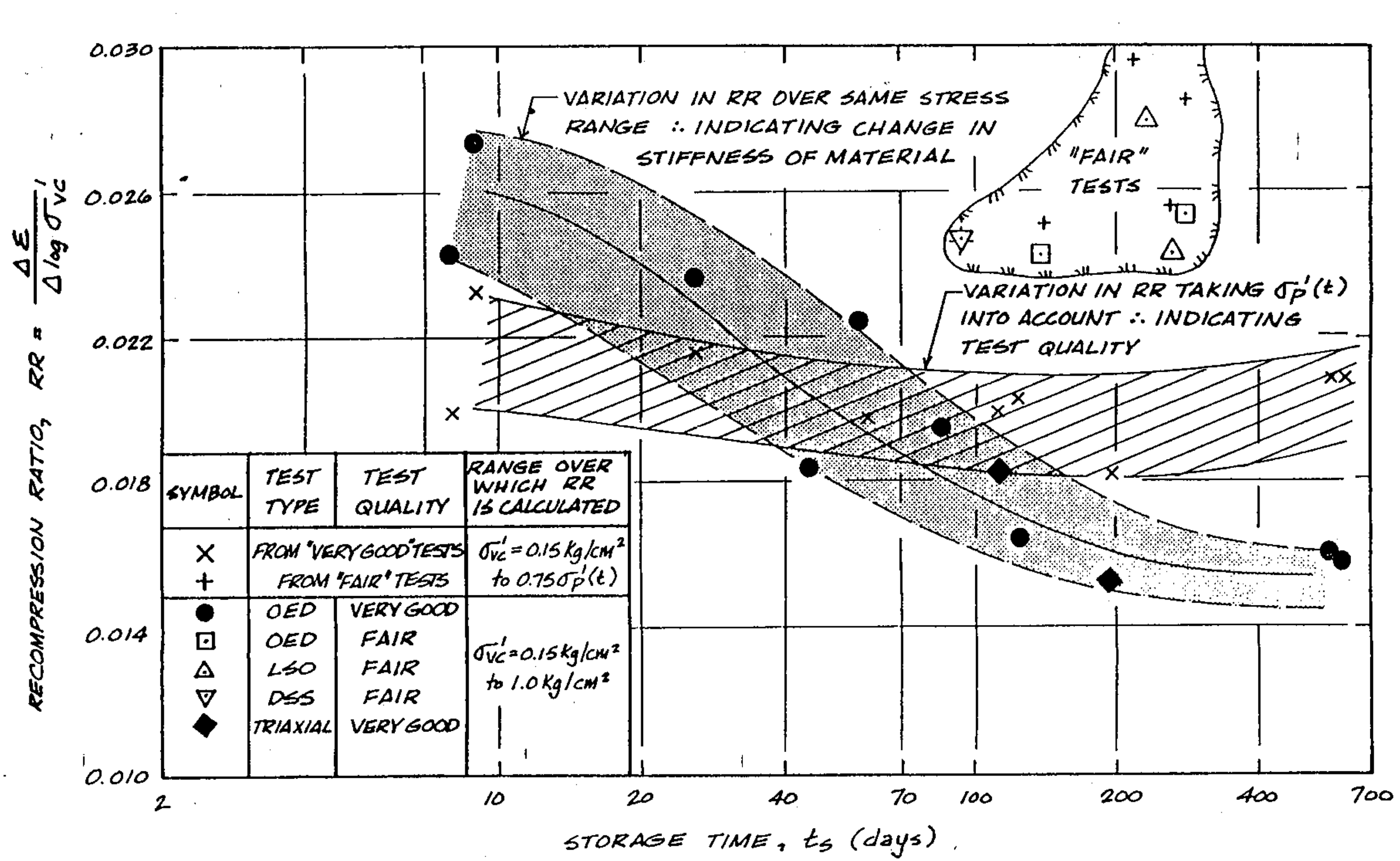


Figure 3-19 Effect of storage time of recompression ratio upon initial recompression of resedimented BBC (O'Neill, 1985).