SITE INVESTIGATION OF THE SIWALIK CLAY BEDROCK, MANGLA DAM PROJECT

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ABSTRACT

Site investigation on the clay bedrock of the Mangla Dam Project from 1961-65 is described. The Project consists of an approximately £150 million civil and electrical work comprising the Mangla, Sukian and Jari dams and associated hydroelectric and flood control schemes. The Civil Contract commenced in 1962.

The thesis is divided into two parts. Part I deals with the descriptive aspects, the local and regional geological setting and the field and laboratory techniques used and developed in the investigation. Part II deals with the chronological development of the investigation programme, presents results and discusses findings.

The clay bedrock is part of the Middle (?) and Upper Siwalik System of the south-eastern region of the Potwar Plateau. The clays occur as beds which may be up to 100' thick and continuous over many 1,000s of feet and are interbedded with beds and lenses of sandstone and occasionally gravels. The Siwaliks were deposited in a freshwater environment south of the growing Himalayan mountain chain, in alluvial plains and basins by rivers bringing in detritus from the freshly eroding mountains. Since their deposition they have been buried and consolidated by up to 20,000' of sediment in places and folded and faulted by early Quaternary earth movement.

Clay bedrock is typically stiff to hard, fissured and heavily overconsolidated. Typical clay fractions range from 20-50%

and liquid limits 30-60% for the older clays on the west of the site at Mangla and 20-60% and 35-90% respectively for the younger clays on the east of the site at Jari. Field densities of the older clays are typically 142 lb/cu.ft. and of the younger clays 135 lb/cu.ft. Activities are usually less than 1. Of considerable interest and engineering significance is the tectonic shearing which has produced low shear strengths in the clays affected by shearing. These clays usually show little or no peak and at Jari residual strengths typically range from 10-20°Ø' and Mangla 10-25°. Unsheared clays from Jari have peak strengths from 20-30° and from Mangla 20-35° and residual strengths of 10-25° and 15-25° respectively. Figures given here are with c' = 0.

Engineering properties of the Sukian clays, occurring midway between the Jari and Mangla clays, show both Jari and Mangla characteristics although differences are small. Some weathering of the clays has occurred at Sukian where little erosion is taking place unlike Mangla and Jari where there is river action which is constantly removing surface clay.

Field and laboratory work contained here was carried out while the author was employed at the Mangla Dam Project, by the Consulting Engineers to the Project, Messrs. Binnie & Partners, M.I.C.E. of London. The author wishes to express his deep gratitude to Messrs. Binnie & Partners for permission to publish the work and to reproduce drawings and results belonging to the Partners.

The author is solely responsible for the accuracy or otherwise of all statements, drawings and figures contained herein.

FOREWORD

The fieldwork of this thesis was carried out during the latter part of the site investigation phase and early part of the construction phase of the Mangla Dam Project, West Pakistan, 1961-1965.

The site investigation on so large a Project was naturally undertaken by many individuals working in teams. Unless otherwise stated all the work following was either carried out by the author or directly supervised by him. The author was responsible for the fieldwork described but not laboratory soil testing. Where laboratory or otherwork is described, or results used, that were not the responsibility of the author, they are marked by ±. Drawings included that were not the responsibility of the author are acknowledged. The majority of soil tests were performed in the Mangla soil laboratory under the direction of Mr. K.H. Head; soil tests carried out elsewhere were all performed by Soil Mechanics Ltd. of London unless indicated otherwise. Boring and tests in boreholes, up to the end of 1961, were carried out by Swissboring of Paris and from 1962 onward by Continental Drilling of San Francisco, unless indicated otherwise.

Results of soil tests are given on the drawings where appropriate, or as graphs or tables. Additional details of results, and laboratory data not given is on file in the London office of Messrs. Binnie & Partners, Artillery House, Artillery Row, London S.W. 1. Permission to view these and

their reports cited here can only be obtained from Binnie & Partners and the Clients of the Project, the West Pakistan Water & Power Development Authority of Lahore.

The frontispiece shows the River Jhelum at Mangla from the air, looking north towards the damsite on Sultanpur Peninsula 1962. Photo published by permission of Douglas C. Pike, Institute of British Photographers.

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P A R T I

INTRODUCTION

The Mangla Dam Project now under construction is a multi-purpose hydroelectric, irrigation and flood control scheme. It is part of the Indus Basin Plan being carried out by the West Pakistan Water & Development Authority. For location of this Project in relation to the Indus River Basin, see fig. 1.

The Project has three earth fill dams, which will impound the flood waters of the River Jhelum. They will create a reservoir of live storage 4.75 million acre feet initially and 8.45 million acre feet ultimately in the second or high stage after further heightening.

The Main works (see figs. 2 and 3) now under construction since early 1962, for the first or low stage are:

(i) The Mangla Dam, earth fill, 11,000' crest length, 380' maximum height;

(ii) The Jari Dam, earth fill, 15,000' crest length, 234' maximum height;

(iii) Sukian Dyke, earth fill, 17,000' crest length, 100' maximum height;

(iv) A concrete Main Spillway, 6,700' long to discharge 900,000 cusecs at pool elevation of 1,202' S.P.D.;

(v) A partially lined Emergency Spillway to discharge 230,000 cusecs at pool elevation 1,228' S.P.D.;

(vi) Five 36' external diameter tunnels, 1,950' long;

(vii) A hydel power station developing 300 MW initially and 1,000 MW at the second stage.

More complete data on the civil and electrical works of the Project is given in Appendix I. Billig (1959) discusses recent irrigation projects in the Indus Basin.

The bedrock consists of beds of Siwalik clays, siltstones, sandstones and occasional conglomerates of the late Tertiary and early Quaternary eras. These materials though behaving on a large scale as soft rocks were classified and tested as soil, since the sandstones were mostly uncemented or poorly cemented and friable and the clays and silts, although heavily overconsolidated, were not appreciably indurated. The reservoir perimeter was investigated broadly for over 30 miles along the southern boundary from Mangla to Kas Guma (see fig. 4 in the end pocket). Everywhere along this boundary (apart from the damsites) the elevation is no more than a few hundred feet above top of reservoir level. The damsites themselves at Jari, Sukian and Mangla were investigated in detail. The geology of both the reservoir area and the catchment area was also investigated, but the description of this investigation does not form part of this thesis.

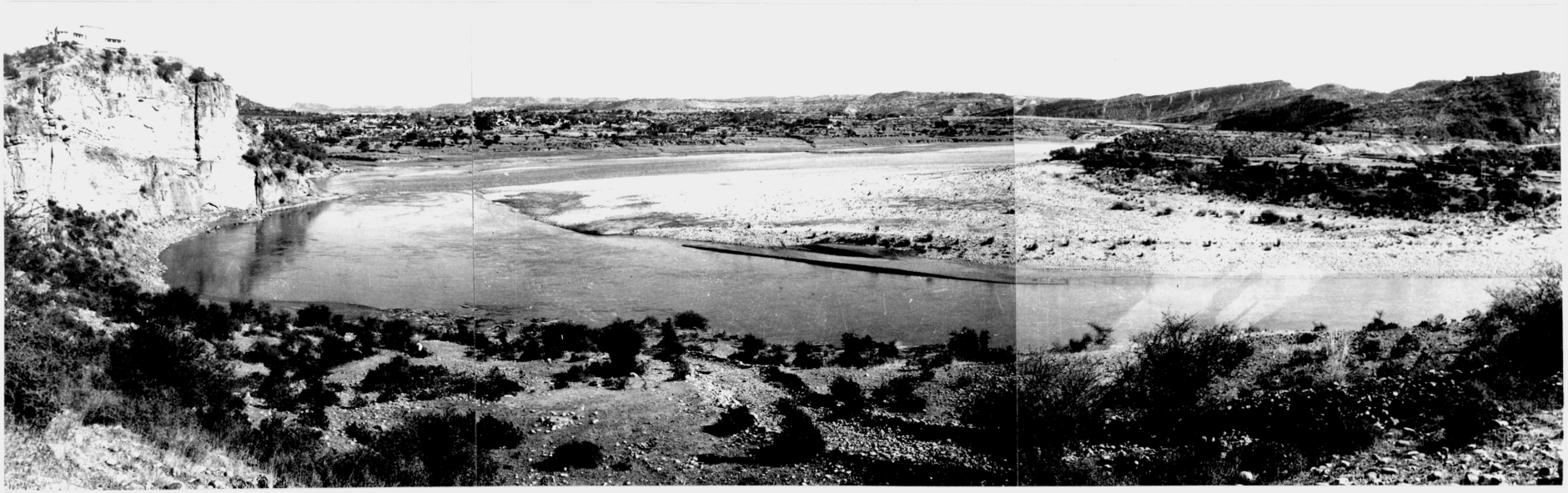
Plate 1 shows the Mangla damsite looking upstream, before commencement of construction.

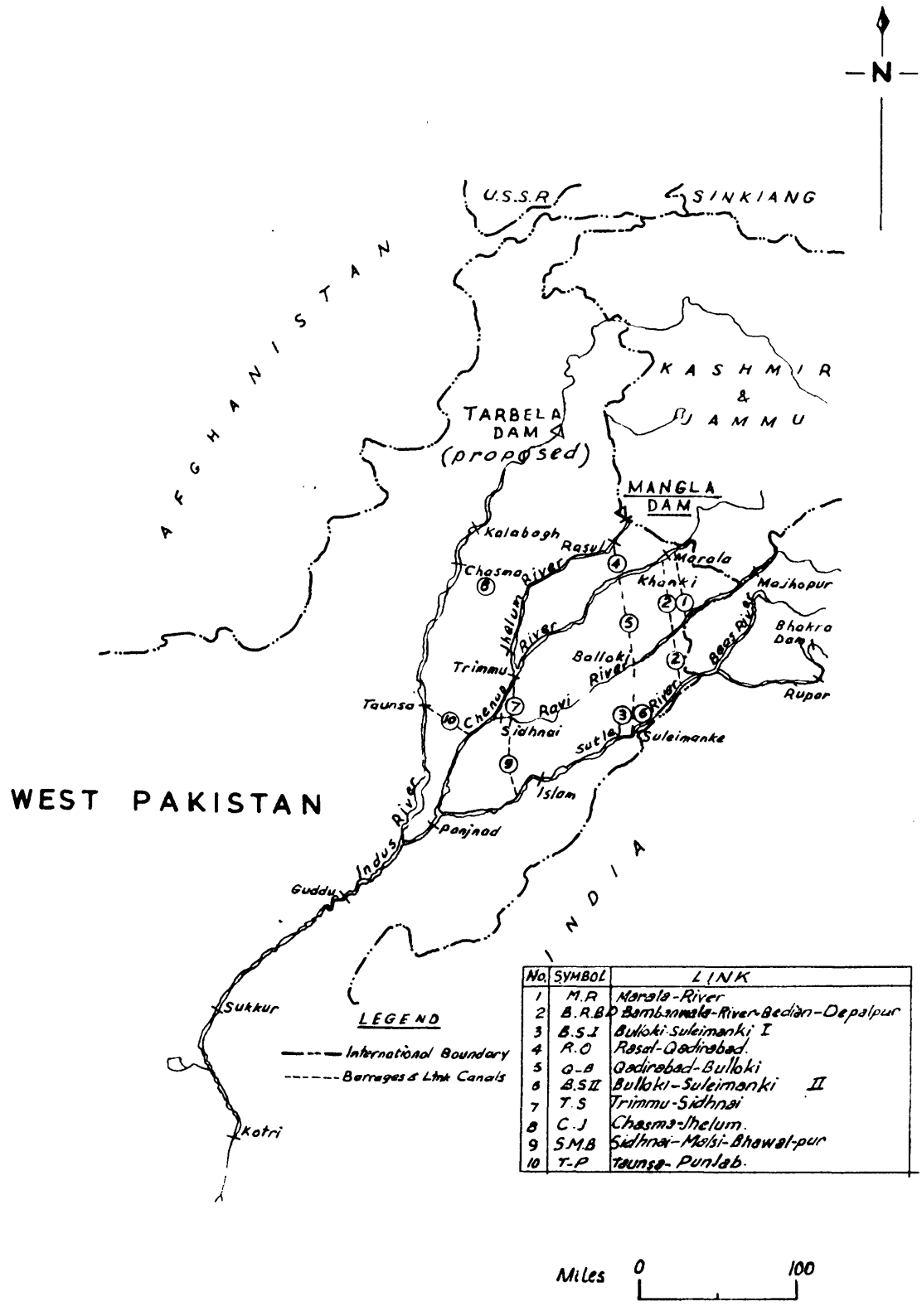
In the following 'the Project' means the damsites, associated hydroelectric works and reservoir area; 'the site' should be considered in context and refers to the particular damsite, Mangla, Sukian or Jari, or a previously named location.

S.P.D. is Standard Pakistan Datum which is used for all elevations.

PLATE No. 1 December 1961

Mangla damsite looking upstream from a point on the right bank about $\frac{1}{2}$ mile downstream of the centreline of the Main Dam. The floodplain terraces of the right bank (middle foreground) and of Sultanpur peninsula (rear foreground) are clearly shown.

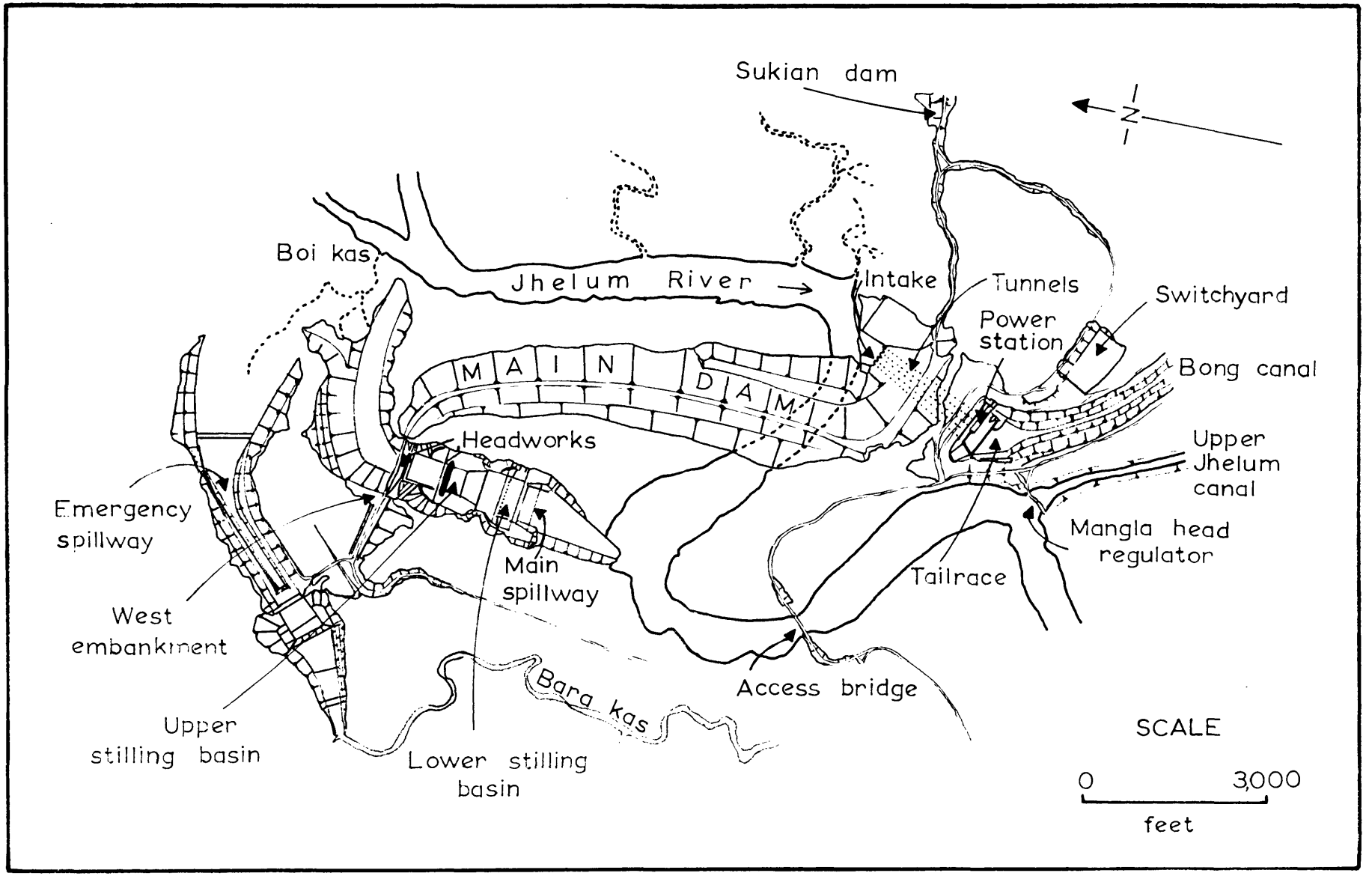




No.	SYMBOL	LINK
1	M.R	Marala-River.
2	B.R.B.D	Bambannala-River-Bedian-Depalpur
3	B.S.I	Bulloki-Suleimanki I
4	R.O	Rasul-Qadirabad.
5	Q-B	Qadirabad-Bulloki
6	B.S II	Bulloki-Suleimanki II
7	T.S	Trimmu-Sidhnai
8	C.J	Chasma-Jhelum.
9	S.M.B	Sidhnai-Maisi-Bhawal-pur
10	T-P	Taunsa-Punjab.

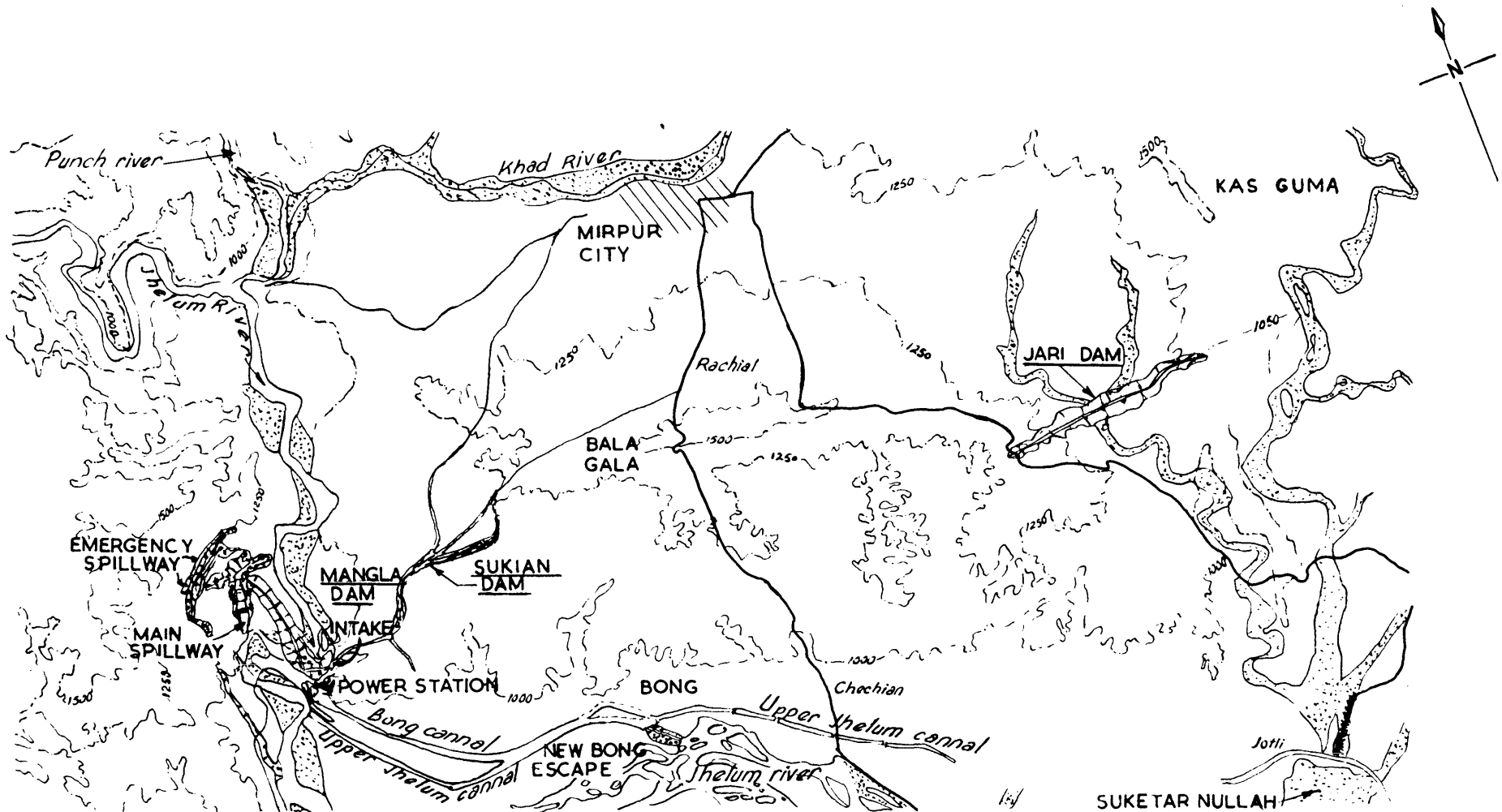
MANGLA DAM IN RELATION TO PUNJAB WATER DISTRIBUTION SYSTEM

FIG. 1.



MANGLA DAM SITE

FIG. 2.



MANGLA

PROJECT LAYOUT PLAN

FIG. 3.

LANDFORMS OF THE AREA

Landforms in the area of the Project are the product of geologically recent weathering*, erosion** and deposition. South of Mangla and Jari, the Punjab plain abuts against the Siwalik foothills*** which stretch from Mangla to south of Jari and beyond. The plain is flat and almost featureless and continues nearly 1,000 miles south to the sea at Karachi. It is being built at the present day by the vast Indus river system which is depositing the load of weathered debris it has brought down from the Himalayan mountain chains of the north.

* Weathering is used throughout to mean the alteration and decay of rocks as far down as the depth to which atmospheric agencies can penetrate. Weathering is regarded as rock decay by agents involving little or no transport of the resulting products.

** Erosion is used throughout to mean the lowering of the land surface by agents such as weathering, corrosion or transportation under the influence of forces such as wind or water. Erosion is regarded as land destruction by agents which simultaneously remove the debris. (Holmes (1965) for example, gives a fuller discussion).

*** The damsites and reservoir lie in the 'Sub-Himalayas' of Gansser (1964, fig. 1) and are also on the south-east part of the Potwar Basin. Gill (1952) defines the Potwar plateau physiographically as 'the elevated dissected peneplain which lies between the Indus and the Jhelum river...'. On this definition only the part of the site on the right bank of the River Jhelum is, therefore, in the Potwar. However, as the left bank reservoir areas of the site are largely the Mirpur Silt Plateau which is similar to the rest of the Potwar, the whole site is loosely considered part of the Potwar Plateau.

Some of the sedimentary features now being laid down in the plain* can be used to study the ancient features found in the Siwalik bedrock. This knowledge can help in elucidating some of the engineering problems, for example, the dimensions of buried channels or the inclusion of clay balls in sandstone which frequently occur in the bedrock of the Project. Plate 2 is a view looking south towards the Punjab from the Siwalik hills west of Mangla.

The southern perimeter of the reservoir is formed by a ridge of hills from Mangla through Sukian, Bala Gala and Jari to Kas Guma (fig. 4). Gaps in this ridge occur at Mangla, through which the River Jhelum passes, at Jari through which the Jari Kas passes and at Sukian, which is a low portion. Plate 1** shows the valley and damsite at Mangla; plates 3 and 4 show the valley and damsite at Jari and plate 5 part of the ridge and damsite at Sukian.

At Mangla the valley is over half a mile wide at the damsite and the bedrock dips gently north-east. Erosion is active and has produced long dip slopes of sandstone and steep scarps of nearly vertical sandstone cliffs and degraded slopes of clay. The dip and scarp features give the appearance of 'sawtooth' topography (for example see plate 6 showing the left abutment at Mangla Damsite and plate 7, part of the

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* Several authors (for example Gee (1952), Gill(1952) or Wadia (1957)) have gone as far as suggesting that part of the Siwalik succession was laid down by a proto Indus.

** A liberal amount of photographs of the terrain has been included as it is of a type not found at present in the United Kingdom.

Gharder Kalan fold west of Mangla). Natural failures are usually by vertical slabs of sandstone, the height of the bed, peeling off from a cliff face and collapsing into the valley (for example see plate 8). Behind the failure surface is a large crack, often filled with plant and soil debris, that has been made by tension stress in the sandstone due to the natural erosional formation of the valley. No clearly distinguishable ancient or fresh scars of circular slides in clay were found. The absence of this type of failure, which at first sight is surprising when the laboratory effective shear strengths are considered; is thought to be due to the low water table and dry (apart from the monsoon) climatic conditions. These features tend to give a high suction within the pore spaces (high negative pressure could amount to 2 or 3 atmospheres) and would account for the high apparent strengths. In addition the active pace of the erosion rapidly removes weathered rock and continually sculptors fresh surfaces. Measured figures on the rate of erosion are not available, but the principal erosion processes are almost certainly of two types. Firstly, the vertical slab falls in locations undercut by water action. This is the main method of sculpting the Jhelum valley at the damsite. Secondly, abrasion by water action. This must be quite small, although perceptible over long periods of observation. Erosion tell-tales consisting of metal pins sunk in concrete on typical sandstone bedrock on the river bank under Fort Hill (fig. 2)in 1959 showed no measurable erosion on the majority of pins when

removed during construction in 1965. On two or three pins erosion of a millimetre or so had occurred. The pins were submerged for about 10 months of the year and were on the outside bend of the river where current flow was strong. Away from river and stream action erosion is by wind and rain-water removal of weathered material. Plate 9 shows marked differential erosion in sand and clay beds in a nullah; plate 10 shows a small butte or erosion relic and plate 11 'badland' erosion pillars in Siwalik clay/siltstones.

The valley contains a flood plain terrace and various terraces at higher levels. Prominant terraces occur on the right bank of the River Jhelum upstream of Mangla at elevations of 1,020' at Sultanpur, 1,200' at Dhangroat and 1,650' at Kunbli. The prominant terrace of the left bank in the areas of Ther Chak and Pel Karin is ca. 1,100'. These terraces are shown on fig. 4. The dam itself is aligned along a peninsula formed by a large meander of the River Jhelum (fig. 2). Approximate elevation of the river at the damsite is 890' and the Sultanpur peninsula 930'. The shoulders of the dam are founded on terrace alluvium and the clay core of the dam is taken down by a core trench to bedrock. The spillways, tunnels and power house (see fig. 2) are founded on bedrock. Plate 1 is a view taken before construction started looking upstream from a point about $\frac{1}{2}$ mile downstream from the centre-line of the main embankment.

Sukian Dyke follows the crest of the ridge for a distance of $3\frac{1}{2}$ miles eastward from Mangla (see figs. 3 and 4). The

crest is on average 60' below reservoir top water level for the low dam; it forms an almost unbroken watershed between small nullahs* draining northward into the river Jhelum and nullahs draining southward to the Jabba Nullah (which eventually leads back into the Jhelum). The ridge is a product of gentle slow sub-areal erosion with gradual downwearing of the crest and backwearing of its flanks (plate 5 shows a general view and plate 12 a view of the 'ridge'). The sawtooth topography found at Mangla and Jari is the product of more rapid erosion, where bedrock has been worn away quickly with a result that the action of weathering has not had time to affect the bedrock deeply; but at Sukian as the bedrock is only being eroded slowly, weathering has had a chance to penetrate deeper. The bedrock of the Sukian site is obscured by the debris of this weathering. The weathering has affected the engineering properties of the clays and this is discussed in Part II. It is of interest to note here that appreciation of the erosion mechanism enabled areas of weathered bedrock to be anticipated during the investigation. Only at Sukian was any stripping of foundation directly required because of weathering affecting strength properties of the soil material**. Elsewhere foundations were stripped to get below near surface effects, for example, drying cracks or root penetration.

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* Water course, usually dry except during rainy seasons.

** Soil material - used in analogy with 'rock material' (Fookes & Wilson 1966).

East of Sukian, the Jari Dam will block a valley through the Bala Gala ridge. Geomorphologically this ridge is not a continuation of the Sukian ridge, but is part of the southern rim of the Mirpur Basin (fig. 4). The Sukian ridge cuts across the strike of the bedrock and joins the Bala Gala ridge near the village of Sukiban. The Bala Gala ridge has a typical dip and scarp topography at the western end as the beds dip shallowly northward to the axis of the Mirpur syncline, but at Jari although the strike is still east-west, the dip has steepened up to 50^{o} and the ridge is almost a hogsback*. Scars of numerous slab slides are found on the dip slopes where clay beds had failed by sliding along bedding planes, shear or thrust (shear) joints**. The underlying sandstone beds are removed by erosion over a period of decades and this reveals the next clay bed beneath and the cycle is repeated. This type of slope failure was not recognised at Mangla and Sukian where the dip of the bedrock is shallow. One large and several small circular(?) slips were found on the scarp face; above the large slip was a spring. The large slip involved some 100,000 cu.yds. of material and occurred on an almost vertical scarp face composed of several clay and silt beds. The slip occurred an unknown period of time before the commencement of work on site and the exact path of the failure surface followed was uncertain. Plate 13 shows a view of the

* Approximately equal slopes on each side of the ridge.

** Discussed more fully in part II

right abutment, from $\frac{1}{3}$ mile downstream and includes the large slip. Plate 14 shows a typical nullah and bedrock in a strike valley of the right abutment.

South of the Bala Gala and Sukian ridges and north of the line of hills on the left bank of the Upper Jhelum Canal where the Punjab plain commences, the topography is rugged and has the appearance of 'badland erosion'. North of the Bala Gala ridge within the Mirpur basin, bedrock is covered by Mirpur silt, a water-lain loessic deposit that is currently being rapidly eroded by numerous small streams which run in summer monsoon but are dry at other times. These streams cut back by headward erosion and form a series of small terraces that rise to a central north-south watershed (see fig. 4); eastward streams drain into the Jari Nullah and westward streams drain into the River Jhelum. At one time a dam alignment was considered along this watershed (elevation ca. 1,200 ft) but laboratory and field tests showed the behaviour of the silt foundations would be doubtful especially under earthquake conditions*, so the alignment was shifted to its present position at Jari. Plate 15 shows typical badland erosion in the Mirpur silt.

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* For discussion of the seismic behaviour see Ambraseys (1960).

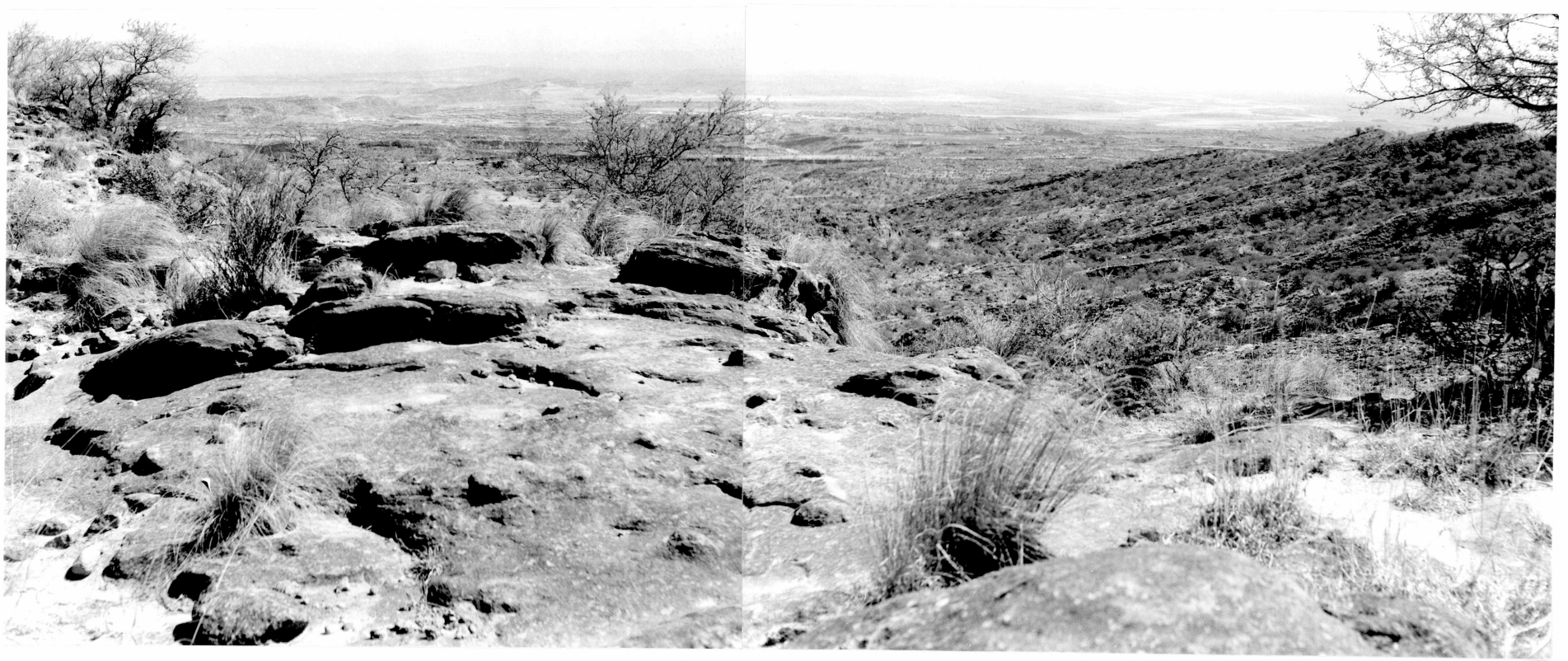


PLATE No. 3 June 1962

The floodplain south of Jari damsite looking north-east and showing the left abutment and rimworks in the background. The cliff face (arrowed) in the left front background is trench DE (discussed in Part II and shown as plate 22).



PLATE No. 4 June 1961

Jari damsite looking west approximately along the centreline of the Main Dam towards the right abutment, taken from the right bank middle terrace.



PLATE No. 5 June 1963

The middle and eastern (Jari) end of Sukian damsite taken from the Bala Gala ridge and looking westwards. The line of rounded hills on the right is the north western end of Bala Gala ridge and the hills on the skyline form the reservoir rim on the right bank of the River Jhelum. Mangla Fort is arrowed.

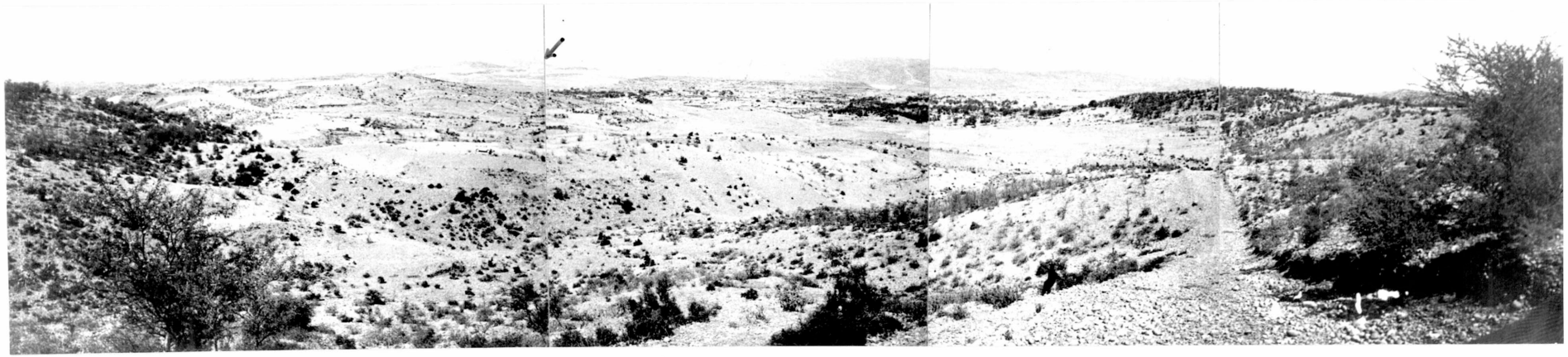


PLATE No. 6 July 1962

Fort Hill and the right rim and abutments, Mangla, taken from Sultanpur rest house, looking east. Sultanpur peninsula occupies the left middleground, the early stages of the intake excavation just beneath the skyline behind Fort Hill, is clear.



PLATE No. 7 February 1965

Typical Siwalik country, Lehri Reserved Forest, west of Mangla. The beds form part of the Gardar Kaklan 'anticline', the strike ridges, shallow dip slopes of sandstone and steep degraded slopes of clay are clearly shown.

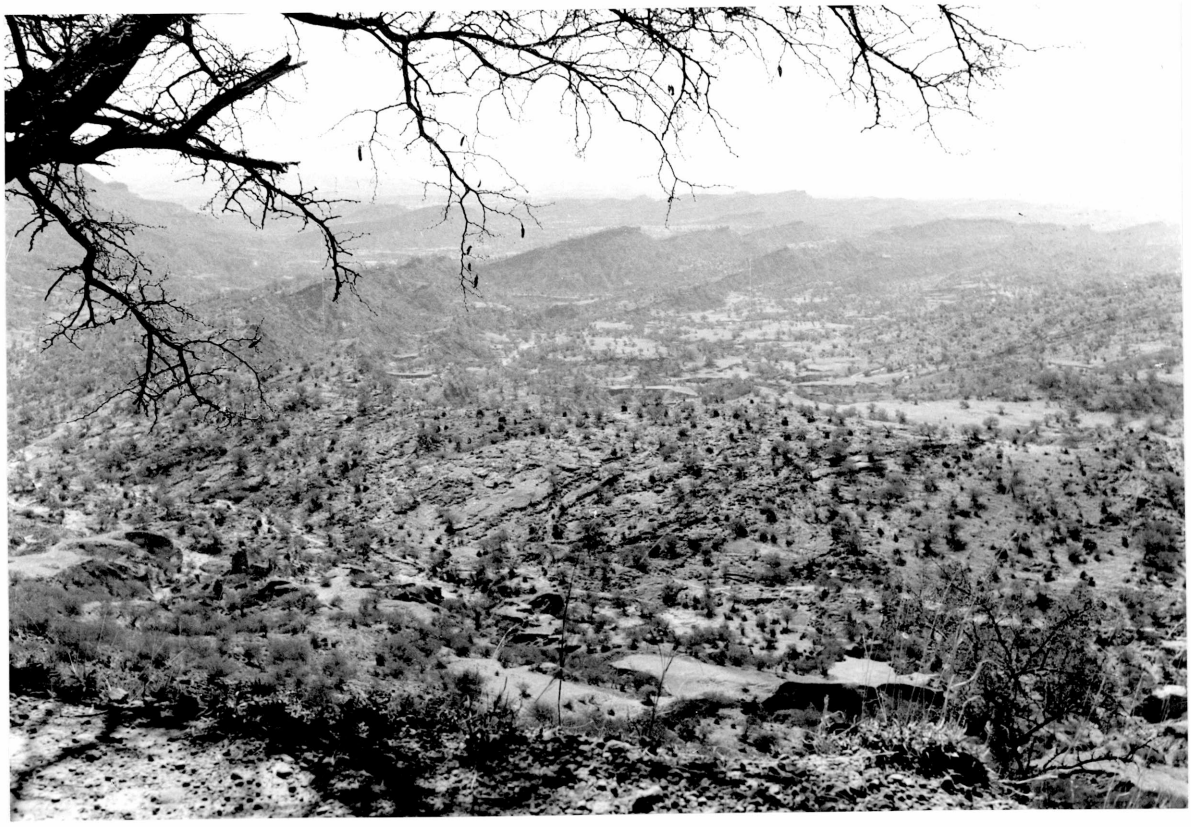


PLATE No. 8 March 1965

Nearly vertical Siwalik cliff face, ca. 20' high, showing typical development of vertical tension cracks behind the cliff face and a vertical slab nearby nearing collapse. The cliff face is composed of thin beds of sandstone and clay. Taraki haul road, Lehri Reserved Forest.



PLATE No. 9 March 1965

Differential erosion of nearly vertical sandstone and clay beds of Middle (?) Siwalik in a nullah bed west of the Main Spillway, Mangla. The hard partly cemented sandstone beds have been picked out as ribs traversing the walls and floor of the nullah. The stream floods several times in the monsoon and winter rainy seasons with flows of up to 30 cusecs (eye estimate) for a few hours at a time.



PLATE No. 10 January 1965

Typical small butte of sandstone capping a clay bed, Sukian. The harder sandstone forms vertical faces and the degraded slopes beneath are of clay plus some sandstone debris, which forms about a 20° slope.



PLATE No. 11 January 1965

Earth pillars of Siwalik sandstone capped by hard lenses of cemented sandstone, west of the Main Spillway, Mangla.

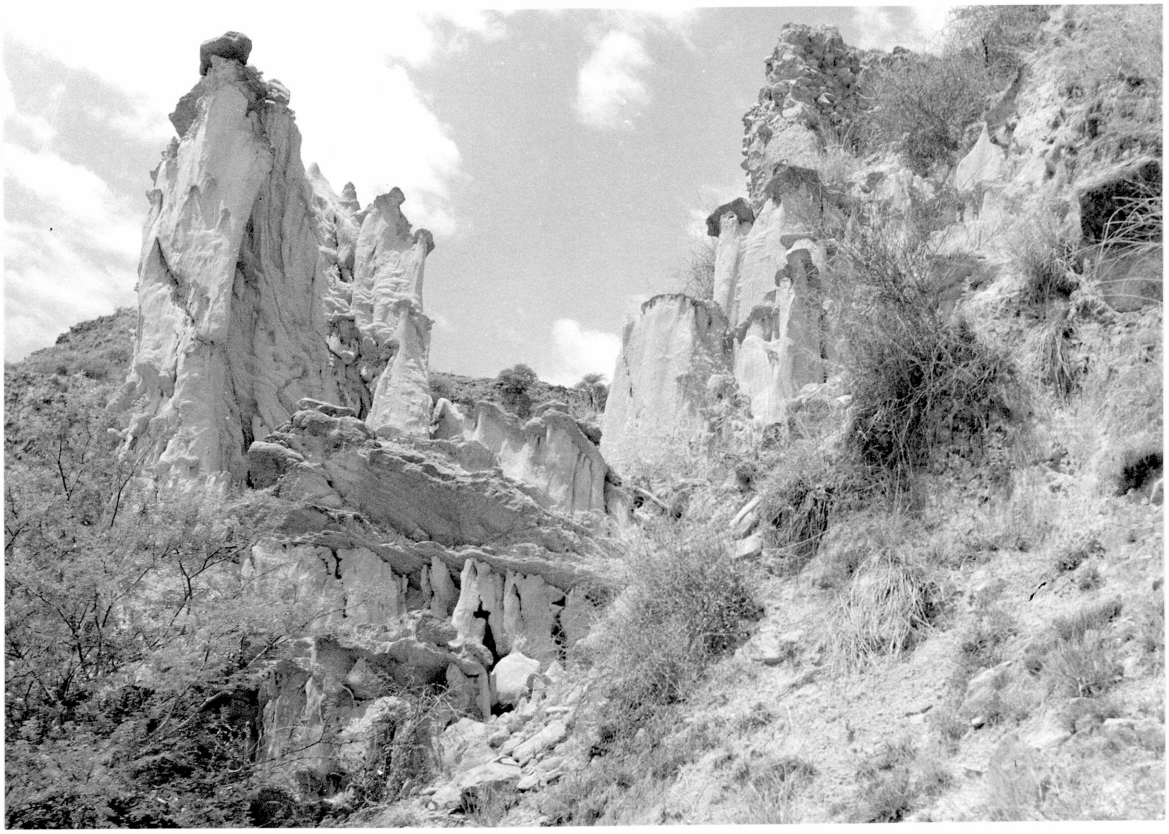


PLATE No. 12 February 1962

Part of Sukian damsite, looking north, approximately along the centreline from chainage 330 to 360. In the immediate foreground is alluvial gravel which caps the higher parts of the centreline ridge of the eastern end of the site. The hills in the background are the eastern end of the Bala Gala ridge and form part of the reservoir rim.



PLATE No. 13 July 1961

View of part of the right abutment at Jari, looking north from a point approximately $\frac{1}{3}$ mile south of the dam centreline. The stream in the foreground floods in the Jari nullah during the winter rains and summer monsoon. Immediately right of centre of the hills forming the abutment is a large circular (?) slip mass (arrowed) partly obscuring the bedding.



PLATE No. 14 April 1965

A strike valley immediately south of the eastern end of Jari right abutment, the highland on the left forms part of the reservoir rim. The view shows the uniform dipping sandstone and clay beds of the Upper Siwalik, with steep dip slopes and scarp faces forming an approximately symetrical ridge. This sort of country gave very difficult access during site investigation mapping, drilling and sampling.

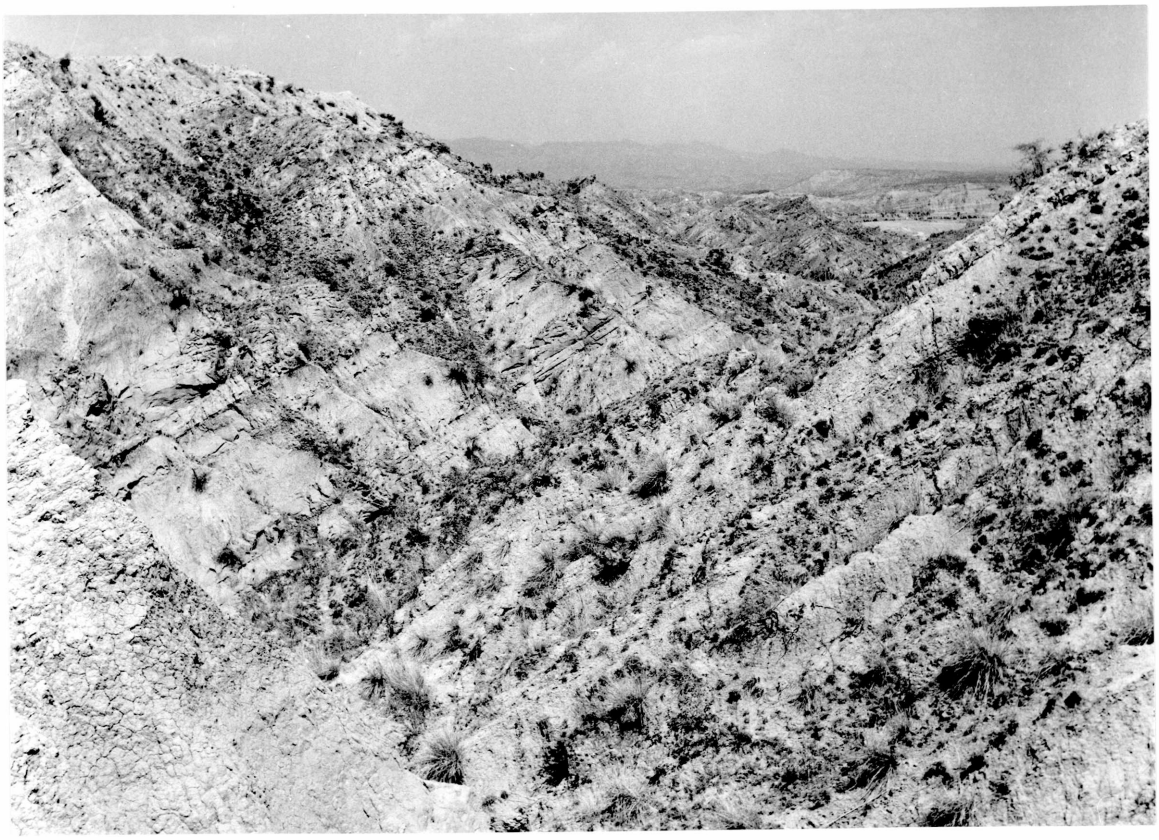
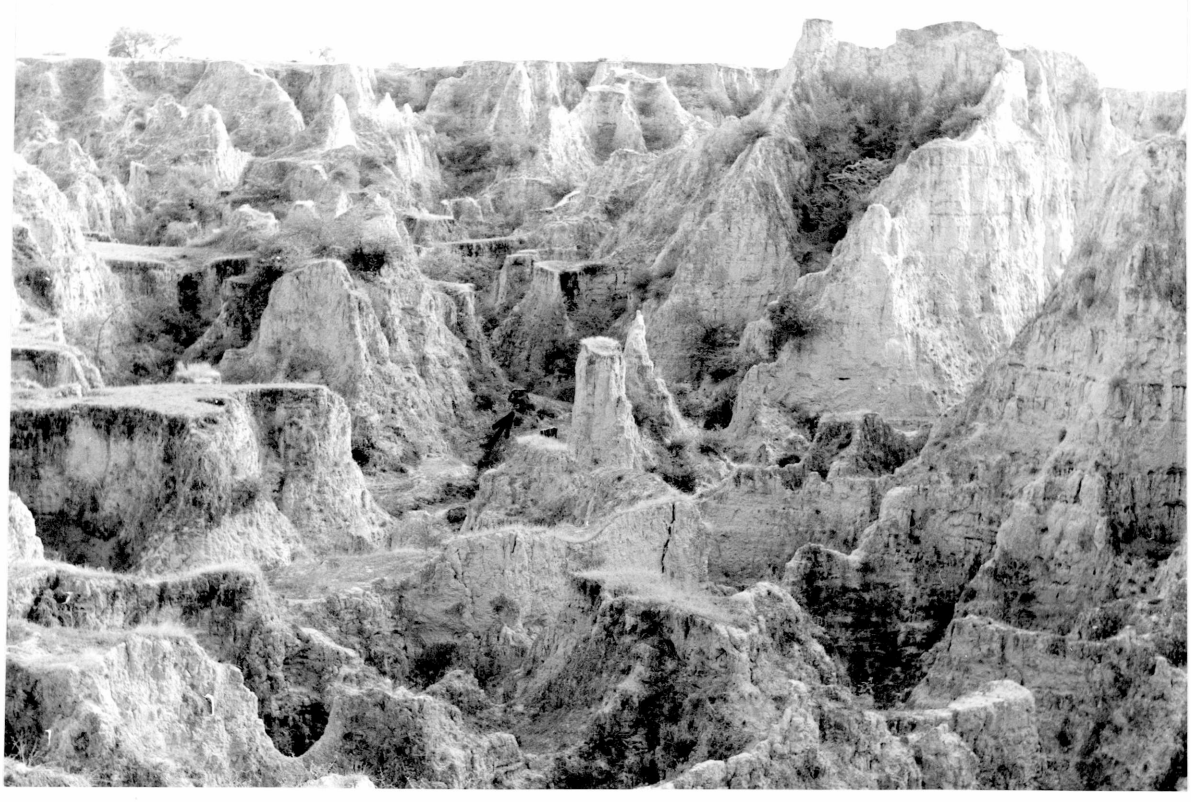


PLATE No. 15 April 1965

Typical badland erosion of the Mirpur silt, view looking northeastwards towards the abandoned Khad alignment. The silt shows marked bedding features indicating it is not a true 'loess'. Rucksack (arrowed) gives scale.



GEOLOGY

The geology is given here in outline, to form part of the essential background information for the descriptions that follow, and as a basis for understanding some of the engineering features of the clays. Sub-surface geological information on the area greatly increased pre construction information when the foundations were more fully exposed, 1963-65.

The site is underlain by predominantly fresh water sedimentary deposits of Mio-Pliocene-Pleistocene age, known as the Siwalik System. The Siwaliks outcrop along the southern foothills of the Himalayan mountain chain (see fig. 5) and are described in more geological detail by several authors, notably Anderson (1927), Gill (1952) and Wadia (1957) who consider them to be the deposits of an ancient river system. They have been folded and faulted during the geologically recent movements of the Himalayan mountain building and are gently folded at the localities of the actual damsites. South of Mangla and Jari the folding is more severe. The Siwalik System is generally fairly well exposed in the abutments of Mangla and Jari dams, but in the valley sections of these sites and at Sukian it is covered by alluvial or weathered deposits.

Stratigraphy

(i) Alluvial Deposits

Fig. 4 shows the broad distribution of the alluvial deposits. The Mirpur Basin contains up to several hundred feet thickness of post Siwalik water-lain wind blown (?) silt. At Jari the river has deposited in places up to 30' thickness of sand, silt and gravel lenses and a floodplain at ca. 1,000' elevation and at least two other terraces at ca. 1,030' and 1,050' are recognised.

The River Jhelum has filled its present valley with alluvium up to an average depth of 75', though this figure is quite variable. The lower part of these deposits consist predominantly of gravel with lenses of silty sand and are overlain by floodplain silt and sand with gravel of up to 40' thickness. The sand and gravel of the alluvium is composed of similar Himalayan rock fragments to the sandstones and conglomerates of the Siwaliks. The alluvial deposits were investigated, 1958-61, in some detail for borrow material in areas outside the dam foundations and in greater detail in areas that were to form the foundations. Several river terraces are also present (plates 1 and 6).

(ii) Bedrock deposits - The Siwalik System

a) Regional Geology

For an introductory paragraph it is difficult to improve upon the writing of Wadia (1957) the present doyen of Indian (the Sub Continent) geology.

'... the composition of the Siwalik deposits shows that they are nothing else than the alluvial detritus derived from subaerial waste of the mountains, swept down by their numerous rivers and streams and deposited at their front*. The process was very much like what the existing river systems of the Himalayas are doing at the present day on their emerging to the plains of the Punjab and Bengal. An important difference is that the former alluvial deposits making up the Siwalik System have been involved in the latest Himalayan system of upheavals, by which they have been folded and elevated to their outermost foothills, although the oldest alluvium of many parts of northern India serves to some extent to bridge the gap between the newest Siwaliks and the present alluvium.'

The Siwaliks consist of clays (in the younger Siwaliks) clay/shales and shales (in the older Siwaliks), silts, siltstones, silty sands and silty sandstones, sandstones, sandy gravels, gravels and conglomerates. The System

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* These deposits were laid in the 'Nimadric geosyncline' (Anderson 1927) that received Middle and Upper Tertiary freshwater deposits which border the Himalayan mountains throughout their length from Assam to the N.W. frontier (fig. 5). Most authorities agree the Nimadric trough was analogous to the Molasse basin of the Alps (Middle Oligocene to Upper Miocene). This basin is the type area for 'Molasse' deposits which are apparently similar in most respects to the Siwaliks, though the Molasse basin did have occasional marine transgressions. These have not been proved for the Siwaliks.

The oncoming of the Upper Siwaliks reflect a profound change in the deposition environment with fan shaped deltaic deposits. The earlier Siwalik deposits suggest a strong influence of longitudinal river transport (Gansser 1964).

has been sub-divided partly on faunal and partly on lithological grounds, into three main groups, the Lower, Middle and Upper. This threefold division can be recognised in most of the Sub-Himalayan sections, 'a rather surprising fact considering the fluviatile nature of the deposit' (Gansser 1964). Gill gives a schematic correlation and facies table in the Potwar region (this is given as Appendix III), which serves to underlie the difficulties of correlation; these difficulties were also found on the Project. They are due to local facies changes, general absence of marker beds and fossil horizons. It is certain that no Lower Siwalik occurs on the Project and possibly no Middle. Accurate correlation and dating of the beds depends on the fossil vertibrate forms and although a roomful of bones and teeth (elephant, tiger, rhinocerous and horse?) was collected, largely from Sukian, to date no accurate identification has been made. In addition, several complete lamellibranchs were found from dark grey clay horizons at Mangla (in the Main Dam core trench and from the Intake area) and Jari (adit JA 3). Again to date no identification has been made.

Some disagreement occurs in the recent literature on the stratigraphical position of the Siwaliks. Table I below outlines the situation.

T A B L E I

Summary of Recent Stratigraphical Positioning of the Siwaliks

		Wadia (1957)	Gill (1952)
PLEISTOCENE		(3rd Himalayan Upheaval)	Upper Siwalik (6,000')
PLIOCENE		Upper Siwalik	Middle Siwalik (7,000')
		Middle Siwalik	Lower Siwalik (8,000')
MIOCENE	Upper	Lower Siwalik	Murree
	Middle		
	Lower	(2nd Himalayan Upheaval) Murree	
		Total say 20,000'	

(figures in brackets are maximum thicknesses in feet)

The stratigraphic succession of the area of the Project is given as columnar sections, fig. 6. Mapping information from Mangla and Jari was collected during construction and from Sukian in the investigation prior to construction. From this detailed geological cross sections were constructed for each damsite; stratigraphic thicknesses were then obtained by measurement perpendicular to the bedding on dip sections. It will be possible to make a final section after completion of all the excavations but the section given is thought to be accurate to say 100'. There were no problems of

correlation within each damsite as overlapping sections could be readily produced. Correlation between sites was more difficult. Between Jari and Sukian it is based on the assumption (which is almost certainly correct) that the main 'bentonitic clay' seam at Sukian and the one occurring immediately south of the Jari site are one and the same. This seam can be traced for most of the way between Jari and Sukian though actual confirmed exposures are rare. Correlation between Mangla and Sukian was achieved by walking over individual beds from immediately above the Intake area to Sukian.

At Jari and Bala Gala (north-east of Sukian) the Mirpur Silt (probably equivalent to Gill's Potwar loessic Silt (group 8) overlies the clay and sandstone beds at Jari and the gravels at Bala Gala, unconformably. The gravels (or strictly gravel/conglomerate) of Bala Gala overlie the local Siwalik clay and sandstones. It consists of thick (up to 50') lenses of gravel plus cobbles and boulders in a silt or sand matrix, with little or no cementing. The coarse fraction* is predominantly quartzitic types with a fair proportion of more basic igneous and metamorphic rocks. About 5% of coarse fraction is rotten due to weathering. In addition there are subordinate lenses and beds of silty clays and sandstones. These gravels are dipping conformably with the underlying Siwaliks and are, therefore,

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* fine gravel to boulders. See Fookes[1] (1963).

considered equivalent to Gill's 'Siwalik conglomerate' (Tatrot / Pinjor) group 6* or Wadia's 'Boulder Conglomerate' (immediately above his Pinjor stage) which both authors place in the lower Pleistocene.

The clays and sandstones immediately underlying the Bala Gala gravels are Upper Siwalik for on lithological evidence are similar to Gill's (Tatrot/ Pinjor) group 5. The sandstones are light brown and buff in colour with a small 'tail' of fines. In the Soan area, Gill suggests this group is up to 3,500' thick. Therefore, as the rocks at Mangla are stratigraphically deeper than this (about 4,000' below the base of the Bala Gala gravels), they may be Upper Middle Siwalik.** Wadia's description is not detailed enough in the Mangla area to permit more than speculation, but his Middle/Upper Siwalik boundary is either similar or only a little lower, than Gill's (Gansser) so on his succession, the Mangla beds may still be Middle Siwalik. Wadia's (1928) map, although on a 1" to 4 mile scale shows only Upper Siwalik. Lithologically, the beds at Mangla are similar to those at Sukian and there is no obvious place to put an Upper/Middle boundary anywhere on the Mangla damsite, though towards the lower part of the Mangla succession, the sandstone beds clearly get a little thinner and whiter (or 'greyer') which is one of Gill's criteria for his Soan Dhok Pathan stage. The author

* Gill (1952) table II, p. 382.
** i.e. equivalent to Gill's (Dhok Pathan) group 4.

places the local boundary about 2 miles west of the Emergency Spillway in the Lehri Reserved Forest*. On balance, therefore, it is convenient to consider all the beds of the Project Upper Siwalik (on grounds of thickness and lithology) but to keep an open mind on the possibility that the lower part of the Mangla sequence is Middle Siwalik.

The only recent published work found on the clay mineralogy of the local Siwaliks is by Bibhute Mukherjee (1964) who, states "The Siwalik strata which commenced to form in the Middle Miocene have all the characteristics of fluviatile deposits (alluvial detritus) laid down in a shallow freshwater basin. In the type areas of Siwalik at Potwar, Kangra and parts of the Northwest Punjab a continuous sedimentation took place from the Ranokot stage to the Lower Pleistocene period with a gradual change from a brackish-environment to increasingly freshwater conditions for deposition, this was accompanied by a change from lacustrine to fluviatile conditions. Three samples of sandstone (sic) and Nummulitic Grit of the Kamlial stage of the Lower Siwalik formations in the Potwar area and in the Salt Range near Bhalwal contained 40-50% illite, 20-30% kaolinite, 20-30% montmorillonite and no chlorite was detected. Six samples of calcified sandstone and sandy-clay from the Siwalik formations of Dehra Dun, Potwar and other areas of Middle Miocene age in the north-west Punjab consisted of 40-50% illite,

* Where the lithology changes and appears to be similar to Gill's (Dhok Pathan) group 4.

30-40% kaolinite and 20-30% montmorillonite with no detectable amount of chlorite. The composition of the Upper Siwalik deposit indicates a significant change in the character of the sediments, since six samples of 'sandy clay' in soft sandstone from near Murree and Nara Chita Pahar consisted of 40-50% kaolinite, 30-40% montmorillonite and 20-30% illite with no detectable chlorite. Interstratified illite-montmorillonite is present in most of the samples of the Siwalik formations. The non-clay accessories are mainly calcite, feldspars (predominantly alkali feldspars), quartz, hematite and dolomite (scarce)". Clay minerals are discussed following and again in Part II.

b) Geology of the Project

In the Mangla/Jari area bedrock consists mainly of alternating beds of sandstones, clay and silt/siltstone (for example, plates 6 and 14). Gravel beds occur in the upper parts of the System which outcrop at the eastern end of Sukian and Jari. Thin lenses of bentonitic clay and volcanic ash were found near the eastern end of Sukian Dyke and downstream of the dam at Jari and are reported by Taquib Ali from several other locations south of the Mirpur Basin rim towards Dhangroat. Individual beds of clay, sandstone or silt could also be called 'lenses' since they often thin out and disappear over distances of a few hundred feet. At site the term 'lens' was restricted to beds proved to be no greater

than 500' in length. Some of the sandstone and clay beds exceed 100' in thickness (see fig. 6). These were traced for considerable distances so making it possible to correlate the strata in various parts of the Project, though generally the amount of lateral variation produced by lensing out of the beds was so great that a detailed correlation during the site investigation mapping was not satisfactorily made until later when the foundations were exposed. The beds of sandstone often contained thinner lenses of clay and beds of 'pseudo-conglomerate' (local term for clay balls in a sand matrix) and the thicker clay beds often contained thin lenses of sandstone. Contacts between sandstones and clays were either sharply defined or gradational. Occasionally infilled erosion channels occurred (for example plate 16) which could be sufficiently deep to cut through a bed and terminate it abruptly. The bed would then continue on the far side of the channel; this condition made production of geological sections from borehole data somewhat difficult.

The clays have been overconsolidated by the weight of overlying strata which have been subsequently removed by erosion. Typically they are stiff to hard and fissured; some of the fissure surfaces are slickensided (for example, plates 17 and 18). They are usually silty and have little if any cementing material; they crack readily when exposed to air and slake when subject to alternate

wetting and drying. Results of a few clay mineral analyses indicate that the clays at Jari contain approximately 20% montmorillonite whereas the older clays at Mangla contain approximately 10%. They also suggest that the Jari clays may have been a little more weathered* soon after deposition than the Mangla clays (as they have less chlorite and ferrous iron**).

The silts and siltstones commonly occur as transitional zones between clays and sandstones; they are usually weakly cemented with calcium carbonate and bonded with clay.

The sandstones are generally silty and fine to medium grained although some may contain up to 25% coarse sand, mafic minerals form about 5-15% of the sand fraction and the remainder is quartz so they could be classified as 'sub greywackes'. They are light brown or buff in colour, weakly cemented with calcium carbonate in clayey silt, except for hard lenses and nodules which form up to 10% of the rock by volume; the lenses and nodules are

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* The weathering may have been a result of the more severe climatic conditions of the time, heralding the approach of the Pleistocene ice ages. Changes in composition due to difference of source material were not investigated. Morris (1938) recognises a 'tillitic' deposit in the Upper Siwalik of the Salt Range east of Mangla, which he correlates with the Alpine Günz glaciation, on a Villefrancion fauna from the grits above and below his Boulder Bed. This bed is 6,000' below the top of the local Siwalik succession.

** Mineral analyses were carried out by Robert H.S. Robertson, (Mineralogist), Pitlochry, Scotland.

cemented with calcium carbonate. The poorly cemented sandstones* are friable and disintegrate into loose sand when submerged in water; sometimes there is a local case hardening of the sandstone outcrops which produces a satisfactory 'ring' to a hammer. Generally there is little variation in lithology, colour and properties of the sandstones occurring in different parts of the Project. The beds of gravel that occur in the upper part of the Siwaliks at Jari and Sukian consist of fine to coarse gravel and occasional cobbles. The interstices of the gravel are filled with silt or fine sand and occasionally lenses of gravel are found either open or cemented with calcium carbonate.

At several locations on the left bank at Mangla 'gliding slide' structures of contorted clay lenses between sandstone beds were found, 1-2½' thick and up to 20' long. These were considered to be penecontemperaneous slumping soon after deposition and similar in form to those described by Brown (1938), plate XXX from geosynclinal sediments in Equador.

A more detailed discussion of the engineering properties of the clays is given in Part II.

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* Some of the sandstones deserved the name 'sand' but the term sandstone was retained on site to avoid confusion with the initial work of 1958 and onwards.

Structure

a) Regional

The trends of the principal fold axes in and around the reservoir area are shown on fig. 4. The alignment of these axes falls broadly into two groups, one trending north-east and the other trending north-west. They are parallel to two major fold directions, locally called the 'Baluchistan' and 'Himalayan' directions respectively. The major axes of the two fold directions meet at right angles in the vicinity of Muzaffarabad about 100 miles north of Mangla and together form a structure known as the 'syntaxial bend of the Himalaya' (Wadia 1936 and 1957). The axis of the bend runs approximately north-south and is shown by Wadia and others to pass approximately through the Mangla area.

Gill (1952) on the Siwaliks of the Potwar basin recognises three major zones of deformation.

(i) A southerly zone of open folding, affected to a varying degree by fold-faulting;

(ii) A fault zone, displaying a number of 'reversed' faults of steep northerly hade and great lateral extent with open folds between them and in places gently dipping monoclines...;

(iii) A northerly zone with closely spaced strike faults and severely compressed folds bordered by the so-called Main Boundary fault...

Gill concludes that analysis of the (major) faults shows no genetic relationships to the fold axes. He considers

them to be fractures due to shearing stresses principally with a vertical orientation whilst the folding represents a subsidiary (later) compressive force.

Although site investigation fieldwork was not specifically directed to consider the regional geological structural problems but was done mainly on the minor structural discontinuities, the site work when added to more general observations made in the course of regional tours in search of rip rap, does support Gill's hypothesis in a general way. The evidence for the sequence of events remains scanty and makes an interesting problem well worthy of further work.

Simplified geological sections across the reservoir area are given in figs. 7 and 8. Plan locations of these sections are shown on fig. 4. The sections were constructed from 1" and 2½" (where available) topographic maps of the area and by a landrover survey approximately along the line of the section. Dip measurements were made at the ground surface, but the sub-surface geology is only speculative. The final appearance of sections 1 - 1' and 2 - 2' is of uplifted blocks and is not out of keeping with Gill's suggestion of vertical block movement. The form of the folding shown was concluded from observation of dissected cores of the Changhar faulted fold south of Mangla and Sutuh and other folds north of Mirpur. These folds are shown in plan on fig. 4 and are visible in section along the Punch and Khan river valleys. This area is north of the reservoir

and was only visited by occasional landrover recces., but it was clear that fold and fault structures were more severe and complex than further south towards Mangla.* This area most probably corresponds to Gill's zone (ii), page 23.

The area of the Project probably corresponds to Gill's major zone (i). Along the Changhar faulted fold unquestionably considerable major strike faulting has taken place. In the neighbourhood of the valleys of the Kanghah and Changhar, the scene is similar to Gill's sketch (fig. 3) of the Sola Singhi ridges of the Kangra district some 200 miles south-east of Mangla and Gill's description serves for the Changhar area as well as his own "On the north side of the ridge south of the Barsa fault (Gill's equivalent to the Changhar feature) infra-Nahan beds and the lower members of the Nahan Sandstones dip everywhere southwards into the ridge. As the crest is approached the dip increases to the vertical, and then, over to the south slope of the ridge the beds are strongly overturned." The greatest overturning noticed on the Changhar fold in this area was 73°N. Similar sections on this fault line can be seen elsewhere on the site, for example, at Bong Canal and Dhak Raja west of Mangla. In addition north of Changhar village, what may be a large 'flap' or gravity collapse structure some $\frac{1}{4}$ mile long, is visible.

Foundation excavation at the Bong Canal recently (1966) revealed the following sequence (described from approximately north to south); northerly dipping beds hinging over tightly

* The form of the fold near Mangla is shown on plate 19.

southwards in a few hundred feet to a roughly vertical dip. The vertical beds then occurring for about 1,000' followed by a zone some tens of feet wide of intensely disturbed beds with vertical striations on polished clay surfaces, some of the beds with high dips north and some with high dips south. Then immediately south of the disturbed zone nearly vertical beds of gravel. These beds are similar lithologically and in grading to the Bala Gala gravels and in the local stratigraphic sequence thick gravels only occur at Bala Gala, so it is reasonable to conclude they are of Bala Gala age (top of the Siwaliks). If so the highly disturbed fault zone would have a downthrow on the south side of about 3,000'. The form of the fold turnover 1,000' north of the fault, which is also well exposed in the side of the Upper Jhelum Canal just south of its headworks, is of a highly asymetrical anticline, nearly a monocline, and the fault zone with its clearly demonstrated steep hade (a few degrees northwards) may well truncate the vertical (?) monoclinal limb at depth. If this was the case then the fault would almost certainly be the result of vertical shearing in the monocline and formed at the same time or soon after the folding of the monocline. Alternative hypotheses are that the faulting is reverse and that the folding is drag, on an enormous scale, associated with the thrust of the reverse fault, or that the faulting is normal and is not related to the folding. If this is the case then the folding can be compressional and pre or post faulting.

The 'normal' fault hypothesis would require a 90° change in direction of the principal stress in the relatively short time available (i.e. the Quaternary) though being so close to the growing Himalayas it is conceivable. The 'reverse thrust' hypothesis is least feasible as the fold form shows no pronounced overturning and the fault itself is nearly vertical and 1,000' away from the fold axis.

All the minor structural features north of the monocline suggest compressive stress and their strike directions are all more or less parallel to the local fold axis. In addition the two fold directions, the 'Himalayan' and 'Baluchistan' merge and do not appear to cut each other, and again in the short time available, to produce the strong fold movement in directions mutually at right angles they must have been formed more or less contemperaneously.

The picture that emerges is of elongate regions of compression together with up/down block movement, but until the relative sequence of events is clearer, it is still conjectural.

b) Local

(i) Folding

The structure of the Mangla damsite (s.l.) is dominated by the Changhar faulted fold. Minor folds occur trending parallel to the Changhar feature and a few hundred feet north of it Apart from these small flexures, all the engineering structures at Mangla and

Sukian are founded on the southern limb of the Mirpur syncline and the beds have a uniformly north-easterly dip between 10° and 15° to the horizontal (plate 19).

The macroscopic fabric axes* for Mangla damsite (s.s.) are shown diagrammatically in fig. 9. The more gentle folds in the vicinity of the Project such as the Mirpur Syncline are aligned with the regional 'Himalayan' fold directions. Local changes in this direction occur, for example at Jari where the beds strike east-west and have a dip of between 30° and 50°N. This fold system would be considered to be later movement than the vertical displacement of the Changhar strike faulting if Gill was followed and contemperaneous with the Changhar faulting on the local conclusions from site.

(ii) Faulting

Only three small faults were found at Jari and one at Sukian, but many minor faults comprising two principal sets of faults were mapped in the Mangla area. These sets strike either north-east or north-west more or less parallel to one of the regional fold directions and to which they could be related. All the minor faults appear to be thrusts or reverse faults produced by

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* A set of three mutually perpendicular reference axes; the strike direction of the beds is the 'b' axis; the 'a' axis is horizontal and perpendicular to the 'b' axis, and is the direction of tectonic compression; the 'c' axis is perpendicular to the 'ab' plane. 'Macroscopic fabric' refers to the large scale geological features (e.g. the bedding planes and fold geometry) which define the shape and arrangement of the deposit.

compressive forces; displacements along the fault planes of up to 25' have been measured although the majority of faults probably moved less than 3'. Faults have been traced for a distance of several hundred feet and generally dip at between 15° to 45° to the horizontal. Plates 20 and 21 illustrate typical fault forms from the Mangla area.

Shear zones are found in a number of clay beds throughout the Project. They have been formed by bed over bed slip during the formation of the folds*; it was not until this relation was established that the extent and amount of shear zones was realised. Associated with the shear zones and the compressive folding are thrust (shear) joints which occur in two sets dipping in opposite directions, the sets intersect to give a 'diamond' joint pattern (plate 18). This pattern of joints was produced by tectonic forces and is consistent with the fold and fault pattern of the area.

The clays are fissured in a randomly orientated manner though there is some evidence that many fissures dip at angles less than 45° to the horizontal and many of them are parallel to the shear zones or to the faults (Fookes 1965; this paper forms part of the thesis and is enclosed in the pocket at the end).

Tectonic and associated features outlined under local structures are of considerable significance to the Project and

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* A simple analogy is the bending of a pack of playing cards where each card slips a little over the adjacent card in the bending.

their investigation and characteristics are discussed more fully in Part II.

GEOLOGICAL HISTORY OF THE PROJECT

Locally deposition of the Siwalik System commenced during the middle Tertiary, when the area was uplifted during a period of tectonic activity associated with the growing Himalayan mountains to the north. This uplift rejuvenated the mountain streams and rivers which in turn eroded the mountains and carried and deposited their tremendous load of sediments into the Indus/Ganges* geosyncline lying to the south of the mountains. This deposition continued more or less to the end of the epoch (at the beginning of the Pleistocene) when up to 20,000' of freshwater sediments had accumulated. These sediments consolidated and now form the Siwalik System.

After this the evidence from the site, just discussed **, suggests they were involved in an early Pleistocene period of uplift during which time they were folded on a huge scale and then practically at the same time the major faulting occurred. Movement on the major fault may still be going on. In response to the stresses causing the folding the shear zones, minor faults, thrust (shear) joints and some of the tension joints were formed.

The Project folding is aligned with the regional trend of folds found north-east of Mangla and which strike north-west/south-east (fig. 4). The majority of beds of the Mangla

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* Or Nimadric

**i.e. Upper or post Upper Siwalik folding (the Bala Gala gravels are folded).

and Sukian damsites lie on the southern limb of a large synclinal fold and they dip gently and uniformly 10° to 15° north-east. At Jari they lie on the southern limb of the same fold but the strike direction has swung a little to east-west. The shear zones have the same geometry as the beds. The thrust (shear) joints which must be associated with the folding strike approximately parallel to the 'b' direction of the bedding (fig. 9) and occur in two sets which dip in opposite directions and intersect to give a conjugate (diamond) pattern. In general this pattern is remarkably constant over the site; and is illustrated by figs.57 and 70 which are contour diagrams of measured joint faces. These joints dominate other forms of joints and fissures by their greater extent, flatness of plane and polished and slickensided surfaces. These features are discussed more fully later in Part II.

With the folding movements came the minor faulting; all the faults (except the major Changhar fault) found on site to date, are of this type and are thrust faults which were probably formed by compressive stresses. At Mangla two principal sets of minor faults have been recognised, one striking north-west parallel to the local fold axes and the other approximately at right angles striking north-east. Some of the faults (all from the Main Dam core trench) of the north-east set have been observed cutting the north-west set and although this evidence is from

nine faults only they could be the result of a later second period of stress at right angles to the first (though more likely, from small scale adjustment to local stress changes). The regional trend of fold axes west of Mangla is north-east/south-west and it is possible that the north-east faults are related to this fold pattern, though the folds themselves occur a few miles west and south of Mangla. Fig. 70 is a contour diagram of faults at Mangla found during foundation excavation.

During the periods in which the folding and faulting took place, deposition of the Siwalik ceased. Since then erosion has been steadily wearing down the landscape and to date at Mangla and the western end of Sukian some 5-7,000' of bedrock must have been removed by erosion. With the rapid rate of erosion obviously taking place at the moment, if it has been continuing since early Pleistocene, it is not difficult to conceive that large fault scarps which would have been produced for example by the Changhar movement, would now be largely gone. The scarp feature half a mile or so north of the Upper Jhelum Canal must be the remnant of the Changhar fault scarp.

PLATE No. 16 January 1965

A sandstone bed overlying a small typical buried channel in thin bedded sandstone and clay beds. There is a small erosional non-conformity immediately below the massive sandstone bed overlying the buried channel. The exposure is about 1 mile southwest of the Emergency Spillway and is thought by the author to be near the Upper/Middle Siwalik boundary. The overlying sandstones are typical 'brownstones' of the Tatrot stage.

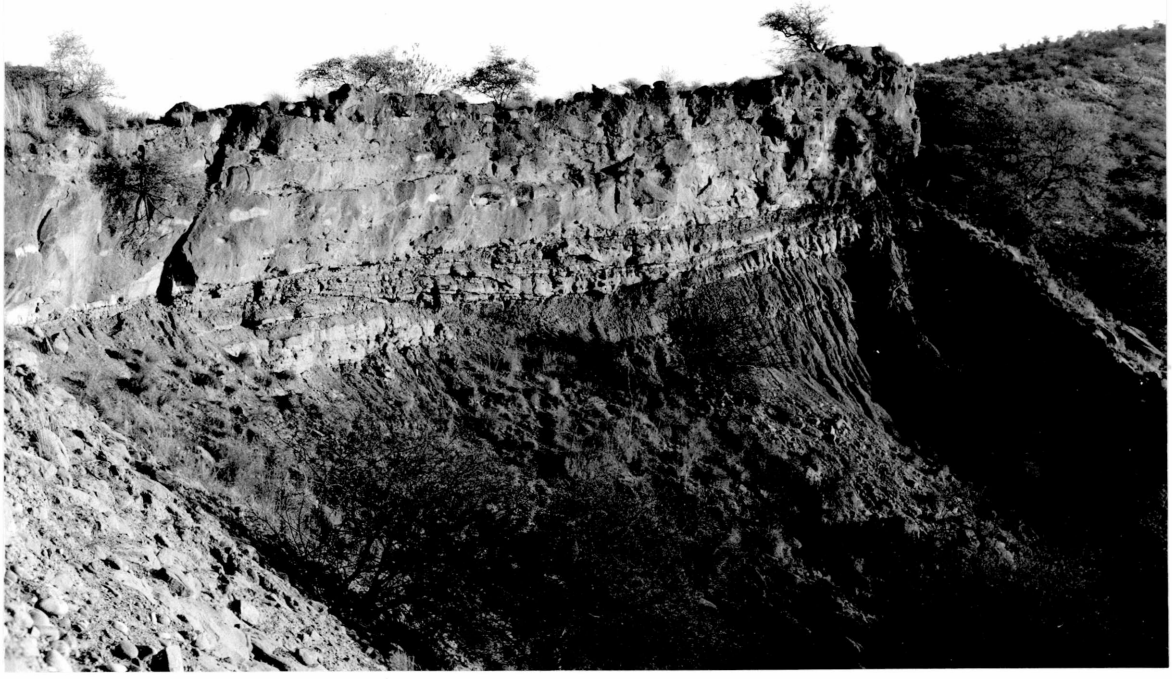


PLATE No. 17 November 1961

A cleaned-up exposure of thin bedded Siwalik clays and silts overlain by massive sandstone, Fort Hill, Mangla. The clean-up was one of many attempting to trace the various faults of Fort Hill.

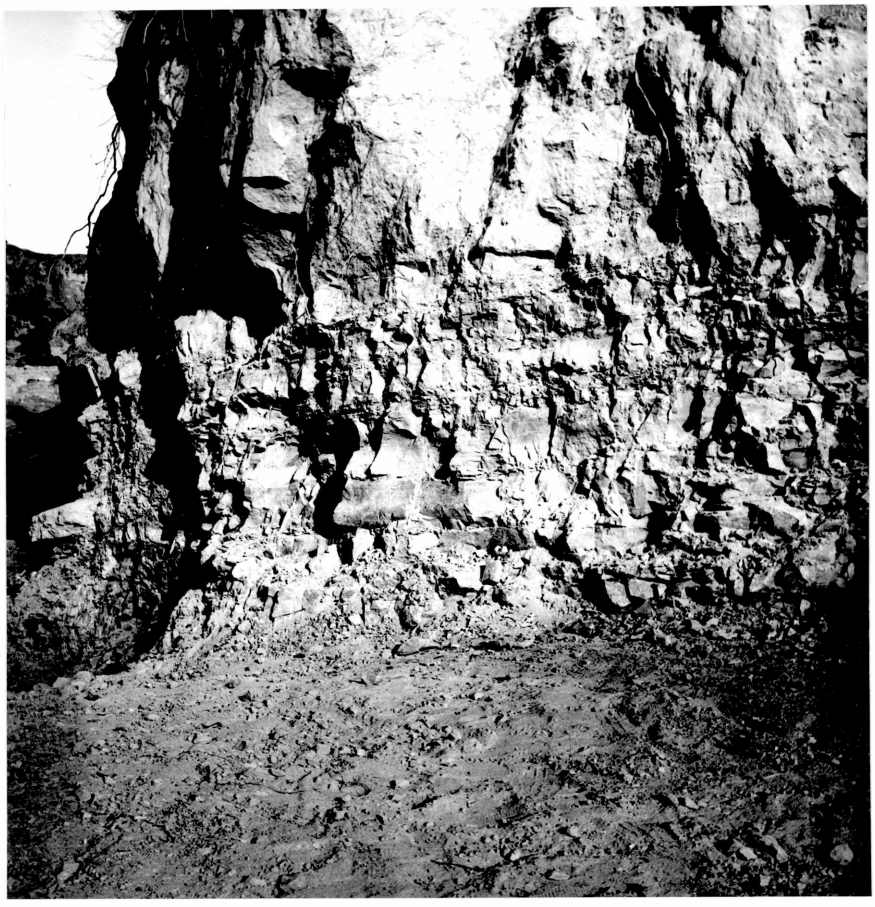


PLATE No. 18 September 1962

The side wall of adit JA 16 showing typical 'fissured' clay (a little dried out) and typical diamond pattern formed by thrust (shear) joints. Some of the fissure and joint bounded clay blocks are slightly disturbed by the digging of the adit (by spade and pick-axe) and by drying cracks. Total length of the photograph about 10'. The adit takes a 30° bend by the central upright.

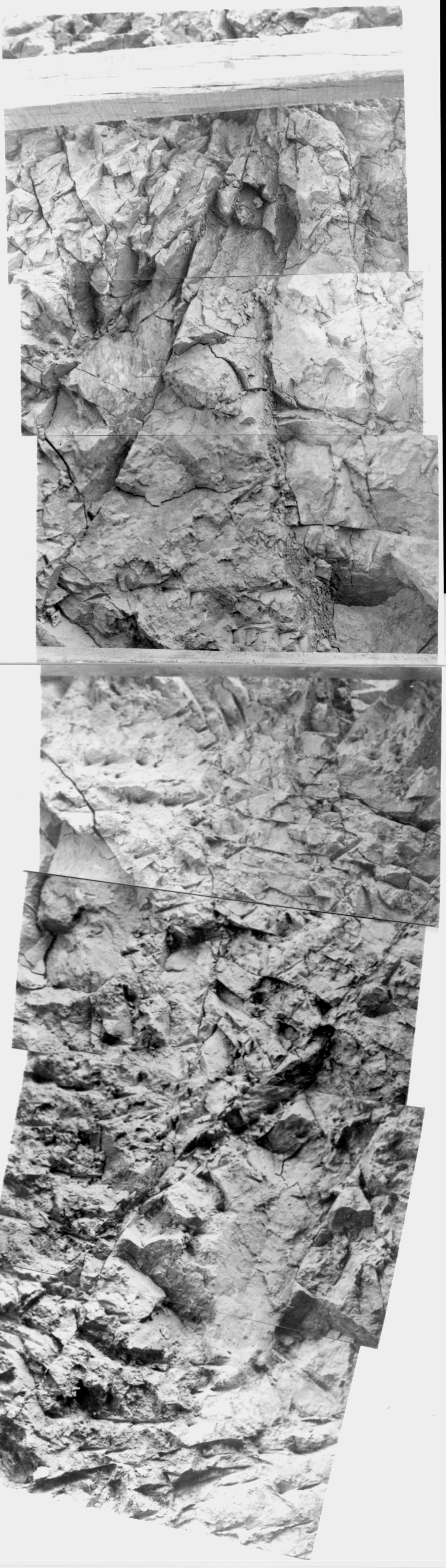


PLATE No. 19 February 1965

A panoramic dip section of the Changhar 'faulted fold' looking northeast from the old Mirpur/Upper Jhelum Canal road, where it crosses the line of the fold axis. The monoclinal form of the fold with its shallow north dipping limb and the near vertical/slightly overturned south limb is clearly shown.

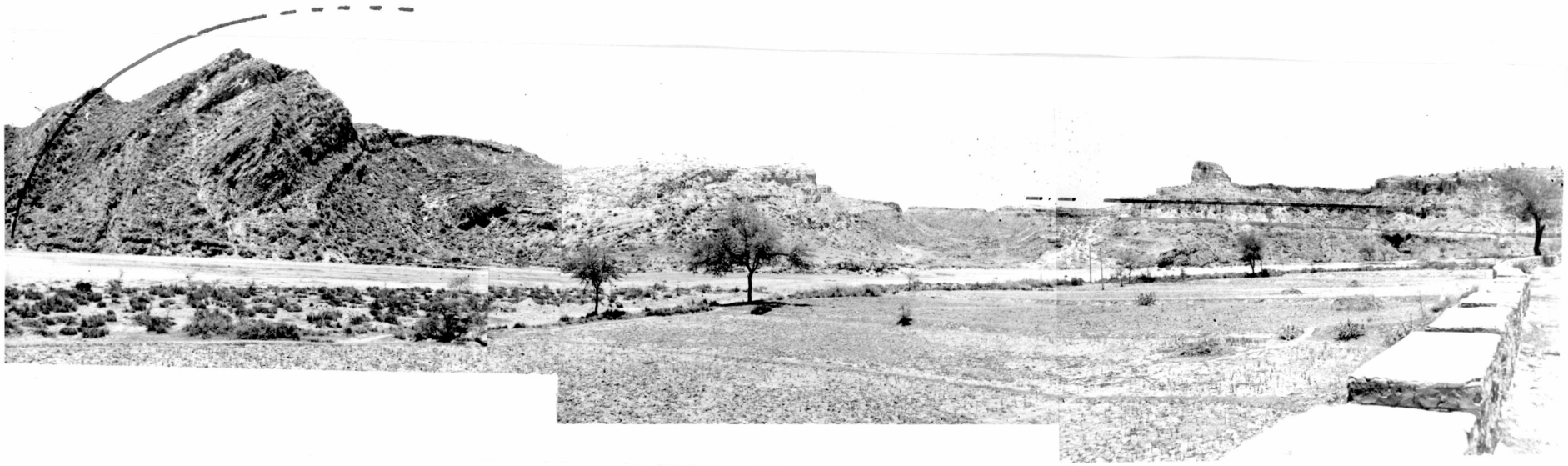

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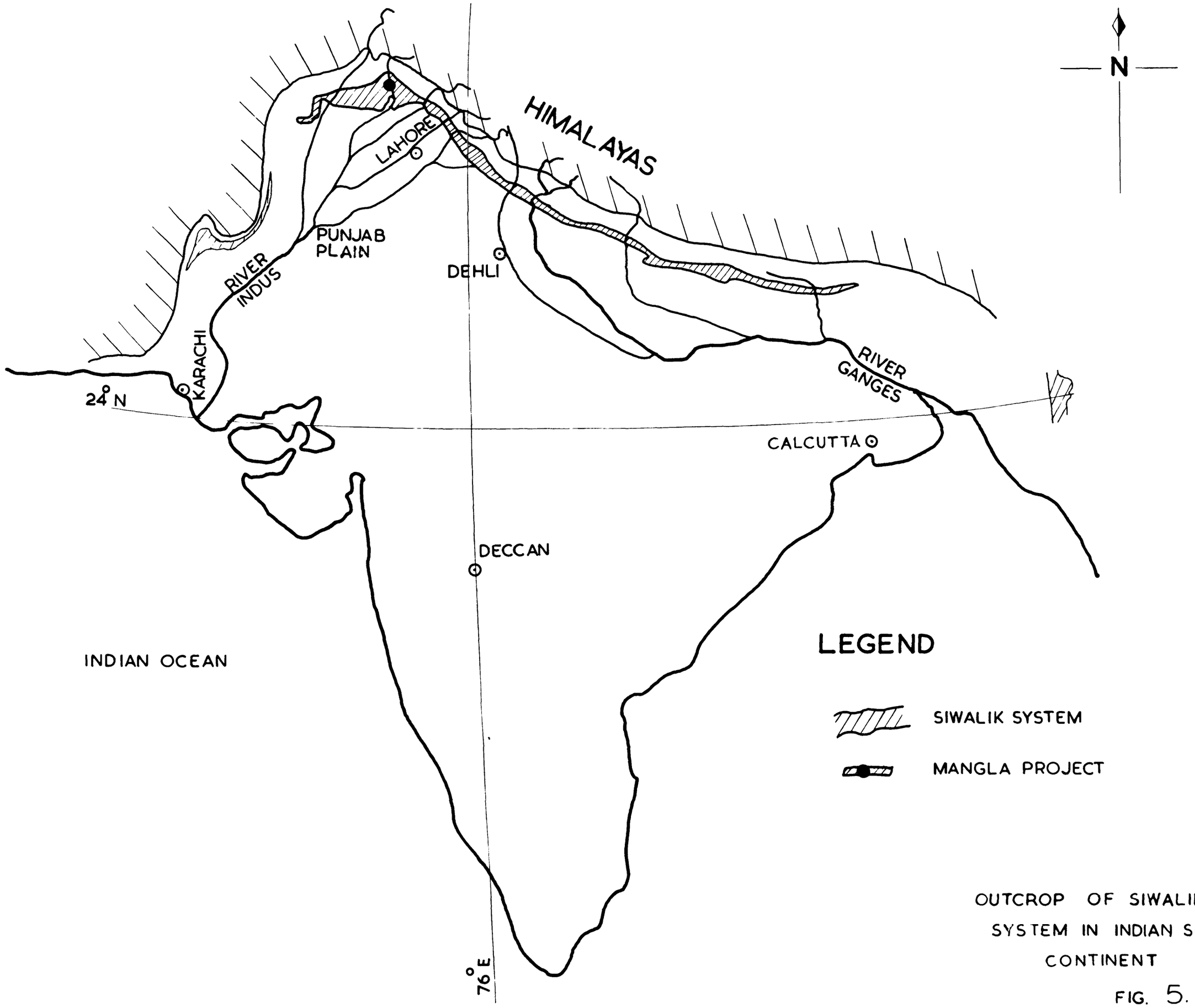
PLATE No. 20 November 1961

Typical Z form of the Mangla minor reverse faults shown by fault RF_a, northeast face of Fort Hill. The hammer is standing on the fault plane; total displacement of the clay bed along the fault plane is about 7'. A slide failure on upstream tunnel portals 2 and 3, occurred on this fault plane during construction operations, 1963.

PLATE No. 21 February 1965

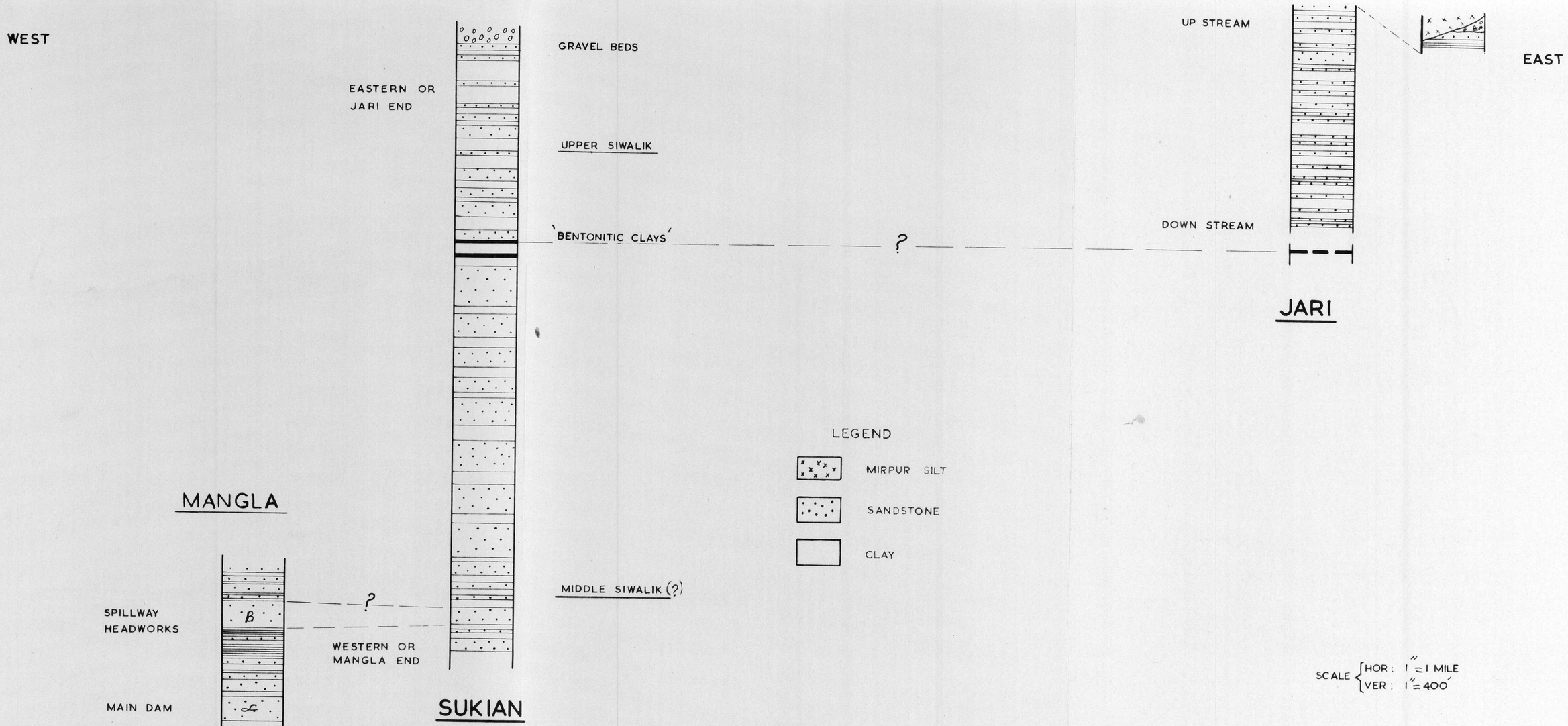
Typical Z form of the Mangla minor reverse faults in the ac plane, Taraki haul road 3 miles west of the Main Spillway, showing good development of associated splinter faults on Riedel and complementary shear patterns (R) in the massive sandstone bed overlying the clay bed. Displacement along the fault plane about 6'.



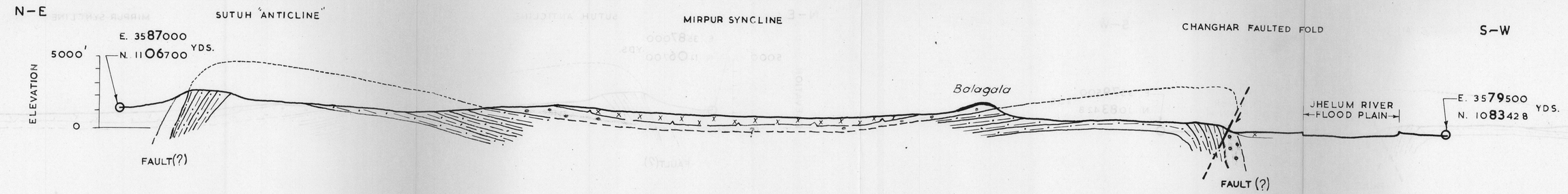


OUTCROP OF SIWALIK SYSTEM IN INDIAN SUB CONTINENT

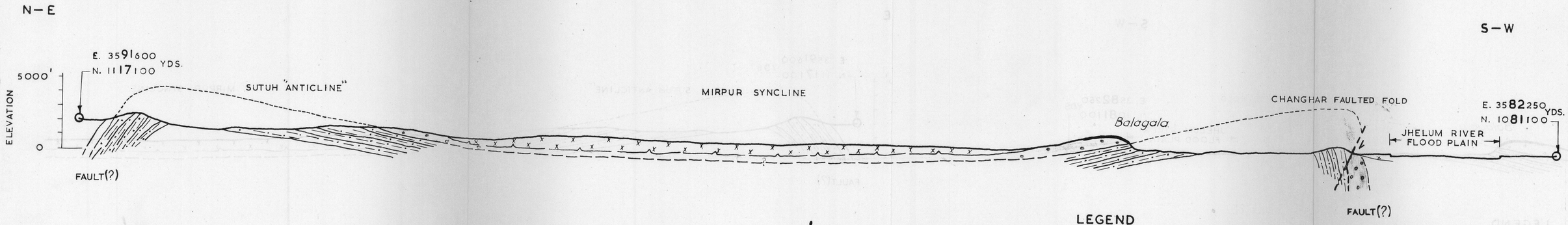
FIG. 5.



GEOLOGICAL
COLUMNAR SECTION
OF PROJECT
FIG. 6.



1—1'



2—2'

LEGEND

- MIRPUR SILT
- UPPER SIWALIK GRAVEL
- SIWALIK SANDSTONE & CLAY

NOTE

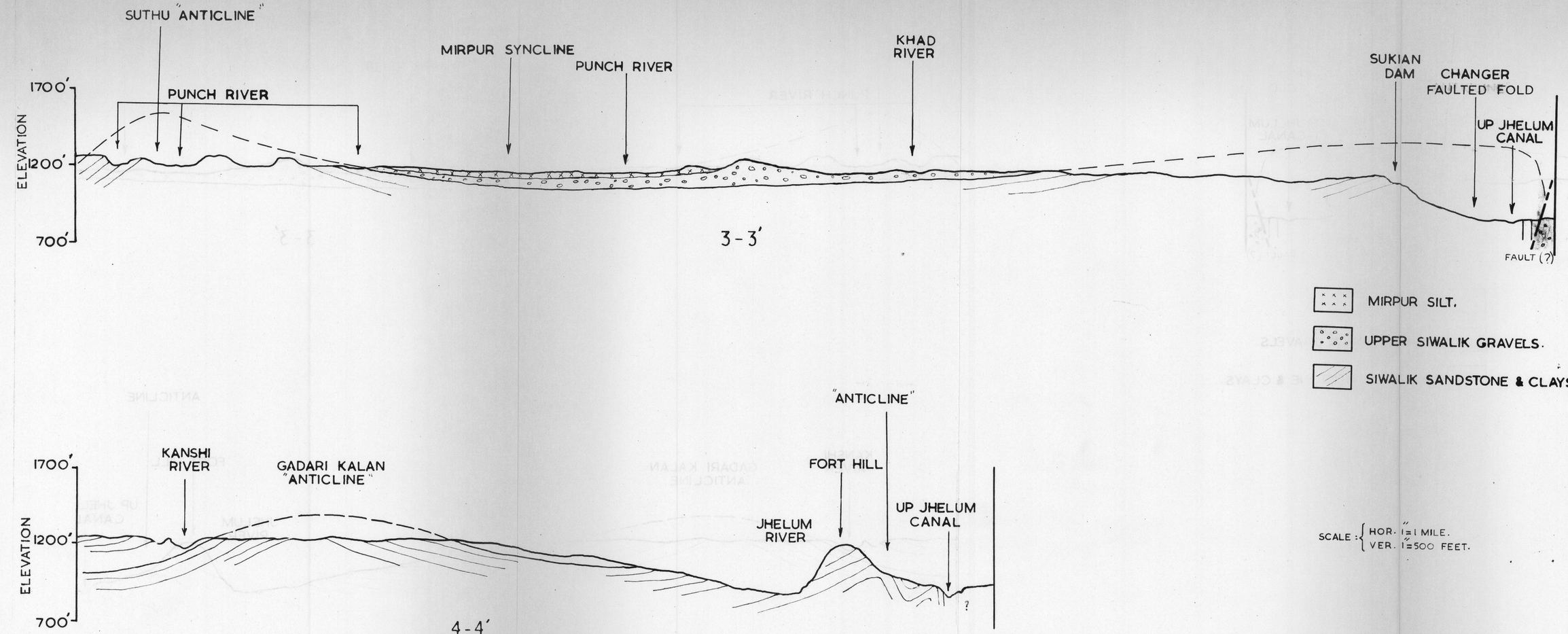
GEOLOGY & TOPOGRAPHY SIMPLIFIED
FOR PLAN SEE FIG.4

SCALE 1 0 1 MILE
1" = MILE

JARI

SITE INVESTIGATION 1961-63
GEOLOGICAL SECTIONS
RESERVOIR & RIM

FIG. 7.



NOTES

GEOLOGY AND TOPOGRAPHY SIMPLIFIED

FOR PLAN SEE FIG. 4

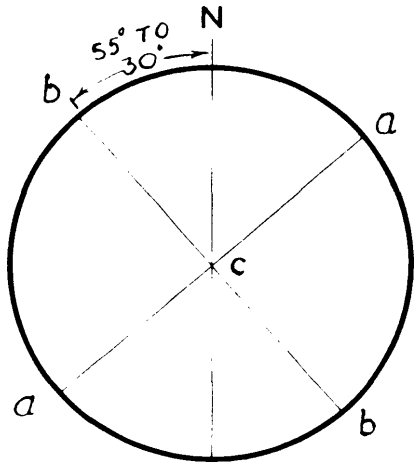
MANGLA

FOUNDATION INVESTIGATION 1965

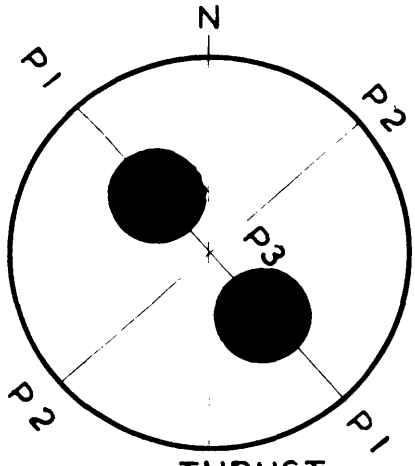
GEOLOGICAL SECTIONS

RESERVOIR

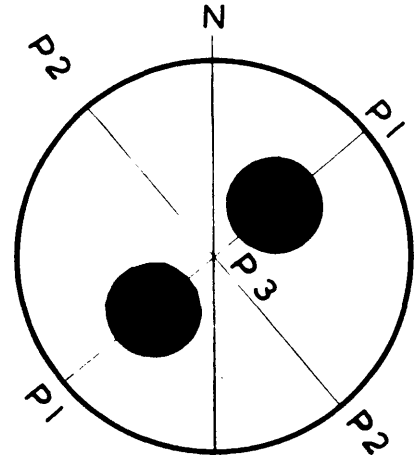
FIG. 8.



FABRIC AXES – MANGLA.



THRUST SHEAR JOINTS/FAULTS – 'BALUCHISTAN.'



THRUST SHEAR JOINTS/FAULTS – 'HIMALAYAN.'

MANGLA

FOUNDATION INVESTIGATION 1964-65
LOCAL TECTONIC AXES

FIG. 9.

SITE INVESTIGATION

Introduction

Site exploration*, which was followed by the site investigation* discussed in this thesis, together occupied a period of about seven years from 1958-65. However, the techniques detailed below were only fully developed during the later years when Jari and Sukian sites were being investigated after the initial site exploration 1958-1961‡ of Mangla was more or less completed.

During the last five years a fully equipped site laboratory was available for all types of soils classification tests, permeability and effective shear strength testing. The presence of a large and comprehensive site laboratory greatly speeded up the production of results and fostered close liaison between field and laboratory staff so that the detail of work required could be planned on a day to day basis. As site investigation proceeded, it became more and more apparent that information on the variation in detail of properties of the bedrock would be essential for the proper understanding

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* For a discussion on the terms 'site investigation' and 'site exploration' see Roberts (1964) and Fookes (1967). 'Site exploration' is used to indicate a preliminary investigation and 'site investigation' a more thorough, detailed study over a longer period of time. 'Foundation investigation' and 'foundation exploration' are analogous to site investigation and site exploration respectively but carried out during the construction period when foundation bedrock of engineering works is fully exposed.

of the foundations. The enormous size of the Project resulted in the need for a very large volume of work, which in turn necessitated the closest contact between field and laboratory staff in order to keep the flow of sampling and testing running smoothly.

Programme Planning

The design of the major earthworks structures of the Project was carried out in the Engineer's Head Office in London; so was the planning of the initial site exploration programme*. The site investigation which grew out of the early exploration was largely developed and programmed on site. The object of the site investigation was twofold; firstly to supply field and laboratory data for the designers and secondly to be in a position to understand fully the geological conditions so that the factual information could be properly evaluated. The importance of the latter objective cannot be overstated. The investigation discovered weak bedrock conditions which were not found by the exploration.

The author considers that in the light of his experience the programming of the investigation on a large damsite such as Mangla could ideally be split into three stages as outlined below:

The first stage is little more than a walk-over survey and inspection of any previous records or work done. Immediately following this, a feasibility report is prepared and

* An outline of programme schedules is given in Part II, page 67.

the preliminary drawings made. Dam, tunnel and spillway alignment are roughly located. This enables site investigation proper to commence in the areas selected for the engineering structures.

The second stage requires the longest time and in this stage the majority of the site investigation is carried out. The broad policy of the investigation is settled and the details left to the jurisdiction of the site personnel. It is essential that the engineering geology mapping* precedes other forms of investigation** so that the geological features and problems of the area become familiar and can be evaluated. The mapping serves as a basis for locating boreholes and samples and intimating sampling and other techniques. From this the testing requirements for engineering evaluation of the bedrock is made. At the end of this stage a report is produced and a second and more definite design is made on which contract documents and design detailing can be based.

In the third and last stage site investigation continues but is largely controlled by requests from the designers for

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* The term 'geotechnical mapping' was introduced for this work. Conventional geological mapping is not adequate for engineering needs and additional information such as appraisal of engineering properties of soil and rock types found, field evidence of movement by creep; slopes; slips; ground water conditions and borrow material, is required (Fookes 1967).

** Where detailed geological maps already exist (as they do for many parts of Britain), the field staff carrying out the investigation must familiarise themselves with the geological situation in sufficient detail to enable them to see the problems clearly and where additional mapping, pits, trenches and boreholes are required. Also where and in what form the sampling and testing should take.

detailed additional information. In this stage subsurface work (e.g. boreholes or pits) can be laid out to confirm the location of engineering structures. The final design should result from this information.

FIELD TECHNIQUES

The normal site investigation techniques were carried out where relevant.

Permeability

Bedrock permeability was studied by insitu tests from boreholes in the bedrock gravels (above the water table) by Lefranc pumping-in tests and in the bedrock sandstones and clays (above the water table) by Lugeon water absorption tests. Pumping-out tests were performed below the water table. In addition well field permeameter tests (USBR method) were carried out from the bedrock surface or in pits or adits. In the laboratory permeability tests were carried out on undisturbed and recompacted samples.

Classification Tests

In the field, density, disintegration in water, loading+ and jacking+ tests were made. On the samples in the laboratory, moisture, Atterberg limit, grading, unconfined compression and consolidation+ tests were made. During the site investigation some 25,000* liquid limit tests were performed and during foundation investigation some 15,000* clay fraction tests were performed by the site laboratory (K. Head pers.comm.). In addition, during foundation investigation some 5,000 liquid limit and 3,000 clay fraction tests were performed by commercial laboratories in London.

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* By the autumn of 1965.

Clay Strength Investigation*

An extensive programme of tests to determine effective shear strength parameters, c', Ø' was undertaken. The term 'Strength' used here refers to the residual effective angle of shearing resistance, Ø', as measured in the triaxial test. A programme of shear box tests and insitu shear tests was also performed.

The study of the geometry and strength of the bedrock in relation to the engineering structures, was important in all cases and critical in many, so very detailed mapping and sampling was carried out. These techniques were gradually developed and elaborated over a period of about 3 years from 1962 onwards. Prior to this during the initial exploration occasional random or selected samples were taken for triaxial strength tests mainly from borehole cores and occasionally from undisturbed blocks cut by hand from the bedrock. The later investigations were based on careful detailed sampling programmes which in turn were based on the geometry of the situation. The techniques principally employed:

i) Either by disturbed or undisturbed sampling from zones or areas of special interest selected by eye; or

ii) Systematic disturbed sampling at regular intervals, for classification tests.

The early exploratory sample tests showed the clays were non-homogenous. Therefore, the problem was to establish

* An extensive programme on sandstone strengths and permeabilities was also carried out, for comparison; summaries of these results are given as Appendix II.

variations of engineering properties in three dimensions. As strength of the clays was the principal property used in design, laboratory tests concentrated firstly on detailed variation of the strength with a limited number of clay beds and secondly correlation of strength and classification tests. Then a massive classification test programme for the whole site involving all clay beds.

The variation of strength with depth below the bedrock surface was studied simply by sampling at increasing depths following the same stratigraphical horizon down the dip of the beds (from trenches and boreholes). The study of variation of strength along the length and breadth of the site was a little more complicated. It was divided into two phases:-

Firstly, the investigation of the strengths of individual beds locally by laboratory tests together with geological mapping and classification tests over short distances, viz;

i) Variation of strength within individual beds or zones within beds, along their strike (i.e. along the 'b' fabric axis of the site);

ii) Variation of strength within individual beds or zones within beds, normal to and in the same plane as their strike (i.e. along the 'a' fabric axis of the site);

iii) Variation of strength from top to bottom of individual beds (i.e. along the 'c' fabric axis of the site).

Secondly, the investigation of beds, or zones within beds over long distances, by classification tests. This then required correlating index properties obtained with shear strength and using this correlation to assess the strength variation for large areas. This programme of classification tests was carried out on nearly every bed at each of the various sites and ran into hundreds of classification samples and tests and dozens of shear strength (triaxial or shear box) tests.

The mapping and the sampling techniques are discussed following:

a) Geological Mapping

The usual scale used for site investigation mapping was 1" to 200'. Mapping on this scale was carried out by plane table and telescopic alidade, using survey control points set out on convenient locations to tie the geological maps into the local survey grid. The scale permitted beds of 3' and thicker to be mapped individually and the maps produced differentiated between beds of gravel, sandstone, and silts/clays (which were mapped as one unit). In addition, the larger geological features such as faults, together with the dip and strike of the bedrock, were mapped. Figs. 10, 11 and 12 show examples of this mapping* together with trenches, boreholes and other investigation features of Sukian Dyke.

* Many maps have had to be reduced for inclusion here; the corrected reduced scale is given on each figure.

Plate 12 shows part of the eastern end of the site at approximate chainage 320. Details of this investigation are given in Part II.

At all sites except on steep dip and scarp faces the bedrock was obscured by either terrace alluvium, weathered rock debris or cultivated soil (plate 12), so that in order to get complete mapping coverage of the site on 200' scale, bulldozer trenches had to be dug through the alluvial cover or if this was too deep, boreholes had to be drilled. To trace the beds the bulldozer or backhoe trenches were dug both parallel and at right angles to the strike of the beds. This technique was very successful and by digging trenches at 300' to 500' intervals abng the strike, a fairly accurate map could be made (see figs. 11 and 12). In addition the trenches were invaluable for sampling the alluvium and the bedrock.

Mapping on a 1" to 500' scale for parts of the Mangla abutments and Sukian was carried out in the initial site exploration 1958-60. At Mangla on the Sultanpur peninsula the average depth of the alluvium was over 50', so no bedrock mapping was carried out but an intensive programme of drilling supplemented by a seismic survey‡ was made to obtain the sub-alluvial bedrock contours and to enable geological sections of the bedrock to be drawn‡. In this area, sampling could only be carried out on cores from drillholes or by sampling at a location of bedrock exposed at some distance away and then projecting the results

along the strike to the area in question. A 1" to 200' map was not made of this area.

At Jari during site investigation in the valley section both drillholes and trenches were combined to produce a sub-alluvium bedrock map (shown in Part II). Extensive north-south trenches were dug (at right angles to the east-west strike, i.e. along the 'a' fabric axis) wherever the bedrock was above the water table; and north-south lines of drillholes located wherever bedrock was below the water table. The trenches and drill cores were extensively used for detailed close centre sampling. Average core recovery from the drillholes was sometimes as low as 50%. The main loss of core was in recovery of the friable sandstones and highly fissured or sheared clay; recovery was improved with mud drilling. Logs with a 100% record could only be made from trenches or natural exposures. Loss of core and ensuing difficulties of correlation meant that the final sub-alluvium bedrock map contained errors. Details of this investigation are given in Part II.

b) Geological Logging

Logging on 1" to 2', 4' or 10' scales and mapping on 1" to 20' or 40' scales, were extensively used during the construction stage when a lot of foundation was well exposed. Logging on these scales was not possible during the site investigation if the natural exposures

of the area were not adequate, but it was necessary in places to log bulldozer trenches and boreholes on these detailed scales in order to get enough information to be compatible with the close centre classification sampling and detailed undisturbed sampling or perhaps most important of all to show the continuity of rock type. Changes in rock type horizontally or vertically were of great importance as they indicated change of engineering property and were always confirmed by sampling and laboratory testing.

Logging on 1" to 2', 1" to 4' or sometimes 1" to 10' enabled nearly all recognisable geological features to be drawn (with the exception of some very detailed work on 1" to 6" scale used in the foundation investigation during construction for the work on shear zones and thrust (shear) joints). Logging and mapping on a small scale showed variations in grain size of the sandstones, silts and clays, together with other sedimentary and tectonic features such as joints, current bedding, clay balls and hard lenses within sandstone beds, or bottom structures such as washouts, ripple marks, flame structures or flute casts. The clays were logged to show graded bedding, clastic dykes, colour banding, weathering, inclusions, colour, estimated grain size and consistency according to C.P. 2001 (1957); and sometimes to show fissure and joint patterns. Examples of logging on a 1" to 2' scale from the Upper Stilling Basin of the Main

Spillway are shown on figs. 13 and 14. A tape measure fixed from an upper peg controlled measurements and distances were measured down the slope (where exposures were not vertical). Dip and strike of beds and slope angle were recorded. Plate 22 shows a logging team working on a natural cliff exposure.

After several months familiarity with mapping and inspection of laboratory results several of the field personnel became proficient at guestimating liquid limit and clay fraction of the clays. Figs. 15, 16 and 17 are examples of field estimates of clay fraction made by three local junior geologists, compared with the subsequent laboratory test results. The guestimates of the geologists were added together to show the range, and the figures give an idea of the proficiency of description on field logs and maps. The logs and maps were not changed when test results became available (if the result did not agree with the description) since the field description was based on several field characteristics (of which the principal was clay fraction, the tested property on the figures).

c) Sampling

Sampling proceeded together with the detailed geological logging of trenches, exposures or boreholes which followed behind the plane table geological mapping.

Four types of sample were taken:

(i) Disturbed samples for all classification tests;

(ii) Disturbed samples specifically for liquid limit or clay fraction test only;

(iii) Undisturbed samples for triaxial or shear box tests;

(iv) Cores from diamond drillholes for classification or triaxial tests.

All samples were taken from freshly exposed material above the water table (unless otherwise stated). Apart from occasional individual classification samples, samples of types (i) or (ii) were taken from a 'continuous groove', a cut of approximately 4" x 4" cross section. In the field this technique was called 'scrape sampling'; about 300 grams were taken by spatula and hatchet for each individual sample and transported to the laboratory in a polythene bag. Use of the term 'scrape' is perhaps a bad choice because numerous individual samples were taken from it, not a continuous scraping of material from the groove to produce one composite sample. The term, however, still remains in site use. Where this technique was first employed in trenches at Jari in 1962, horizontal scrapes were made and individual samples taken at 0.1' or 0.25' centres in clay beds and 1.0' centres in silt or siltstone beds; close centres were used so as not to miss thin zones of weak material (which were suspected of being present). Liquid limit results from these samples were plotted as a graph on the geological

sections of the trenches. Scrapes were cut both parallel and normal to the strike, i.e. along 'a' and 'b' axes. The correlation established later between liquid limit and effective strength was applied to the graph so an approximate strength picture of each bed could be ascertained. After Jari when Sukian was investigated and additional work done at Mangla during the construction stage when considerably more was known about the detailed behaviour of the clays, the sampling interval was increased to one representative classification sample from each distinguishable horizon within each bed. This was called 'type'* sampling (for example see figs. 13 and 14). The correlations obtained between index properties and effective shear strength are discussed in more detail in Part II.

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* By the time the Sukian Site Investigation (1963-64) was in progress the following categories of sample were established:

1) Random - as the name suggests;

2) Selected - taken for a special purpose, for example from across a joint surface or from a shear zone.

3) 'Type' - a sample to represent a band, horizon, bed or zone where all the material within the zone appeared by eye to have similar properties. Taken from a continuous groove (for example see black triangles on figs. 13 or 14).

4) 'Typical' - same as 'type' but not taken from a continuous groove; usually taken in isolation to represent some specific point, for example, a fault zone or pebbly lens within a sandstone or a silty lens within a clay bed.

5) 'Continuous' - samples taken at close centres (say 0.1' or 0.25') at regular intervals along a sampling groove (for example see empty triangles on figs. 13 or 14; these were taken at 0.5' centres but were never actually tested, the 'type' samples shown by the black triangles were tested and the results given on the figures.).

Developments of the scrape technique were used to obtain a two or three dimensional picture of local variation of property; for example, fig. 18 shows a 'continuous groove' of block samples at 1' centres, for triaxial and classification tests, through a typical clay bed in the Main Dam Core Trench at Mangla. A similar scrape was sampled for comparison of classification tests some 200' away along the strike. The results are discussed more fully in Part II. At Sukian where the depth of weathering was investigated in detail samples were taken from both horizontal and vertical grooves (see figures in Part II). The horizontal groove served as a reference to the vertical groove. By ensuring that the horizontal groove was deep enough below the top of bedrock not to be affected by weathering, the variations in properties shown by the testing were due either to testing error or lateral facies variations on bedding horizons or those produced by weathering on the near surface vertical grooves. The vertical grooves were cut from top of the bedrock down to the horizontal groove. Results from the vertical groove were projected graphically down dip for comparison with the horizontal groove.

Samples of <u>type (iii)</u>, block samples, were cut about 1' cube and immediately covered with muslin and three coats of paraffin wax. Some samples were orientated with reference to the macroscopic fabric axes of the site (see fig. 19), so that the trimmed specimens could be set

up in the shear box or triaxial machine with reference to these axes. Locations of block samples were either chosen by eye or by inspection of classification test results. In some cases sets of block samples were taken to geometric patterns in relation to the dip and strike of the bedrock to investigate a particular problem. For example, fig. 39 shows block samples taken from the same geological horizon within a single bed, but at differing depths down dip so that variations of strength with depth below top of bedrock could be ascertained. In addition, block samples were taken on the same bedding horizon along the strike direction and again in the dip direction but by sampling to greater depth from trenches or drillholes. Plate 23 shows a sampling team working on a oriented block sample cut to contain a thrust (shear) joint. Plate 24 shows a close up of the bedrock plus joint, just prior to waxing. See also plates 26 and 27.

Samples of <u>type (iv)</u> (the core samples from diamond drill holes) were weighed and measured for density and moisture content in the field after first removing the coating of drilling mud. Samples were selected in two ways either at 5' centres along the core and at a change of rock type, or for a special purpose. An example of the latter was a drillhole (BH 740, fig. 12) drilled further downdip along the line of trench No.12A so that the same geological horizon already sampled from the surface and at about 15' in the trench was also sampled

by cores from approximately sixty feet depth. These techniques and results are discussed in more detail in Part II, page 126.

d) Geometry of the site geology and the sampling.

As geological mapping proceeded and the overall picture of the geometry of the beds and small tectonic structures began to emerge, it became clear that alignment of sampling and mapping trenches and boreholes could be easily and usefully related to the dip and strike of the bedrock. Fig. 20 shows an ideal simple fold and associated tectonic features which was used as a model for Mangla studies. Fig. 21 is a block diagram of the small scale features occurring at Mangla which were found to be of engineering significance. The attitude of the shear zones, faults, joints and some of the fissures were dependent on their position in the limb of the fold and were related to the local fabric axes.

Trenches were, therefore, laid out both parallel to the strike and dip direction of the beds (for example see figs. 11 and 12) so that all the bedding and tectonic features would be revealed and their attitudes correctly measured. Sample grooves were laid out, as previously discussed, to investigate property changes in three dimensions and so that there was some overlap of each part of every groove to help assess variation in properties over various distances. Fig. 22 summarises the layout of grooves and block samples in a typical trench. Cores

from diamond drillholes lined up with the trench were used to give samples at correct depths.

PLATE No. 22 June 1962

Vertical river cliff face of dipping Siwalik beds and clays overlain by middle terrace alluvium, Jari. This exposure was logged and sampled as trench DE during the site investigation. Thin lenses of clay within sandstone are shown in the centre of the photograph (arrowed) and some large false bedding (crossed) in the bottom left.

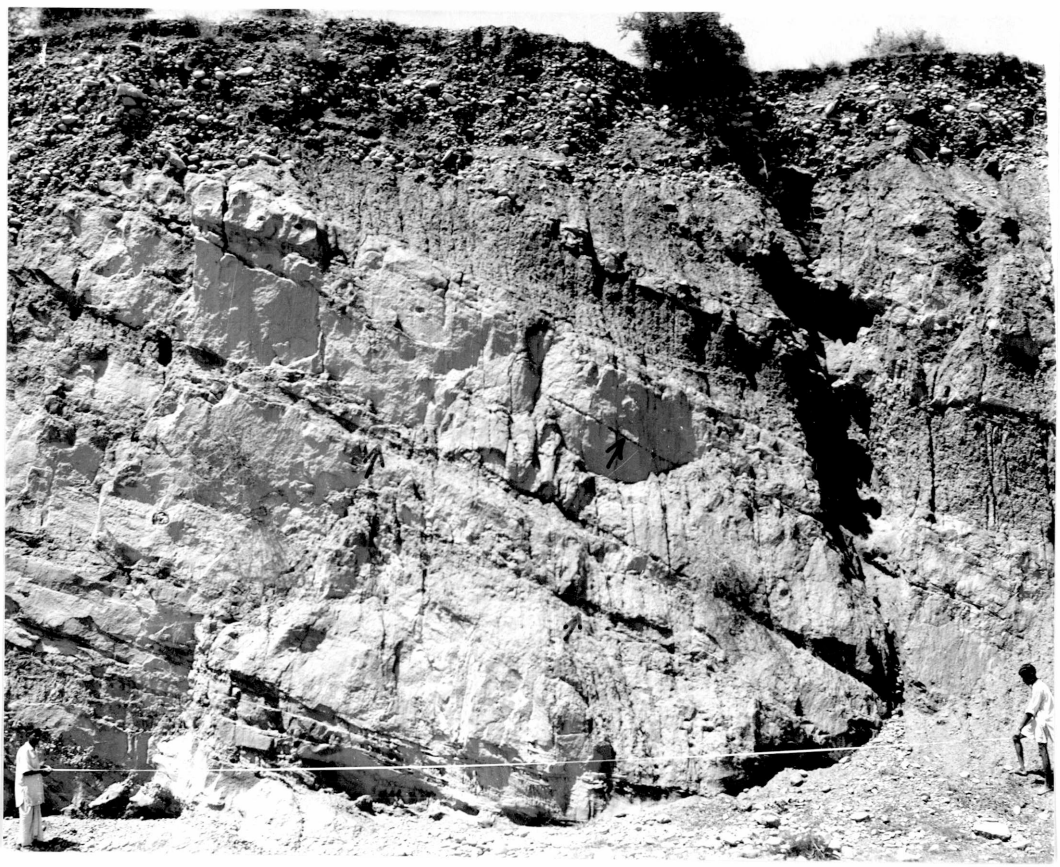


PLATE No. 23 June 1965

A sampling team (one research assistant, one laboratory assistant/stonemason and one labourer) taking an undisturbed block sample of clay containing a thrust (shear) joint. Jari left abutment, during the foundation investigation.

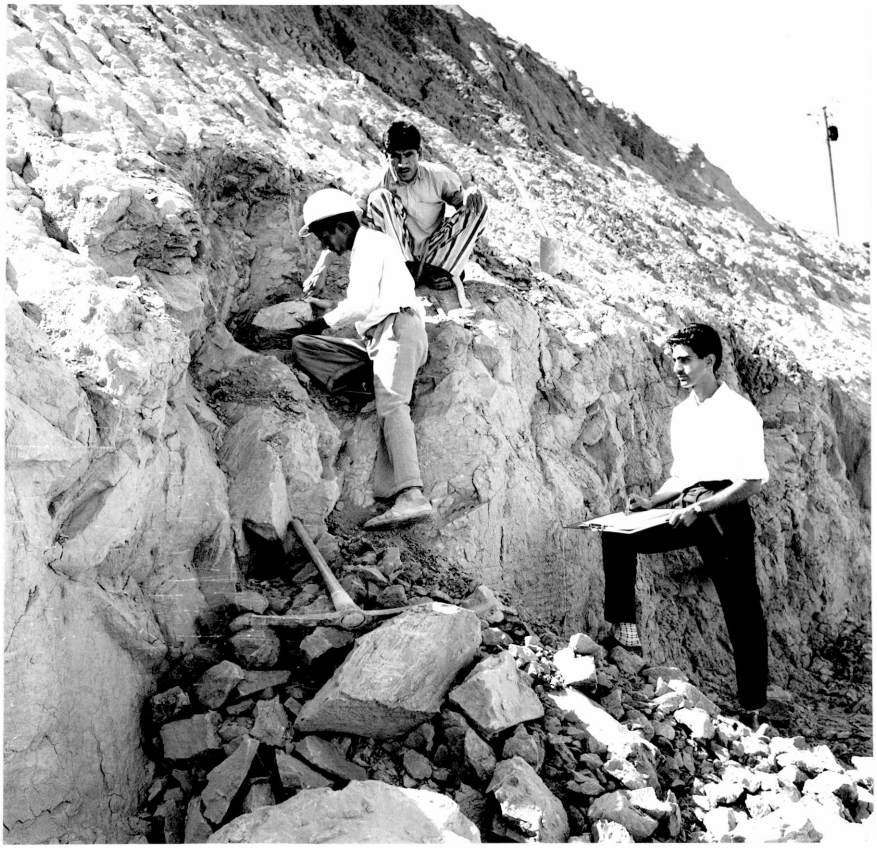
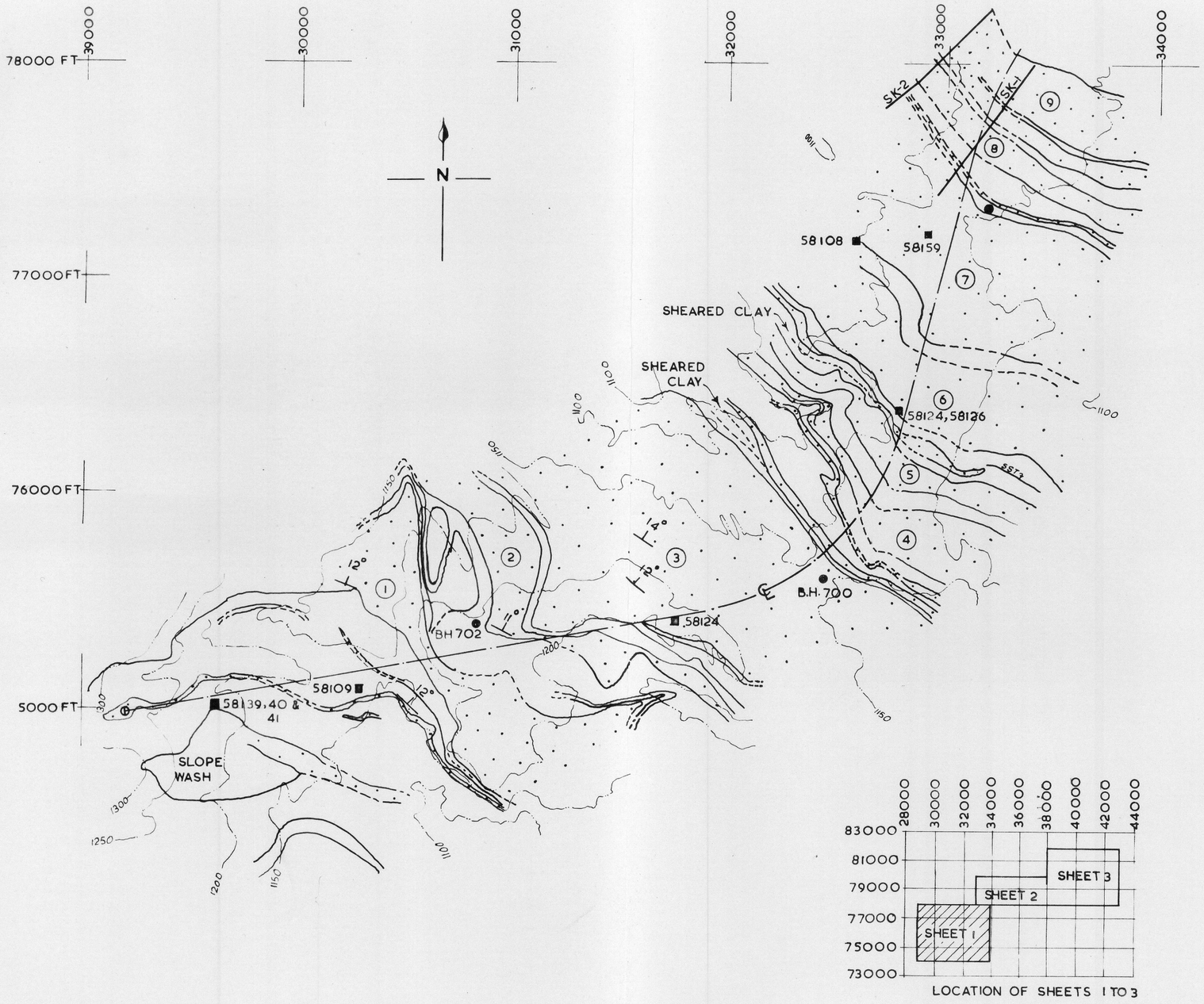
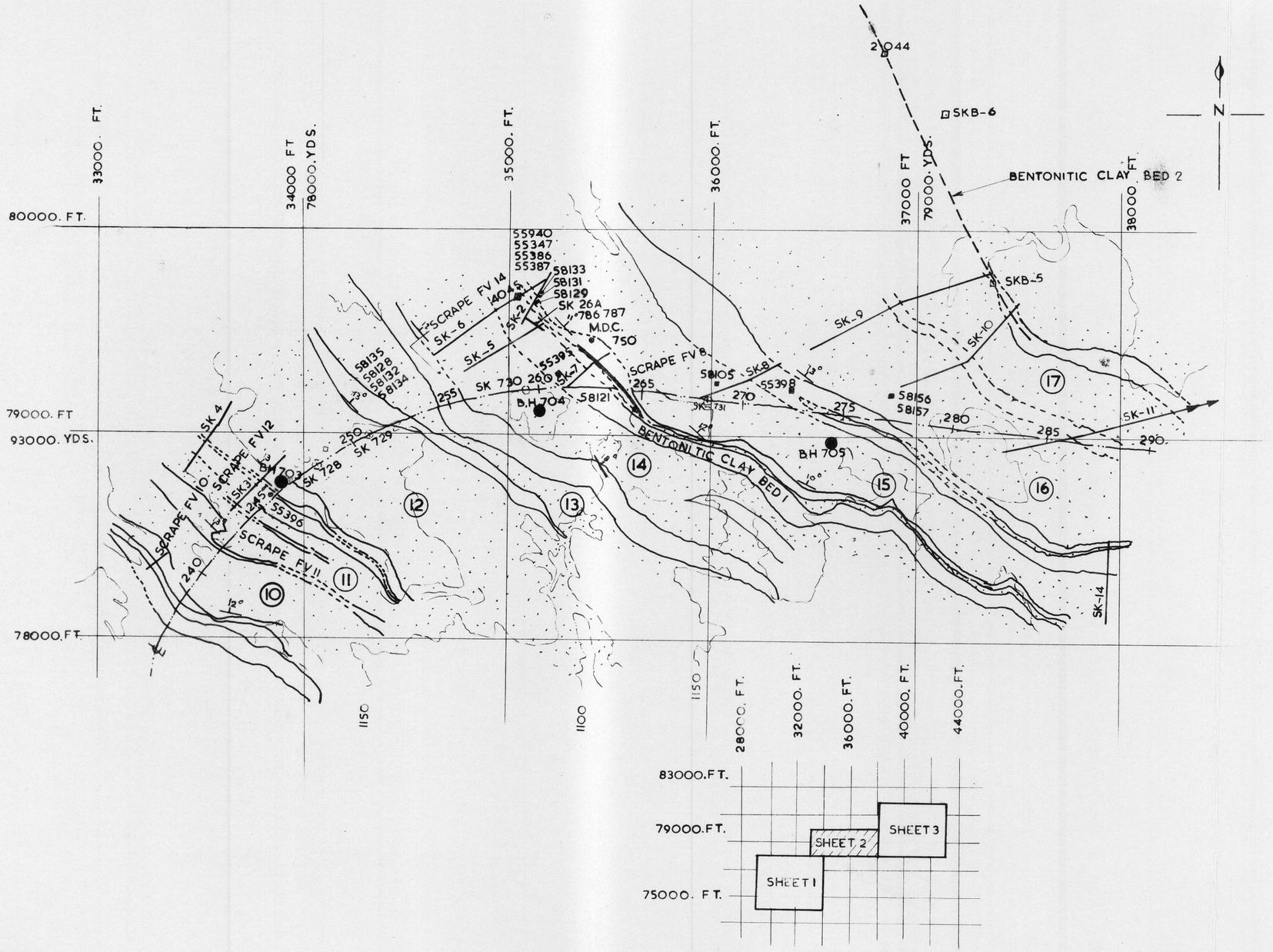


PLATE No. 24 June 1965

A close-up of the block sample shown on plate 23, containing the thrust (shear) joint, immediately prior to waxing.




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LEGEND:-

- STANDSTONE BED No.
- DIP STRIKE.
- BOREHOLE.
- SK-14 EXPLORATORY TRENCH.
- PERMEABILITY BOREHOLE.
- (13) SANDSTONE BED No.
- BENTONITIC CLAY.
- EXPLORATORY PIT.

NOTES:-

1. CONTINUATION OF BEDS BETWEEN TRENCHES IS SHOWN DOTTED WHERE INTERPOLATED
2. CONTINUATION OF BEDS UNDER SLOPE WASH AND OVERBURDEN IS ALSO SHOWN DOTTED.
3. GEOGRAPHICAL LOCATION OF BLOCK SAMPLES IS SHOWN THUS ..... ■
4. ALL TRENCHES ARE SHOWN.

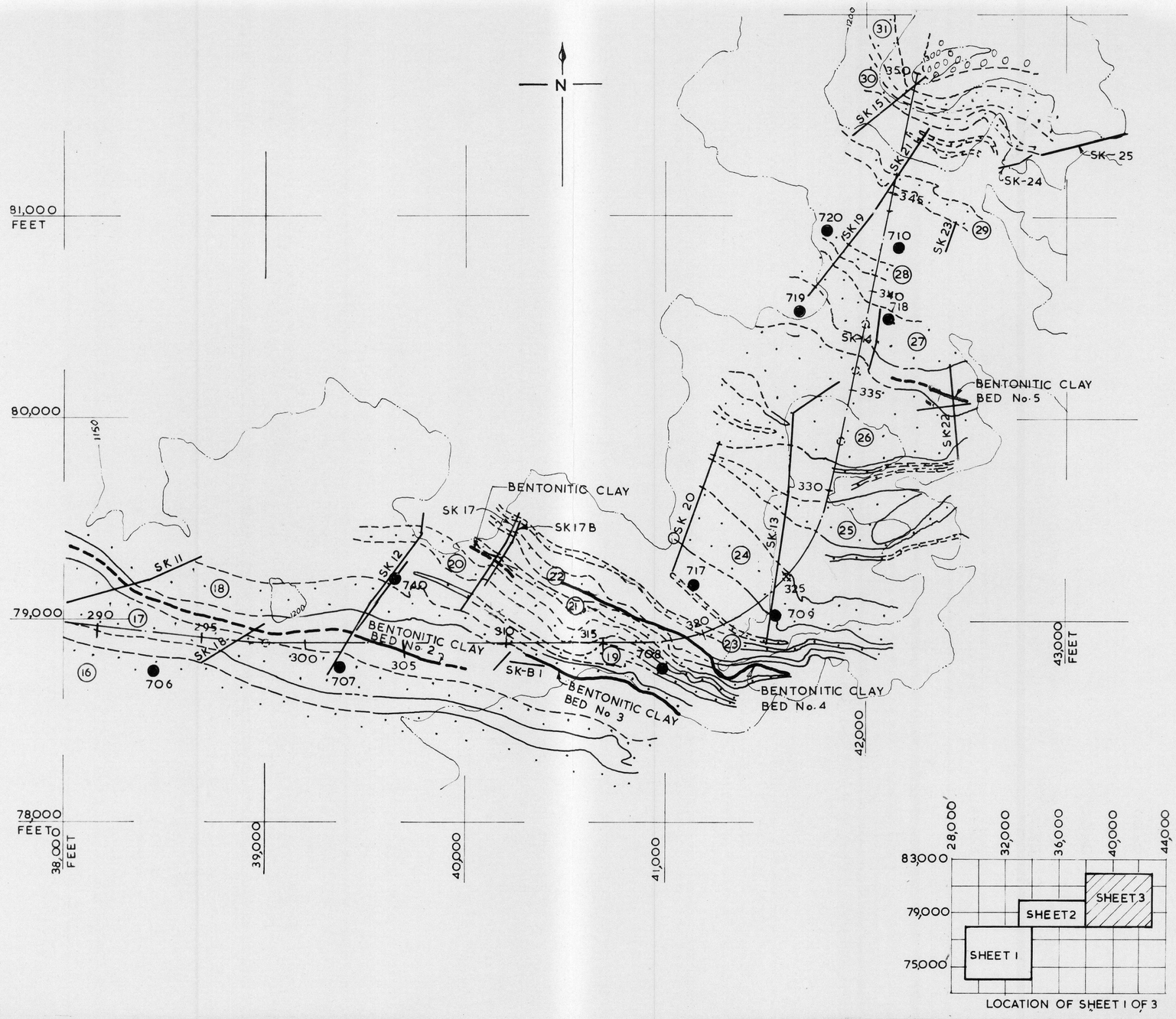
SUKIAN

SITE INVESTIGATION 1963-64

GEOLOGY

(SHEET 2 OF 3)

FIG. 11.



LOCATION OF SHEET 1 OF 3

LEGEND :–

- SANDSTONE BED No
- DIP STRIKE
- BOREHOLE
- EXPLORATORY TRENCH
- BENTONITIC CLAY
- EXPLORATORY PIT
- PERMEABILITY BOREHOLE

NOTES :-

1. CONTINUATION OF BEDS BETWEEN TRENCHES IS SHOWN DOTTED.
2. CONTINUATION OF BEDS UNDER SLOPE WASH & OVERBURDEN IS ALSO SHOWN DOTTED.
3. ALL TRENCHES ARE SHOWN.

SCALE 0 400 FEET

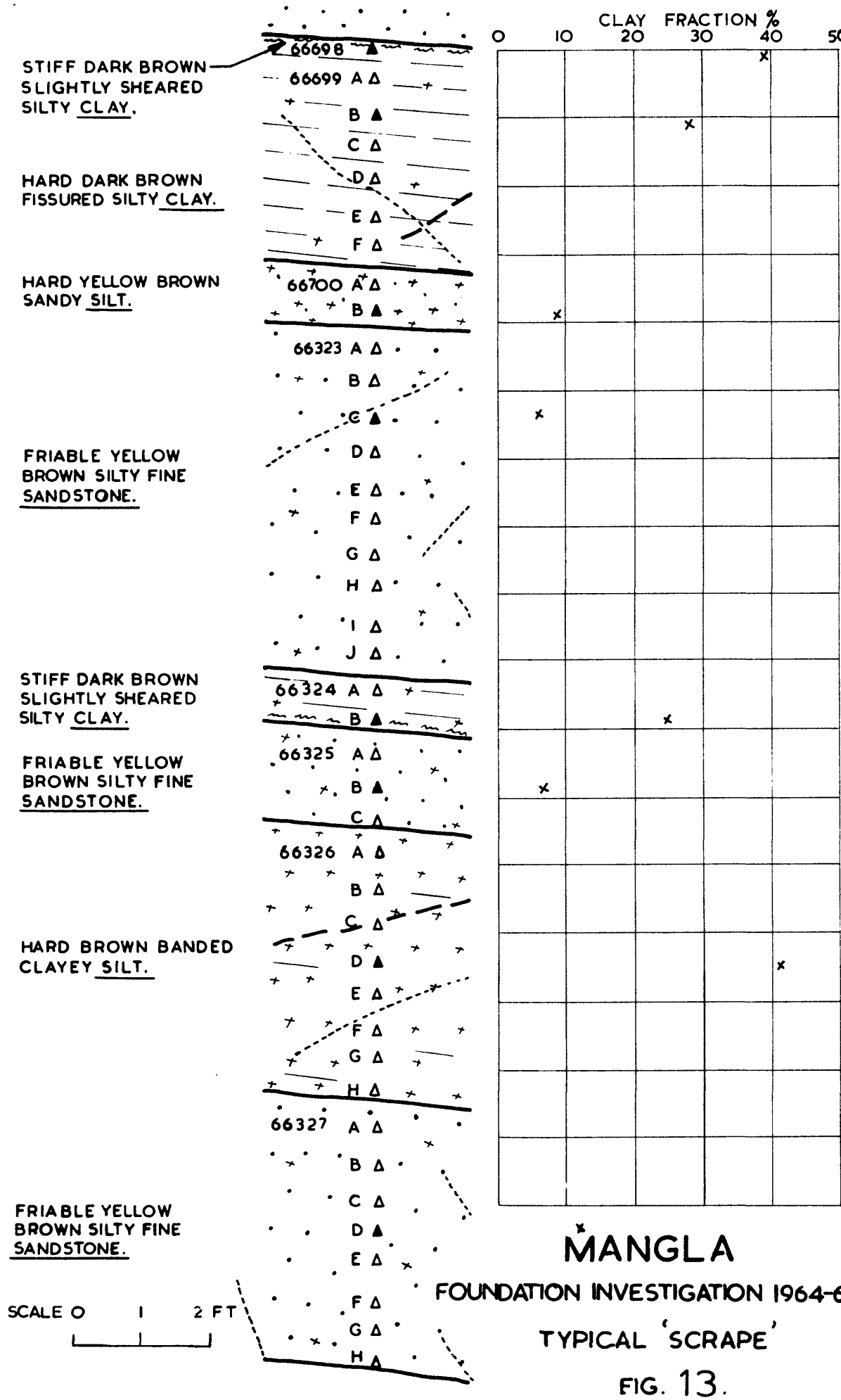
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GEOLOGY

(SHEET 3 OF 3)

FIG. 12.

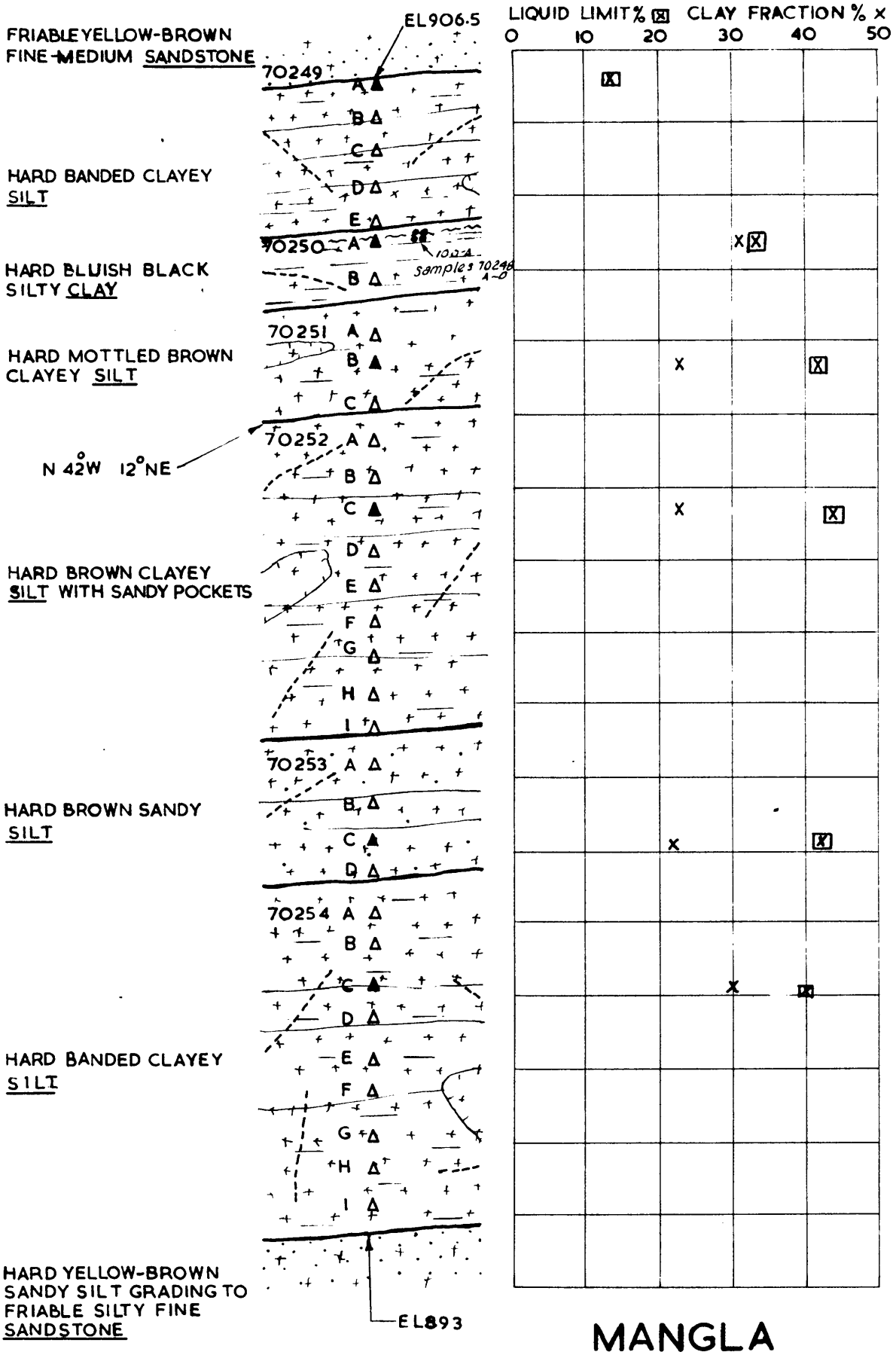


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TYPICAL 'SCRAPE'

FIG. 13.

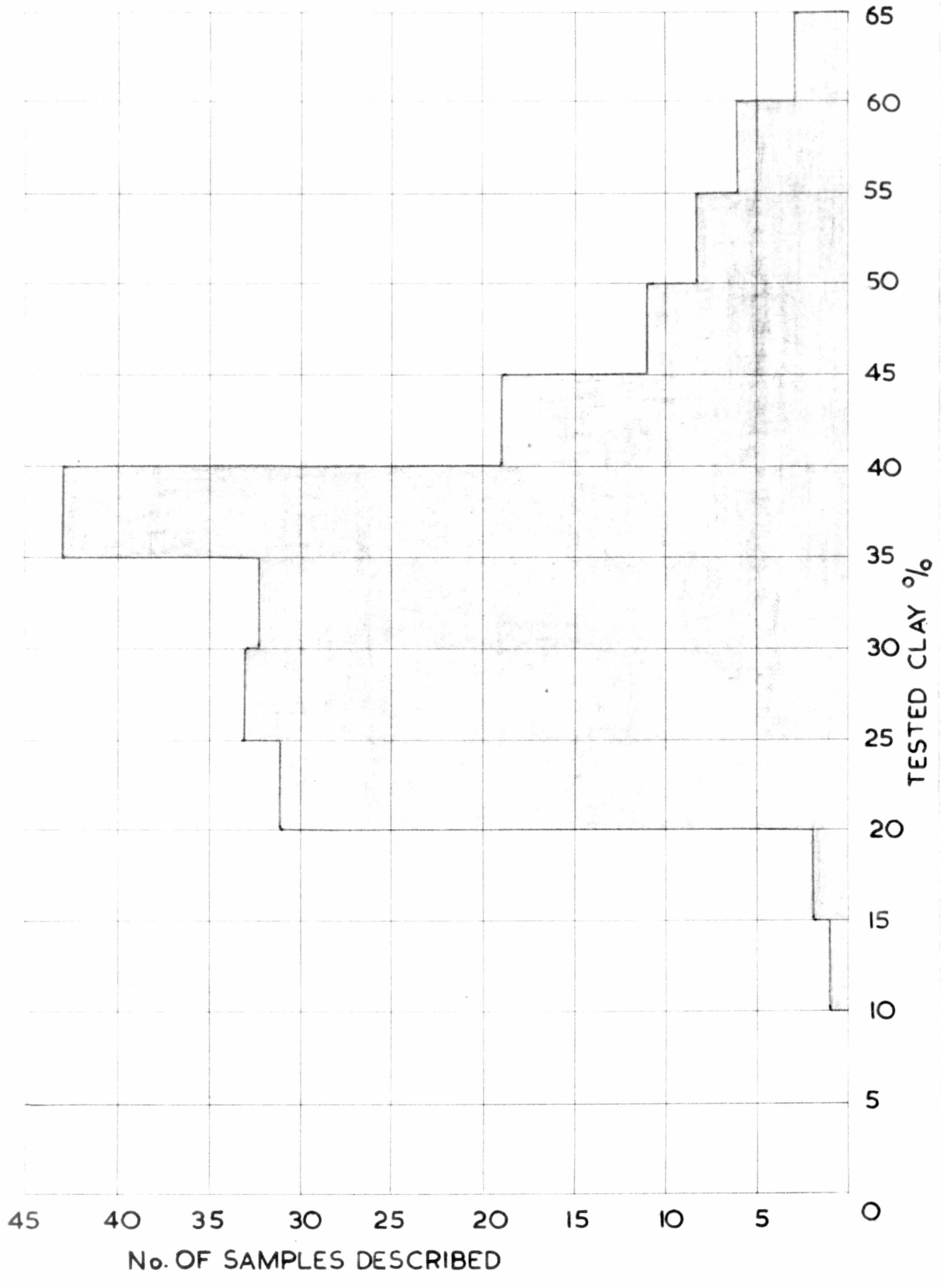


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TYPICAL 'SCRAPE'

FIG. 14.



SILTY CLAY

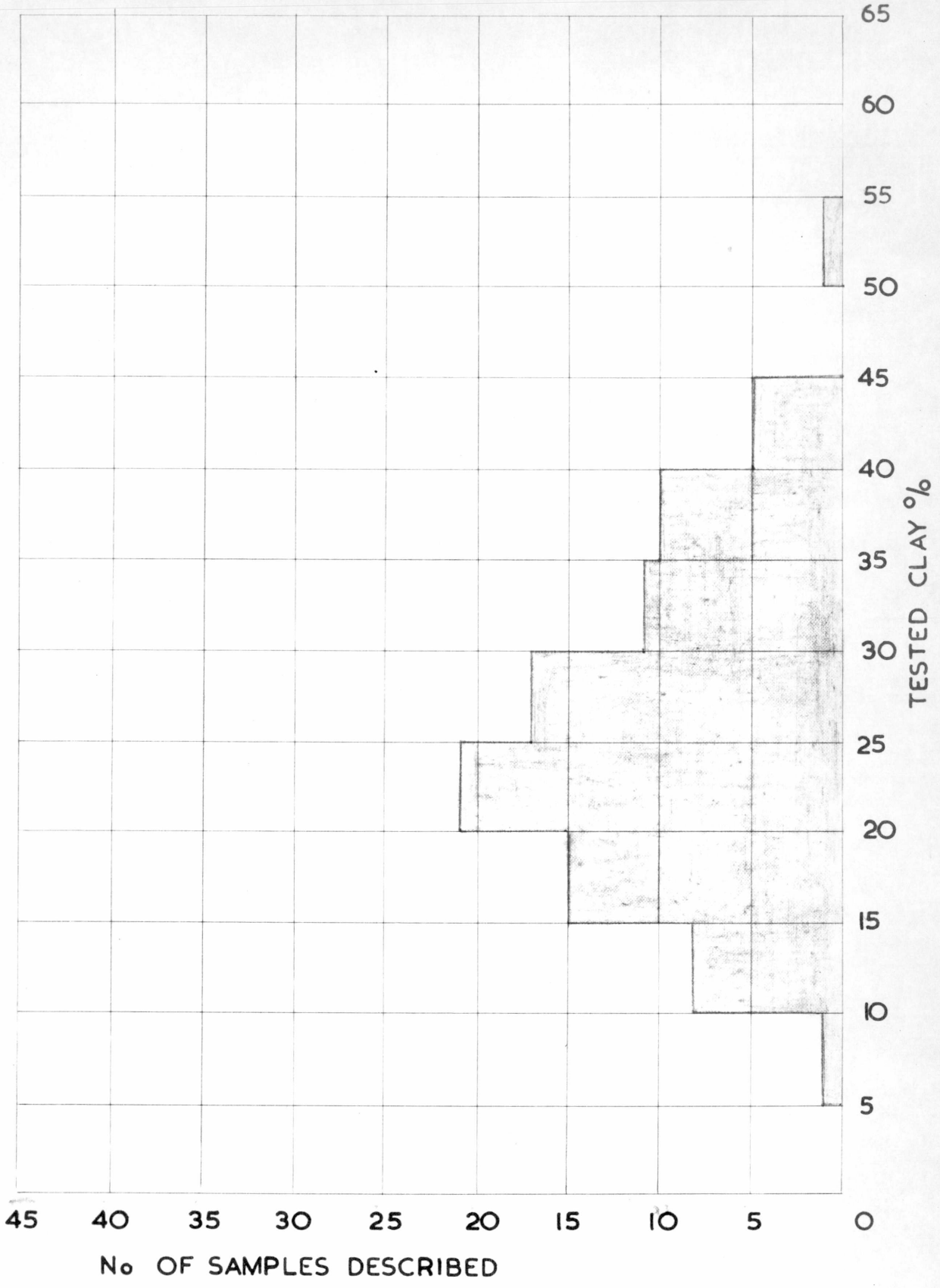
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FOUNDATION INVESTIGATION 1964-6

FREQUENCY DIAGRAM

FIELD DESCRIPTION

FIG. 15.



CLAYEY SILT

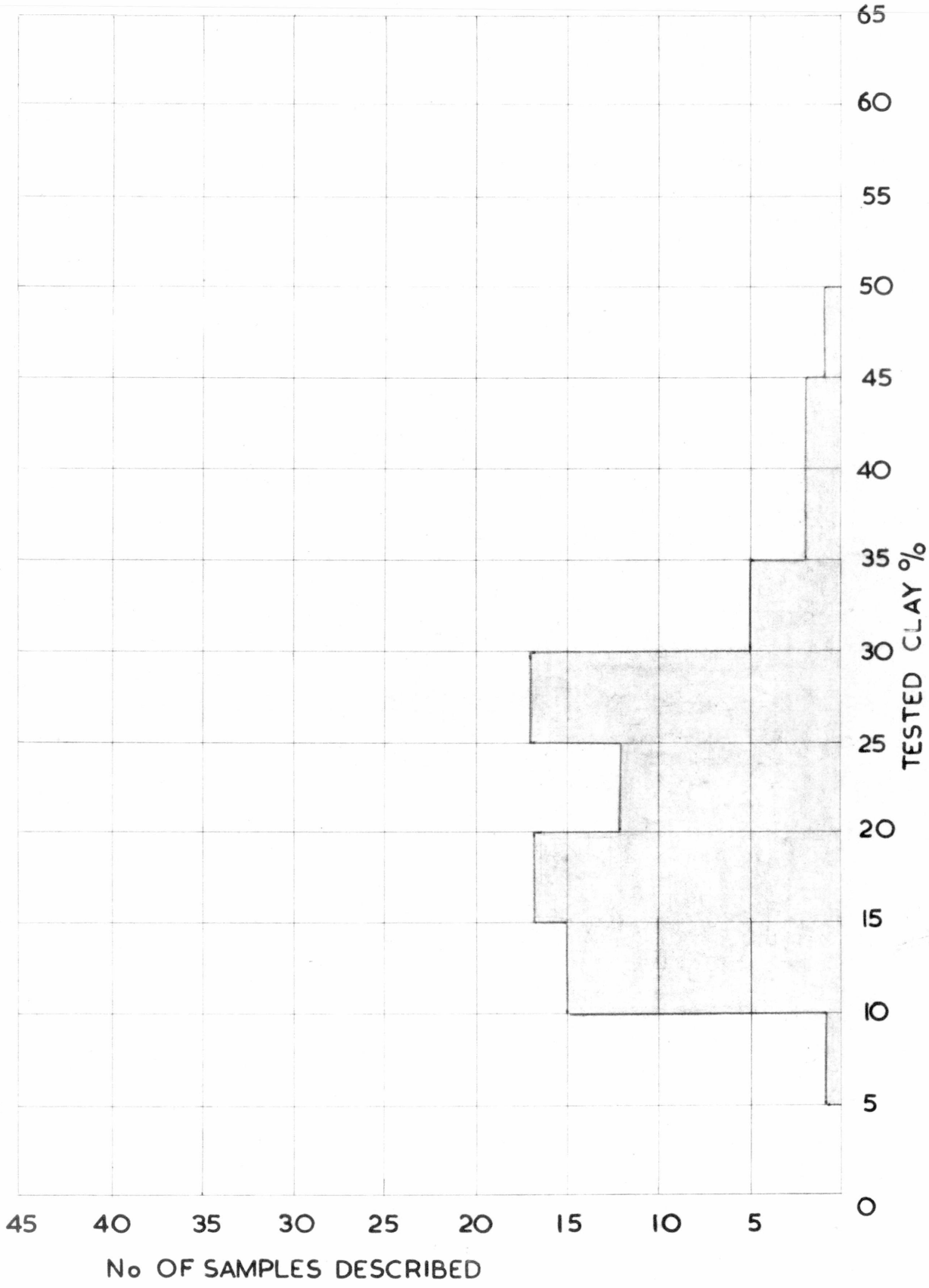
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FOUNDATION INVESTIGATON 1964-65

FRIQUENCY DIAGRAM

FIELD DESCRIPTION

FIG. 16



SANDY SILT

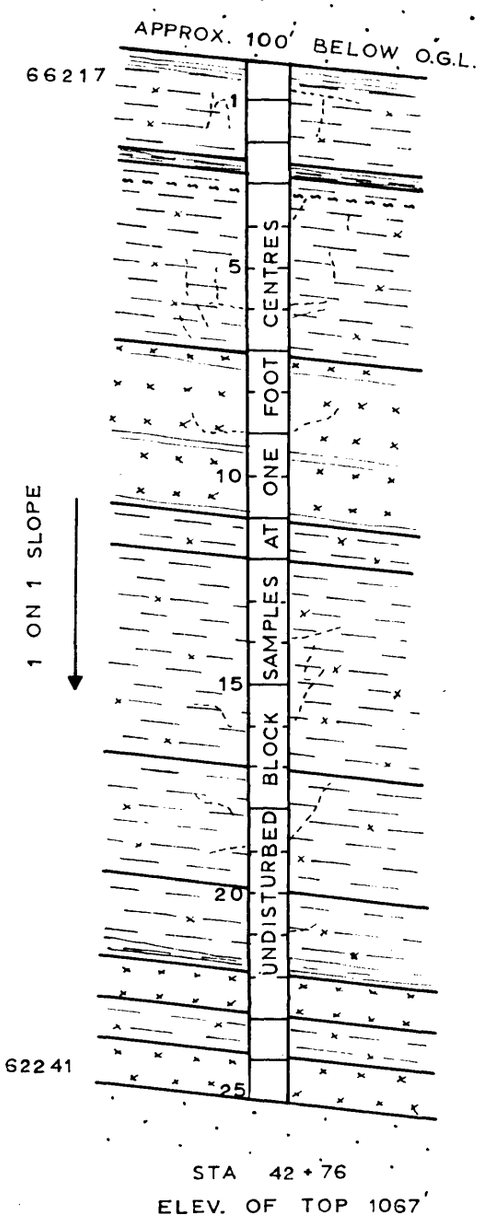
MANGLA

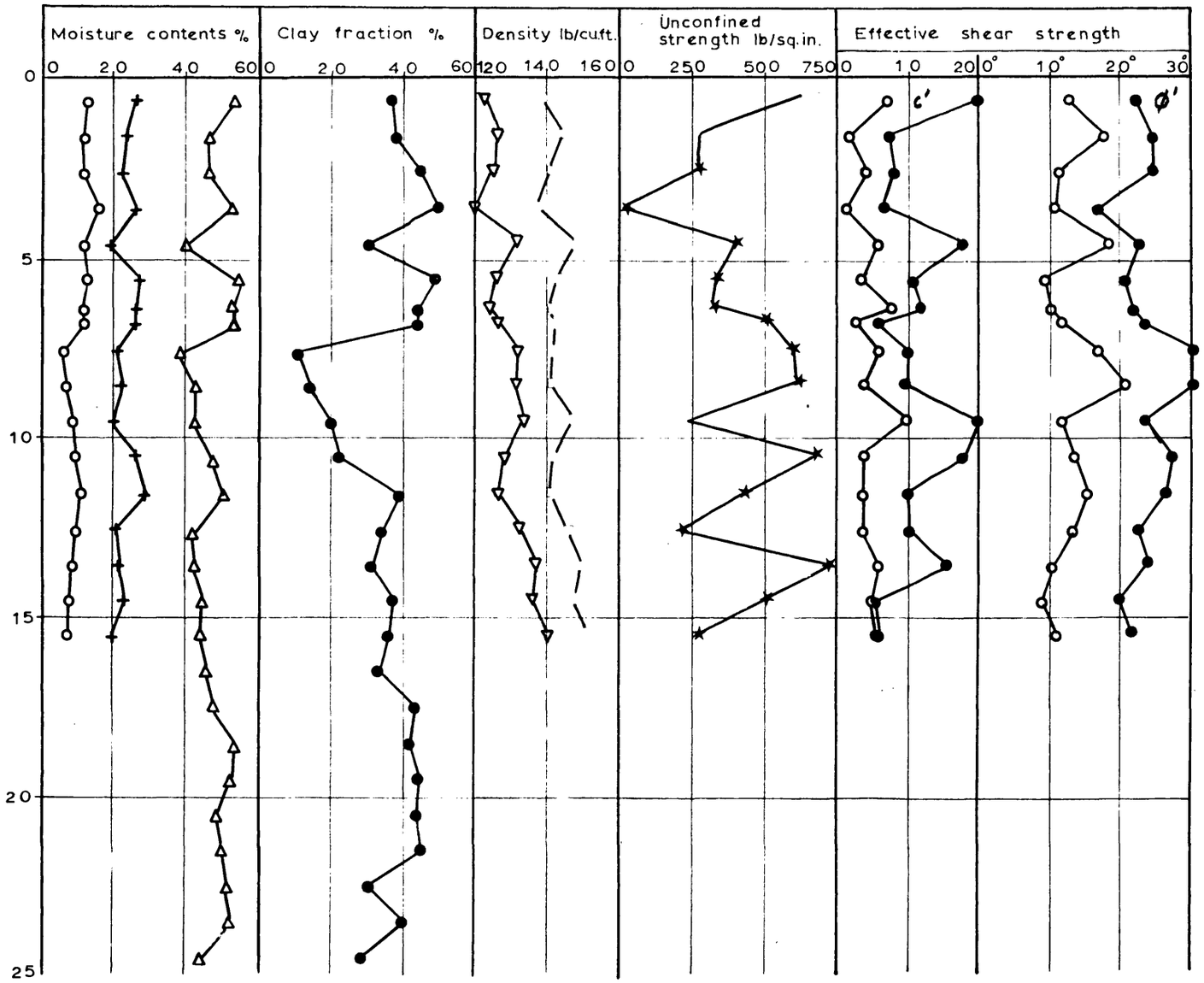
FOUNDATION INVESTIGATION 1964-65

FREQUENCY DIAGRAM

FIELD DESCRIPTION

FIG. 17.





LEGEND

FISSURE

THINLY BEDDED

SLIGHT SHEAR ZONE

SANDSTONE

CLAYEY SILT

SILTY CLAY

WATER

PL

LL

FIELD DENSITY

DRY DENSITY

PEAK VALUES

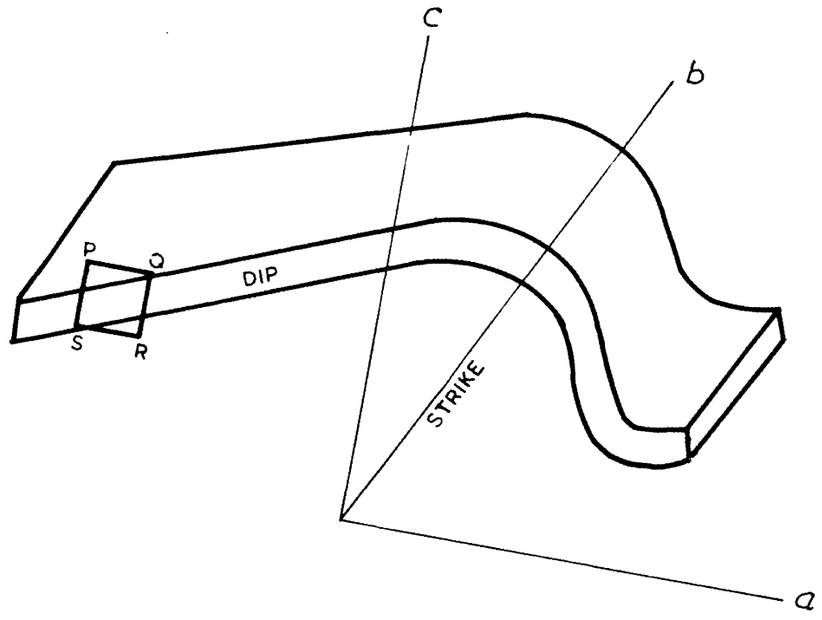
RESIDUAL VALUES

MANGLA

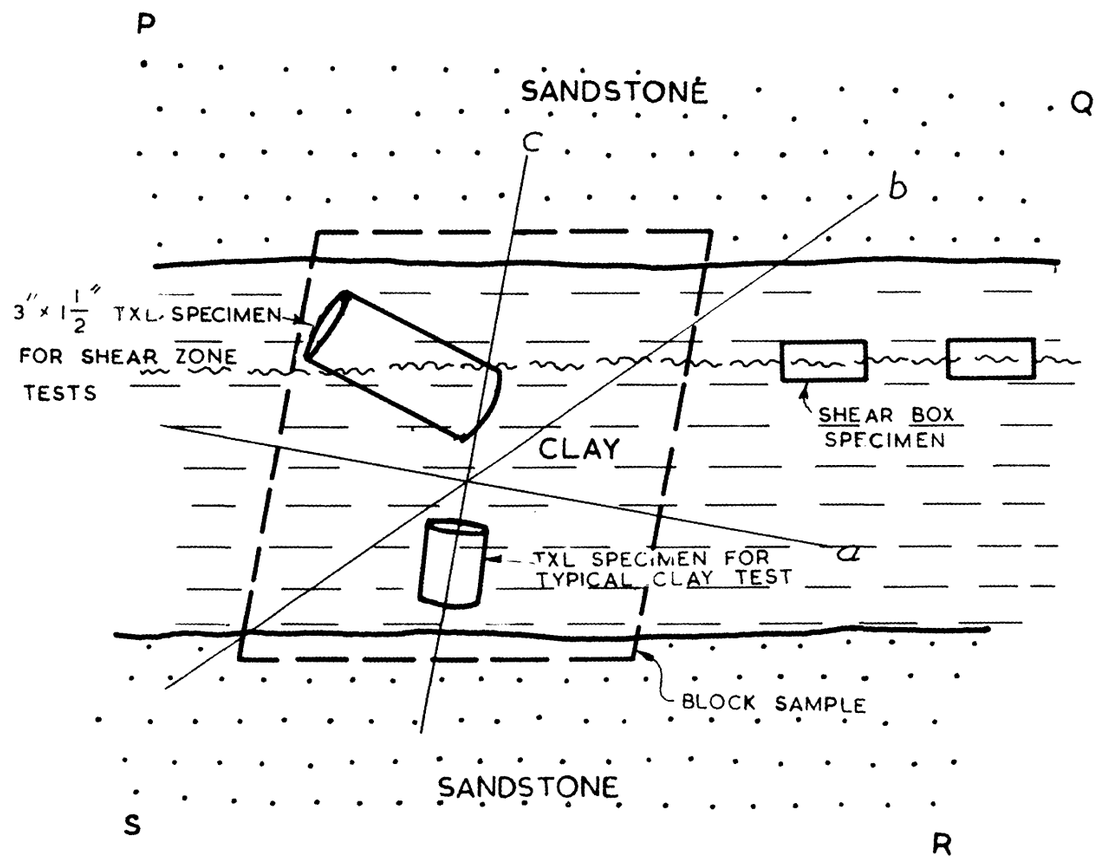
FOUNDATION INVESTIGATION 1964

BLOCK SAMPLING AND TESTING ON CLAY BED 217
MAIN DAM CORE TRENCH

FIG. 18.



A) DIAGRAMATIC REPRESENTATION OF FOLD AND FABRIC AXIS

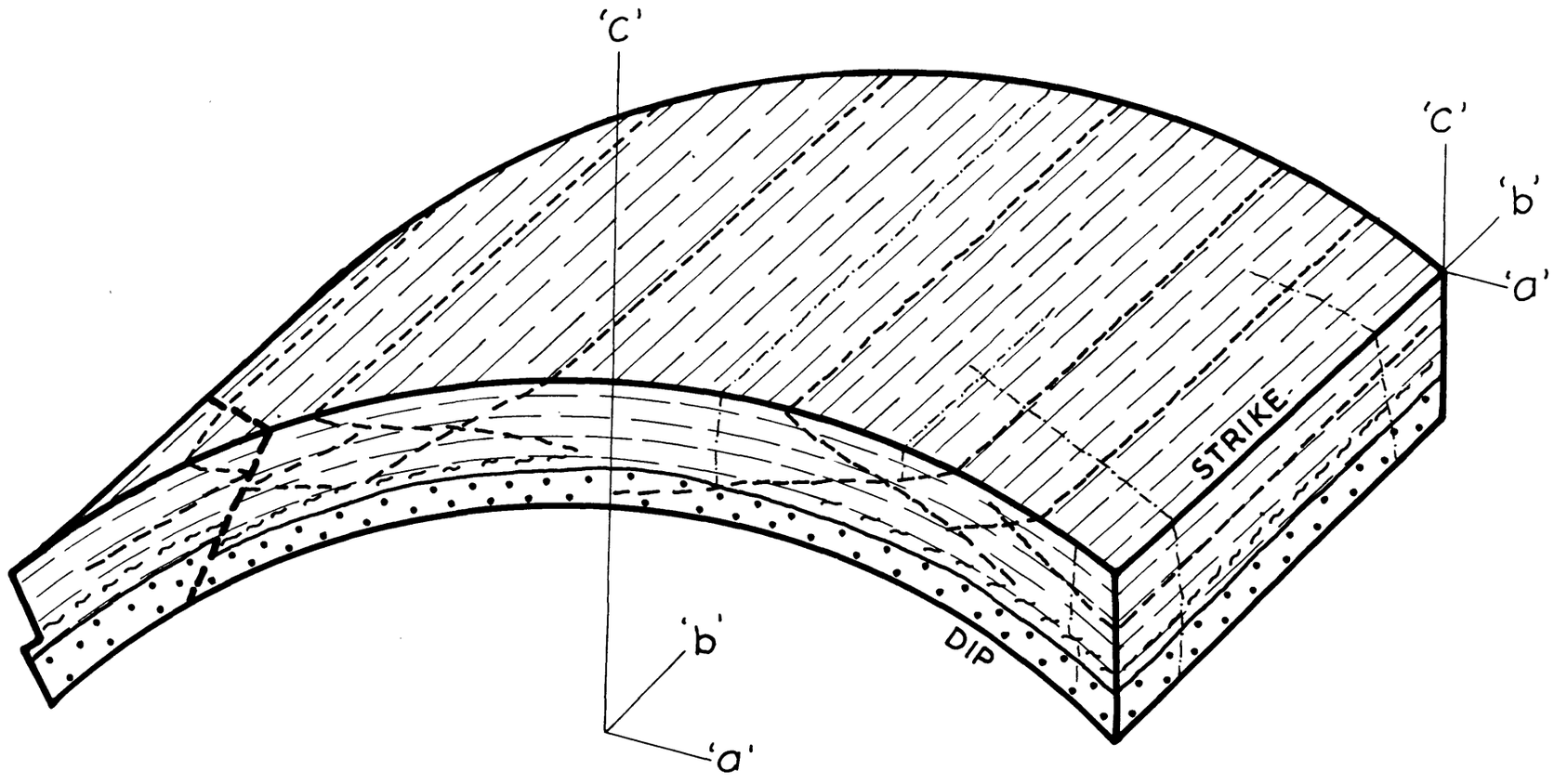


B) DETAIL OF (A) TO SHOW ORIENTATION OF SHEAR TEST SPECIMENS

MANGLA

FOUNDATION INVESTIGATION 1964-65
DIAGRAMATIC REPRESENTATION
OF FOLD & FABRIC AXIS

FIG. 19.



LEGEND

THRUST (OR REVERSE) FAULT.

SHEAR ZONE.

THRUST SHEAR JOINTS.

TENSION JOINTS.

FISSURES.

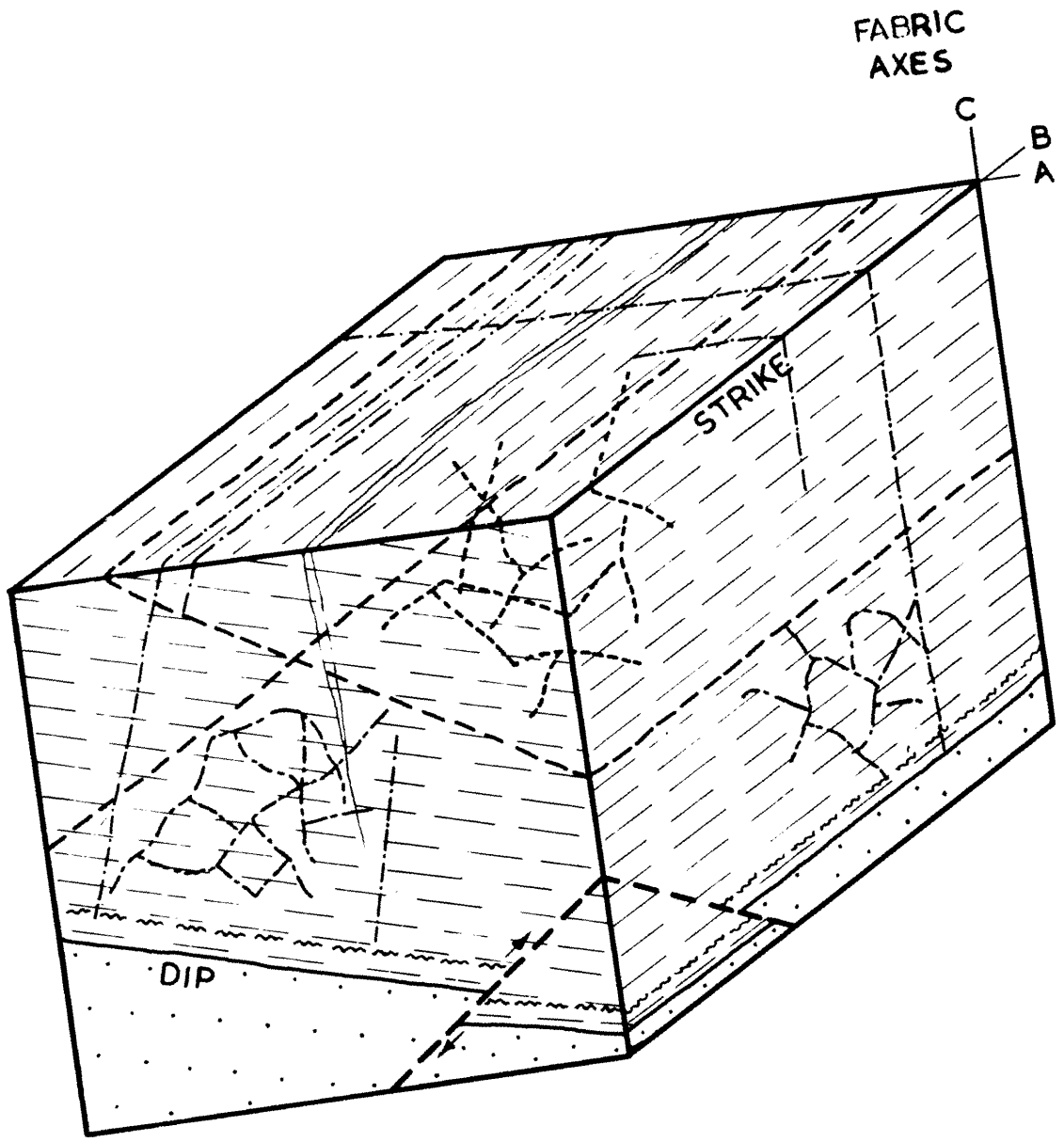
SANDSTONE.

CLAY.

MANGLA

DIAGRAMMATIC FOLD TO SHOW STRUCTURAL FEATURES AND THEIR RELATION TO THE LOCAL FABRIC AXES

FIG. 20.



NOTE

FOR LEGEND SEE FIG. 20.



DRYING CRACKS

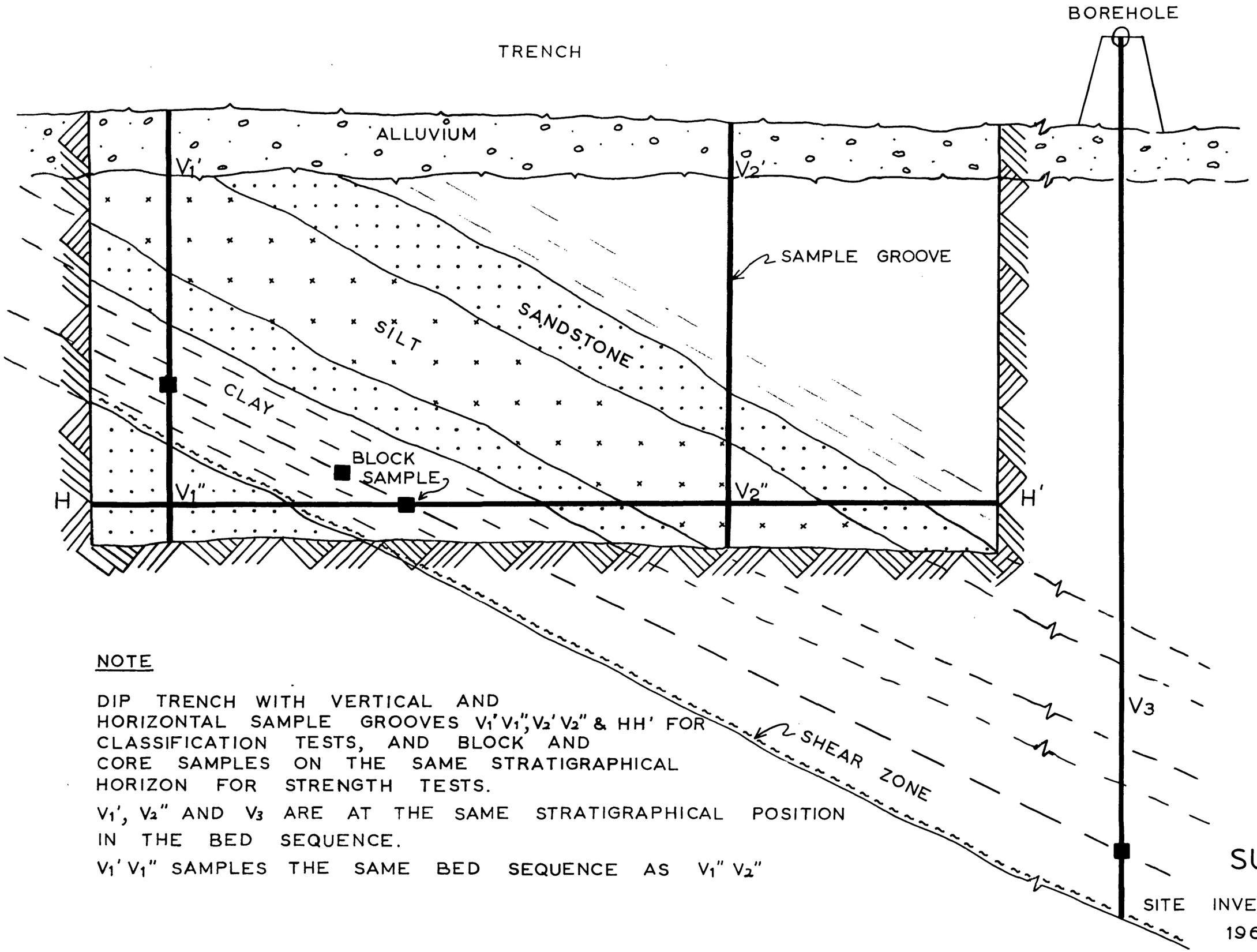
MANGLA

FOUNDATION INVESTIGATION 1964-65

BLOCK DIAGRAM

CLAY FEATURES

FIG. 21.



NOTE

DIP TRENCH WITH VERTICAL AND HORIZONTAL SAMPLE GROOVES $V_1'V_1''$, $V_2'V_2''$ & HH' FOR CLASSIFICATION TESTS, AND BLOCK AND CORE SAMPLES ON THE SAME STRATIGRAPHICAL HORIZON FOR STRENGTH TESTS.

V_1', V_2'' AND V_3 ARE AT THE SAME STRATIGRAPHICAL POSITION IN THE BED SEQUENCE.

$V_1'V_1''$ SAMPLES THE SAME BED SEQUENCE AS $V_1''V_2''$

SUKIAN

SITE INVESTIGATION 1963-64

FIG. 22. DIP TRENCH

LABORATORY TECHNIQUES*

The great majority of soil tests were carried out at the site soils laboratory which was fully equipped to carry out the usual range of soil classification tests. In addition, six multi-speed triaxial machines of three different sizes, similar to those used at Imperial College, London, were installed, complete with mercury constant-pressure systems, volume gauges and pore pressure measurement devices. A 50 ton triaxial machine with triple-cell attachment (see plate 25) and eight constant rate of strain shear box machines with slow speed forward and reverse drive, were added during the construction period. Local staff were specially selected and trained in the testing techniques; once the procedures were understood they showed both aptitude and willingness. A number of difficulties were encountered during the early days of the life of the laboratory due to climatic conditions (summer temperatures up to 118°F and monsoon humidities 95% or more were recorded), but these were largely overcome when an air conditioning plant was installed in 1962.

(a) Classification Tests†

Soils** were classified by particle size analysis, Atterberg limits, specific gravity of particles, moisture

* The author spent approximately 20% of his working time in the laboratory. The laboratory itself was under the direction of K.H. Head and test results were his responsibility.

** Siwalik clay bedrock was called 'rock' in the field (geological convention) and 'soil' in the laboratory (engineering convention).

content, density measurements and limiting porosities (of sands). The relevant procedures of BS 1377:1962 were followed.

For clays the most tested index properties were clay fraction (particle size less than 0.002mm) and liquid limit. Grading analyses were made on the usual range of British standard test sieves. Fine particle analyses were obtained from hydrometer tests carried out in an air-conditioned basement room where it was not difficult to maintain a fairly even temperature. Although the organic content and calcium compounds present were small (the soil pH was typically 7.0 to 7.5), all samples were pretreated with hydrogen peroxide and hydrochloric acid in accordance with British Standards. This ensured uniformity of procedure when at times of pressure of work, it became necessary to send some samples to London for testing. It was found that the omission of pretreatment resulted in an apparently lower clay fraction. Comparative tests showed that clay fractions measured without pretreatment had to be increased by a factor of about 12% for the range of clay fractions from 10% to 55%*.

The standard Atterberg limit tests (B.S. 1377:1962) were supplemented by great numbers of one-point liquid limit tests (for discussion see Norman 1959) which enabled graphs showing variation of the liquid limit of the insitu clay bedrock to be built up quickly. Results of these tests were affected by

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* At the time of writing a series of comparative tests on quartered material from the same parent sample is being carried out by the Mangla laboratory and several commercial laboratories in London. Preliminary results indicate Mangla tests give a slightly lower average clay fraction. The cause of this is not yet clear.

personal variations between one operator and another, but these variations were found to be no more than those existing between several commercial laboratories in England. Indeed the findings from tests on identical samples at Mangla and in London laboratories was partly responsible for the revision of the British Standard for the liquid limit test machine (1963). It was found at an early stage in the life of the laboratory that summer conditions of high temperature and low humidity appreciably affected the liquid limit testing. It was impossible to perform satisfactory tests without air-conditioning because of the rapid drying out of the soil samples.

Unconfined compressive strengths of Siwalik clays were typically from 50 to 300 lb/sq.in, but much higher strengths were occasionally recorded, though with some of the high ones (ca. 1,000 lb/sq.in) the specimens were probably dried out. To measure unconfined compressive strengths the standard portable hand-operated machines were not strong enough, so a larger machine was designed† for the purpose. This was built by the Client's workshops and incorporated a worm drive similar to that in a 3 ton triaxial machine, with a quick-return release. Provision was made for different capacities of proving ring, and for testing samples of any size up to 6 in. diameter. The capacity was up to 3 tons and the machine could easily be transported to site; this enabled unconfined strengths of NX size cores fresh from drillholes to be measured at the drillrig.

Throughout all stages of the investigation, precautions were taken to maintain all undisturbed samples in their field condition as far as possible. Immediately on arrival from the field, samples were stored in a room humidified by a constant spray of water on tiled walls. Storage was an acute problem until a larger humidity room was built and fitted with storage racks; (no storage space is ever too large for soil samples, a fact well known to all who do site investigation work!). As an additional check, moisture contents were frequently measured on site with the aid of a chain dial balance and sand-drying tray on a portable oil-stove.

Preparation of undisturbed samples for triaxial, shear box and oedometer tests was carried out in a separate humidified room fitted for the purpose with adequate light, ventilation (to change the air at intervals) and a bench with plate-glass working surfaces. All samples were carefully trimmed by hand from NX cores or blocks to the required size, using hacksaws, knives or 'surform' blades. A motorised soil lathe was available but was found to be unsuitable for local materials. The frequent inclusion of hard nodules and concretions, typically $\frac{1}{4}$" to $\frac{3}{4}$" in maximum dimension caused many difficulties in trimming. Special samples, such as those from shear zones and other planes of discontinuity within clay beds, were even more difficult to prepare for testing. The local 'stonemasons' employed for trimming, eventually became expert in the various techniques and produced samples of a commendable degree of accuracy and uniformity. Plate 26 shows an orientated block sample cut from a shear zone (Location IV discussed in Part II) just prior to waxing and plate 27 shows the block covered in butter muslin during waxing.

(b) Strength Tests‡

Most of the samples for triaxial tests were $1\frac{1}{2}$" diameter by 3" long, and were set up and tested generally in accordance with the techniques described by Bishop & Henkel (1962). All triaxial tests referred to were consolidated-drained tests. An outline of the principal stages of testing is given following:

(i) Setting up

All samples were enclosed in a thick (0.02") rubber membrane and most clay samples were fitted with filter-paper side drains. As soon as the sample was set on the pedestal, a check was made on the initial pore suction. The measured value was usually 2 or 3 lb/sq.in. suction but since high-air-entry value porous stones were not employed this did not necessarily represent the pore pressure in the clay, which could be minus two or three atmospheres.

(ii) Saturation

The cell pressure and back pressure applied to the top end of the sample were raised in increments, the pore pressure response being measured at the bottom end. Saturation was considered to have been achieved when the value of parameter $B = \frac{\Delta u}{\Delta \sigma_3}$ (Skempton & Bishop) exceeded 0.96 for three successive increments. A typical curve is shown in fig. 23(1).

(iii) Consolidation

The cell pressure (and back pressure if necessary) was adjusted to give the required effective pressure σ_3' for the test and the sample was allowed to consolidate. A square-root-time/pore pressure dissipation curve was plotted from which the coefficient of consolidation, c_v, was calculated for the given drainage conditions. The relationship used for combined radial drainage and single-end drainage was:

$$c_v = \frac{\pi . h^2}{80 t_{100}} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (1)$$

compared with Bishop & Henkel's expressions:

$$c_v = \frac{\pi h^2}{64 t_{100}} \quad \text{for radial drainage only}$$

and $$c_v = \frac{\pi h^2}{100 t_{100}} \quad \text{for drainage from radial boundary and both ends.}$$

From the value of c_v the maximum rate of strain to ensure 95% dissipation of pore pressures during shear was calculated and the rate of strain used in the shear test was about half this value or less. A typical consolidation curve is shown in fig. 23(2).

By combining equation (1) above with Bishop & Henkel's equation 30, (page 125) and putting h = 32, the following expression for time to failure, tf, is obtained:

$$tf = 16 \times t_{100} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \qquad (2)$$

Hence if peak failure occurs at a strain of 1.5% and t_{100} is in minutes the rate of strain should not exceed:

$$\frac{d\epsilon}{dt} = \frac{5}{t_{100}} \quad \text{percent per hour} \quad \ldots \quad (3)$$

Expression (3) provided a rapid check for the appropriate rate of strain.

In the early tests the degree of saturation was checked after consolidation was completed by repeating the saturation procedure for 2 or 3 increments. It was found that, provided the back pressure was not reduced below 30 lb/sq.in the value of B' after consolidation remained above 0.9.

(iv) Shearing

Constant rate of strain triaxial machines were used and deviator stress was measured on a steel proving ring of 400 lb, 1,000 lb or 3,000 lb capacity depending on the cell pressure and type of material. Drainage was allowed from the top of the sample against a back pressure but a constant check was made of the pore pressure readings at the lower end of the sample. Unusually slow drainage or a blockage in the drainage system were detected at an early stage and remedied if necessary by slowing down the rate of strain, or in extreme cases, by abandoning the test before a false result was derived.

To maintain continuity of readings and to take immediate action in the event of a mishap with the apparatus, a skeleton staff was continually on duty during the night and at weekends and holidays. Without this arrangement the volume of testing would have been appreciably reduced.

Tests were extended beyond the peak of the stress/strain curve until the 'ultimate' or 'residual' value (Skempton 1964) was reached or until the sample became excessively distorted. Because of the large strains and consequent large deformations necessary to reach the condition of constant stress with increasing strain in the triaxial tests, the 'residual' strengths derived from these tests do not necessarily have quite the same meaning as the term 'residual strength' used by Skempton. These values represent the ultimate practicable extent of the triaxial test according to present experience, and are compared with 'peak' strengths which can be more accurately measured since they occur at small strains. This point is discussed more fully by Skempton (1964).

(v) Modes of Failure

The principal types of stress/strain characteristics including those relating to the special tests referred to in sections (ii), (iii) and (iv) above, are described following and illustrated in fig. 24 (after K. Head).

All unsheared bedrock samples exhibited a barrelling deformation, however slight, up to the peak deviator stress; at this point, which was typically at 1.5% to 2.5% strain, a single surface of rupture usually developed. Further strain resulted in relative slip along this surface, and no further barrelling. From the peak the deviator stress dropped considerably until the ultimate (residual) value was reached. The ratio of peak to

residual strength ranged from 1.3 to over 3 but was usually between 1.5 and 2. A typical stress/strain curve is shown by curve A of fig. 24. Shearing was usually discontinued at 16% strain because of the increasing distortion of the sample.

After the development of the failure surface (which was not necessarily planar) the relative slip resulted in a continual decrease of effective cross-sectional area of the sample. The deviator stress should, therefore, be somewhat greater than the value $\frac{\text{Load}}{\text{Area at peak point}}$ by an amount that is a function of the inclination of the failure surface to the sample axis and of strain beyond the peak point. However, there were several unknown forces which came into operation as a result of relative slip. The most important was probably the side thrust on the loading ram which was balanced by a horizontal force and a couple at the bush at the top of the cell which increased the frictional force on the ram. No attempt was made to measure this effect but it was assumed that by ignoring the area decrease effect due to slip it would substantially balance out. Eventually the only correction applied was a reduction to deviator to allow for the combined effect of the rubber membrane and filter strips, which took into account both barrelling and single-shear-surface slip. The correction curves were derived from data supplied by Professor Skempton.

Cells fitted with rotating bushes were not available throughout most of the investigation but comparative tests in this type of cell, using slower rates of strain, are currently in progress.

(c) Special Triaxial Tests‡

The above techniques relate to tests on undisturbed samples of bedrock $1\frac{1}{2}$" diameter, 3" long, trimmed either from NX cores or from hand-cut blocks with sample axes approximately vertical. In addition a number of special tests were also carried out, as follows:

(i) 4" diameter samples

To assess whether $1\frac{1}{2}$" samples were giving representative results, a number of direct comparisons were made between results of tests on $1\frac{1}{2}$" and 4" diameter undisturbed samples of similar materials. The 4" diameter samples gave slightly lower peak strengths; and could indicate the weakening effect of the greater number of fissures (many could not be detected on visual examination but specimens broke along fissure planes on slight finger pressure) within the larger samples (Skempton 1964).

(ii) Remoulded samples

After completion of a triaxial test, some samples were broken up and recompacted to the original density and at the same moisture content; and the process of saturation, consolidation and shearing was repeated. Barrelling type failure without shear plane slip occurred in remoulded samples, and stress-strain curves had no peak (curve B, fig. 24).

(iii) Reconsolidation and Re-shearing

Several tests were extended beyond the usual limit by discontinuing shearing when the residual strength appeared to have been reached (curve C, fig. 24), consolidating the sample further by raising the cell pressure, followed by continued shearing after a suitable time interval. In all cases, an increase in strength was recorded but the 're-consolidated' stress/strain curve showed no peak (curve D, fig. 24). The strength achieved was close to the residual which would have been expected if the sample had been sheared from the start at that cell pressure.

(iv) 'Sliced' samples

Many attempts were made to cut triaxial samples from fissured clay with axes orientated so that failure would occur on the fissure surface. At the time of writing no attempts on fissures were successful, but a few 'intact'* samples were sliced along a plane inclined at about 30° to the sample axis after trimming, and the halves carefully fitted together and set up in a triaxial cell. The usual process of saturation, consolidation and shearing was carried out. Effective shear strengths were found to be about equal to residual strengths of 'intact' clay of similar classification properties, except the 'sliced' samples curve gave no peak (curve E, fig. 24). Successful attempts to shear along natural slickensided surfaces

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* Site definition as clay or silty clay of 1' cube not containing any visible fissures (see page 142).

found, for example, in shear zones or on thrust (shear) joints, were made. These are described following.

(v) Orientated samples

When studying shear zones and thrust (shear) joints, 4" diameter samples were cut in situ so that failure in a triaxial test would occur along a natural sheared surface (e.g. fig. 19(b)). These tests are described in more detail in Part II, but a typical stress/strain curve for a shear zone sample is shown by curve F, fig. 24. In addition, a small number of comparative tests were done on $1\frac{1}{2}$" diameter samples of 'intact' clays trimmed with the long axes either horizontal or vertical to the bedding (see fig. 19(b)). No significant difference was found in the strength parameters in the limited number of tests made.

All other triaxial tests were carried out on samples cut with the sample's long axis vertical to the bedding or more strictly speaking parallel to the 'c' fabric axis for the site.

(d) Shear Box Tests‡

Tests on clay bedrock in direct shear box apparatus were generally restricted to the study of shear zones and are described in Part II. More shear box work is currently in progress.

(e) Swelling Pressure Tests‡

Samples of clay bedrock were taken from open excavations at various depths below original ground surface for measurement

of swelling pressure in oedometers using 3" diameter x $\frac{3}{4}$" thick samples. Each oedometer cell was first calibrated, by using a steel disc in place of a sample, to measure the deformation characteristics of the machine itself. If this were not allowed for when balancing the swelling tendency of the clay the swelling pressure is under-estimated, as at Mangla, it can be of the order of several tons per square foot. Coefficient of consolidation, c_v, was derived from the square root-time/consolidation curve for those samples which gave an initial straight line relationship. In these tests as in the consolidation stage of triaxial tests there were many cases in which the straight line portion was absent and c_v could not be defined with any accuracy.

Undisturbed clay samples from varying depths below the original ground surface gave swelling pressures ranging from about $\frac{1}{2}$ t/sq.ft. to 12 t/sq.ft. The latter figure is from samples cut from the intake area where original overburden depth was in the order of 5,000' of bedrock.

PLATE No. 25 December 1964 (?)

The triple cell 50 ton triaxial machine and pressure systems, Mangla Soils Laboratory.

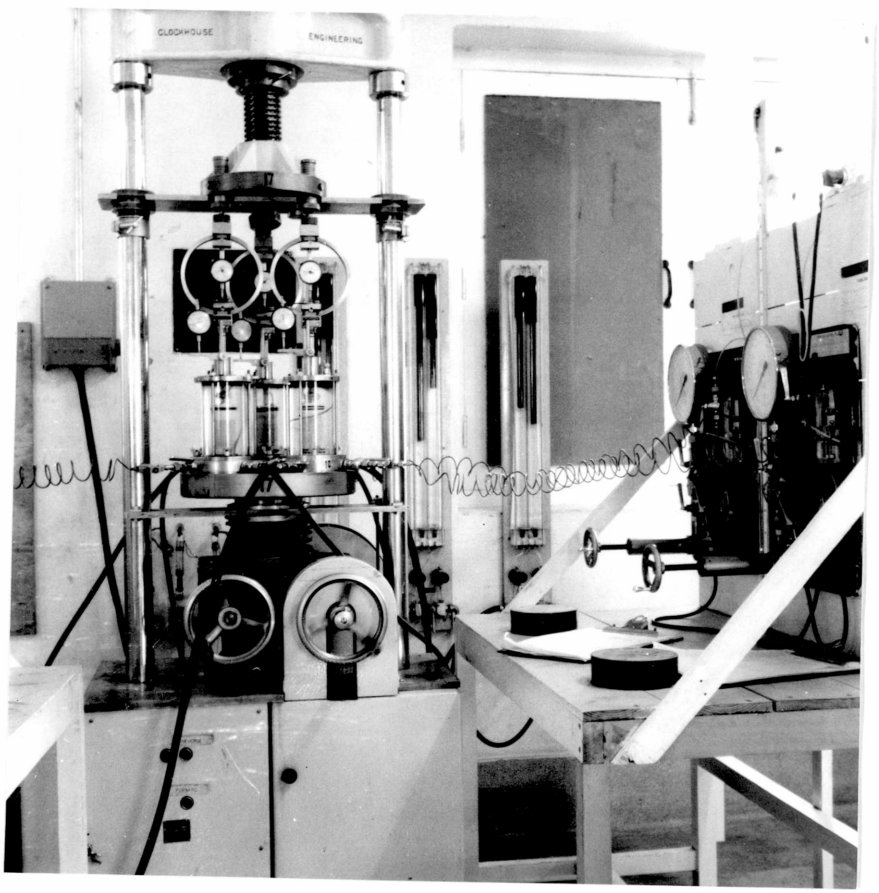

CLOCKHOUSE
ENGINEERING

PLATE No. 26 July 1964

Orientated block sample from the shear zone location IV, Lower Stilling Basin, Mangla, immediately prior to waxing.

IV

PLATE No. 27 July 1964

The block sample shown on plate 26 in butter muslin being waxed


IV

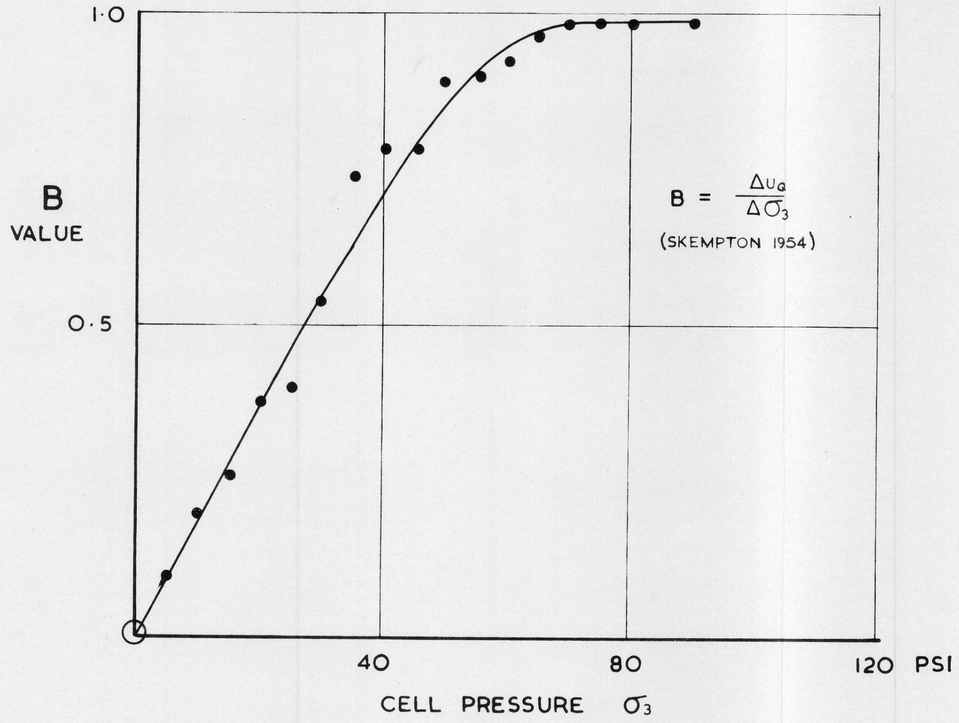


FIG. 1

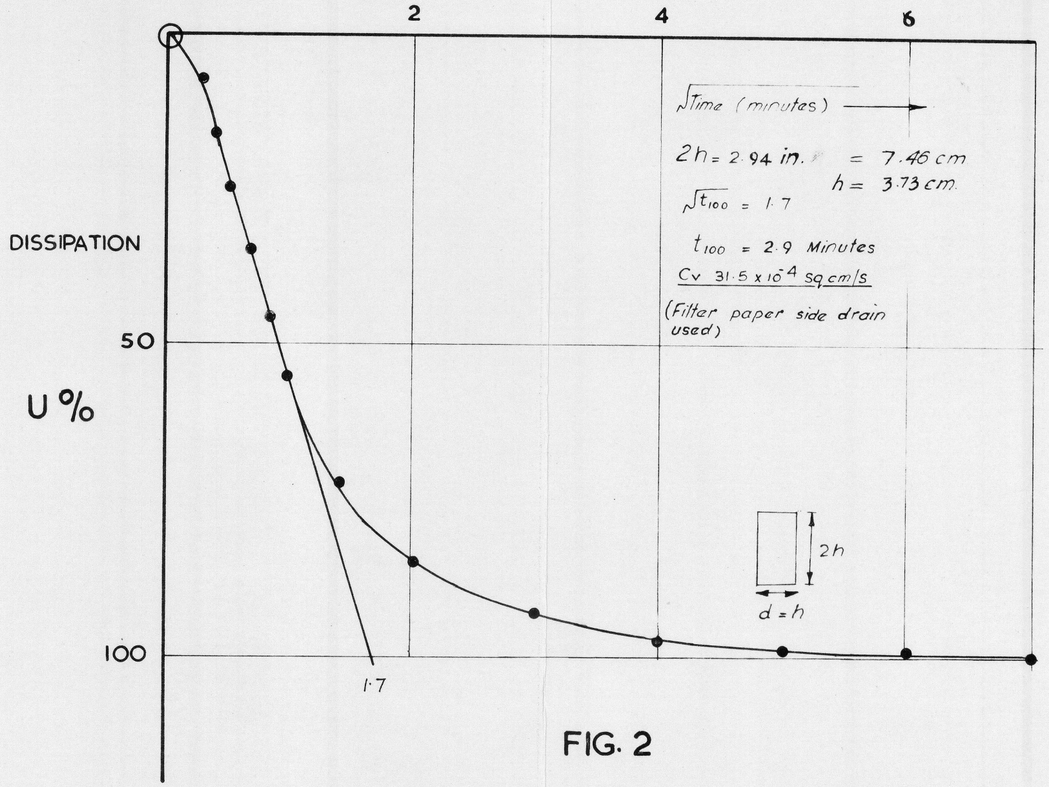


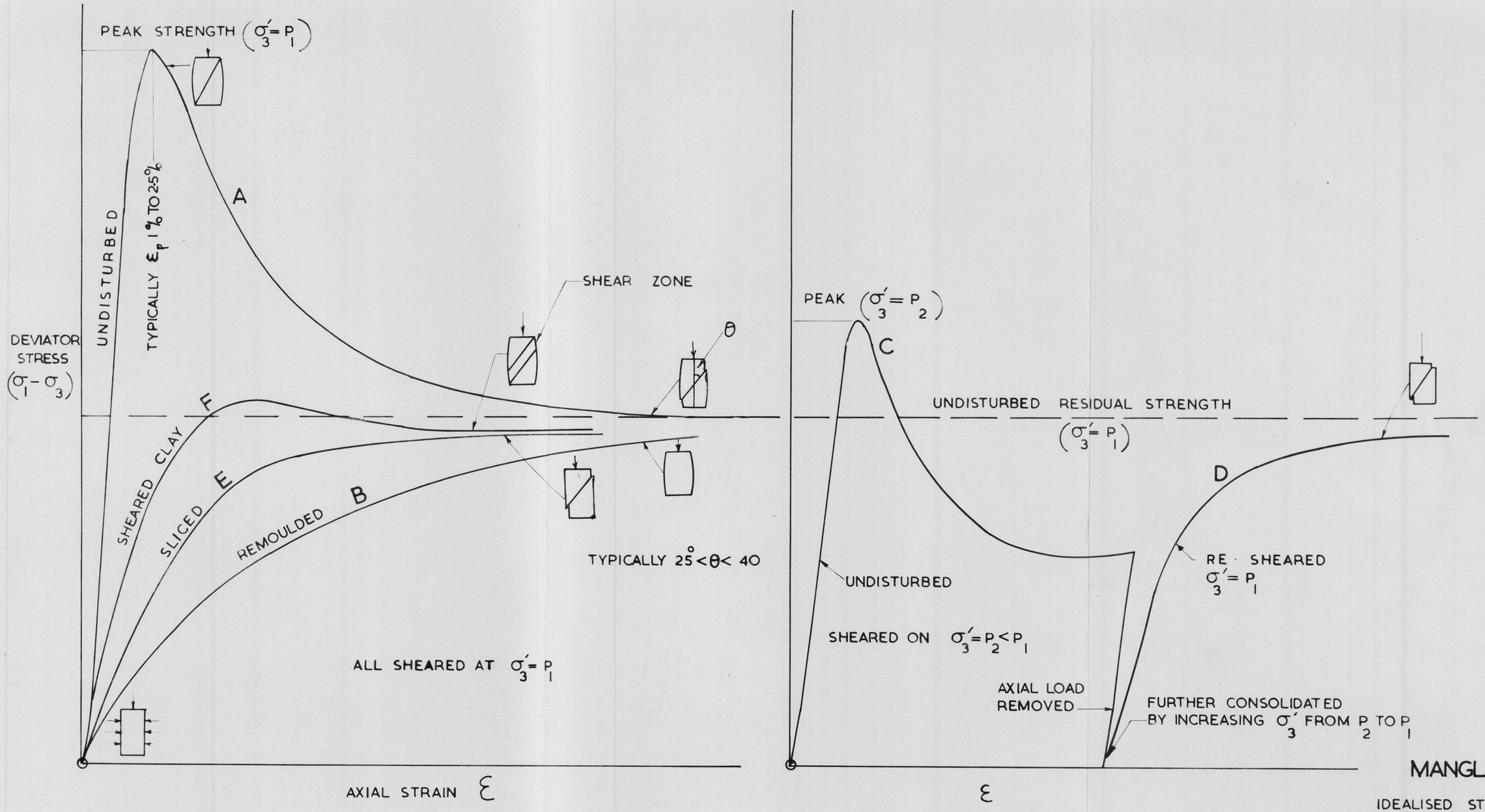
FIG. 2

MANGLA CLAYS

1. TYPICAL SATURATION CURVE
2. TYPICAL CONSOLIDATION CURVE

(after K.H.H.)

FIG. 23.



MANGLA CLAYS

IDEALISED STRESS/ STRAIN CURVES

(after K.H.H.)

FIG. 24.

P A R T II

HISTORY OF SITE INVESTIGATION

Site investigation did not proceed continually or at a uniform pace simultaneously at the three principal damsites, Mangla, Sukian and Jari, but was concentrated at one site at a time. Each site had an initial exploration*, an intensive investigation proper** and a re-investigation later during construction***, when information, techniques and interpretation of laboratory test results had improved and shown the need for re-evaluation of the clay bedrock.

The work presented here was carried out from 1961-1965, during which time the site exploration and site investigation of Jari, from 1961 to early 1963, was carried out; the site investigation of Sukian, mid 1963 to early 1964; and the foundation investigation of Mangla, Sukian and Jari 1964-1965, during construction. Mangla itself never received such an intensive site investigation as did Jari and Sukian. The basis of a 'site investigation' was geological mapping on a

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* Referred to following as 'site exploration'.

** Referred to following as 'site investigation'.

*** Referred to following as 'foundation investigation'.

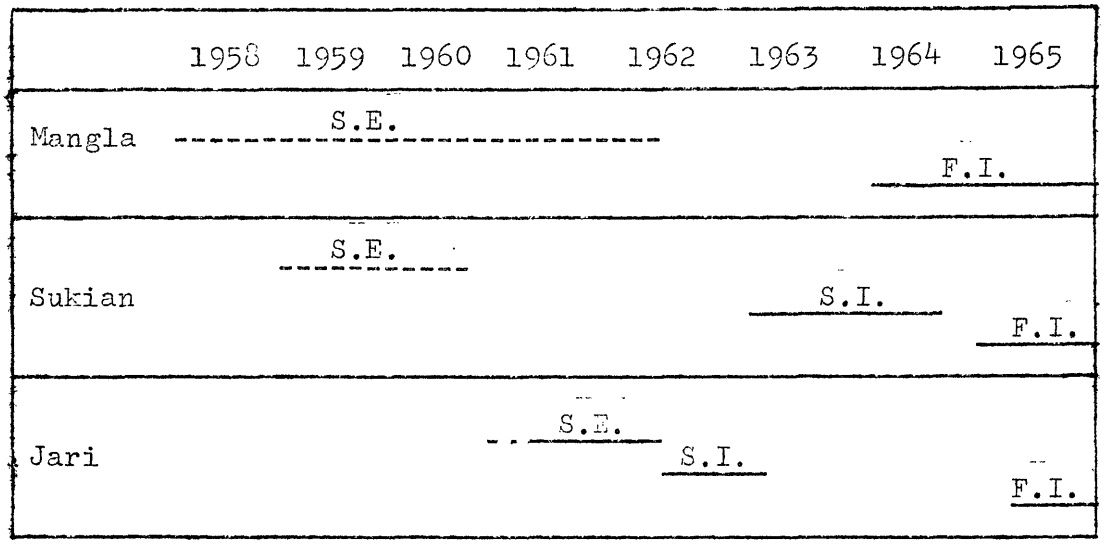
1" to 200' scale supplemented by investigation trenches and boreholes, to enable a full geological picture to develop. On this picture the field sampling and field and laboratory testing were based.

At Mangla damsite until the spring of 1964, investigation was largely controlled by instructions by the Engineer. Site exploration was commenced late in 1958 but it never achieved the concentration of mapping reached by the Jari and Sukian investigations as the site was largely covered by alluvium and much of the work consisted of drilling boreholes along set patterns. After the spring of 1964 Mangla, during construction, received intensive foundation investigation on the Sukian and Jari lines. This work went ahead quickly because by this time considerably better exposures were available from the large construction excavations and the techniques developed from Jari and Sukian were used.

The following chart, table II, summarises the periods of site investigation for each area; those shown in a firm line are described and discussed in this thesis:

T A B L E II

Investigation Progress



S.E. Site exploration

S.I. Site investigation

F.I. Foundation investigation.

Although the chart shows clearly a start and end to the exploration or investigation at each site, in practice minor amounts of field and laboratory work were continually in progress for each site at all times. Foundation work is at the time of writing continuing on all sites.

In the following, the history and development of site investigation, is traced in some detail beginning with Jari in 1962, when the close centre sampling techniques were first employed, to Sukian 1963, where techniques and knowledge was further improved, to Mangla, Sukian and Jari in 1964-1965

which were rapidly re-investigated in the light of previous knowledge. They are described, except where specifically stated, with the interpretation put on the situation at the time of the investigation. The most significant changes since the Jari investigation were in interpretation of laboratory results and in the importance put on geological structural features.

SITE INVESTIGATION OF JARI

LOCATION AND DESCRIPTION OF SITE

The Jari dam is the second largest dam of the Project. It lies some 14 miles east of the Main Dam (which is on the River Jhelum at Mangla). The damsite is located at the south-east end of the Mirpur basin where the rim of the basin formed by the folded Upper Siwaliks is cut by Jari Nullah (see fig.4).

This nullah drains the Mirpur basin south of the watershed dividing the basin. At the location of the damsite the Jari nullah is joined by the Kakra nullah which drains the extreme eastern end of the basin and the gravel covered hills forming the reservoir rim between Kalial Bens and the left abutment.

The damsite is underlain by a series of intercalated lenses of clay, silt, siltstone, sandstone and gravel of the Siwalik system. The bedrock in the centre of the site is covered by alluvium of the Jari and Kakra nullahs. Siwalik bedrock of the abutments has been eroded in places forming several saddles whose elevation is below reservoir level.

Introduction and Objects of Investigation

The site investigation of the Jari damsite was initiated in the early summer of 1962. At the start of the initial exploration it was thought that a dam to complete the Mangla reservoir could be sited east of Mirpur city, but the borehole samples and other considerations indicated that the foundations

were unsuitable at this location, so investigation was from the end of 1960 concentrated on the watergap at Jari Kas. Tender drawings and Contractor's schedules had to be prepared so that construction could be started as soon as possible, consequently there was insufficient time for a complete investigation and a design had to be prepared on the general assumption that the clays at Jari were essentially the same found by the initial exploration at Mangla.

However, results of laboratory tests on random samples from the site exploration of 1961, although limited, indicated the presence of clays of lower shear strengths than had been assumed for the design. The primary object of the subsequent investigation was, therefore, to determine the quantity and distribution of this weak clay. Unfortunately the preliminary work did not indicate any definite areas where these clays may be found, so it was necessary to cover the whole damsite in the new investigation. It was assumed that the weak clays were layers, or lenses, but the reason for these weak zones was not understood, nor was it clear whether they were phenomena of bedding, weathering of shear zones, or some other feature. It was now necessary to determine the form in which these clays occurred.

Other foundation problems relating to the design were also studied. These were the stratigraphy, permeability, geological structural features like shear zones and fissures, weathering of bedrock, distribution and character of alluvium and the stability of slopes.

INVESTIGATION PROCEDURES

Laboratory tests made during the early stages of the investigation indicated that the clays of low shear strength generally had a high liquid limit (see fig. 25). Therefore, the search for low strength clays was based on extensive field sampling and classification by liquid limit tests, as this means at the time, was the quickest and the most convenient method of determining an index property of the clays.

Investigation in search of weak clays consisted of trenching, pitting, tunnelling and core drilling for samples.

Other bedrock investigation consisted of well permeameter tests for near-surface permeabilities, borehole pumping-out tests for permeabilities at greater depths, tunnelling for fissure investigation and plane table mapping for topography and geology. 'Liquefaction*' tests for running sand and 'disintegration*' tests on the reaction of sandstones and clays in water were also performed.

The investigation of the alluvium consisted of mapping and pits and trenches to yield samples for testing.

Site investigation techniques on the clays are briefly described under the following headings:

a) Valley floor - trenches and pits
boreholes
adits
well permeameter - permeability tests
borehole pump-out tests-permeability tests
field tests

* Field tests invented by the author

b) Abutments - trenches

field tests

adits

(a) Bedrock in the Valley floor

Trenches. The principal purpose of the trenches was to permit cutting of continuous sampling grooves and to reveal complete stratigraphic sections beneath the 5' to 30' of alluvium which covered the bedrock. The trenches were dug 5' to 10' into bedrock. Locations of the trenches are shown on fig. 26. They were aligned north-south and located so as to offer the best possibilities for correlation of strata across the site. They also permitted the study of the alluvium and the observation of near-surface bedrock conditions such as shear zones, fissures, weathering, permeability and top of bedrock.

Sampling proceeded hand-in-hand with the geological logging. Samples were taken from a continuous longitudinal groove approximately 4" x 4" in cross section and extending the full length of the trench (see plate 28 and page 46). About 300 gms. of material was taken from each sample location. The spacing of samples was 0.1' in clays and silty clays and 0.2' or 0.25' in clayey silts and 0.5' or 1' in silts. Some sand and gravel beds were sampled by taking a single 25 kilo. composite sample from each bed. Samples were taken by spatula and hatchet, immediately placed in a polythene bag and sent to the laboratory. An average of about 400 samples were taken on a good day, though at the beginning of the work the rate

of collection was only about 20 - 30 per team* per day; this was later raised to about 60 - 80. A total of 12,000 samples were taken over a period of 5 weeks.

Plate 29 shows a logging and sampling team by the side of trench HI during digging.

Trench ABC (fig. 26 and plate 28) was located on a small terrace elevation ca. 1035' at the edge of the left abutment and above the water table; sampling and logging of this trench was very satisfactory as the trench was dry. It was excavated by a D-9 bulldozer to a maximum depth of 12', from approximately 100' upstream to 900' downstream of the proposed dam axis.

Trench A1-B1 (fig. 26) was located upstream of trench ABC and excavated by a dragline as it was below the water table; it was ca. 500' long; a D-7 bulldozer cleaned the slumping sides of the trench, but unfortunately this was only partly successful and the trench was logged for only 300'.

Trenches F1-G1 and F2-G2 (figs. 26, 27 and 28) were located on the 1,035' terrace remaining in the centre of the valley and was dug by a backhoe and D-9 dozer. The trenches were cut about 4' into bedrock and slightly below the water table. They were dewatered with a 4" pump during sampling and logging.

Trench F3-G3 (fig. 26) was located at the eastern edge of a small rise in the bedrock and was excavated by a D-9 bulldozer. It was above the water table.

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* Consisting of a Junior Geologist (one between two teams), a Research Assistant and two or more assistants and labourers.

Trench HI (figs. 26, 29 and 30 and plate 29) was located on the western end of the 1,035' terrace and was 830' long. Chainage 0 to 176' was excavated by D-9 bulldozer and from 176' onwards by backhoe (plate no. 29). Most of the trench was below the water table. A 4" pump was used to dewater but slumping sides of the trench continuously hindered the sampling.

Trench PQ (fig. 26) was located on the southern flank of the right abutment. The first 200' was excavated by a D-9 bulldozer and the remaining 140' by backhoe. The trench was above the water table in places. Part of the trench fell in by material sliding down a shear zone (details are given in Fookes & Wilson 1966) and blocking the trench; it was re-excavated by dozers.

Pits (fig. 26). Several pits were dug at various locations in the valley floor. These were ca. 6' x 6' in cross section at the surface and excavated down to the water table. The sides were closely timbered for support and samples were taken by scrapes from the wall of the pit. Some undisturbed block samples were taken for triaxial tests.

Adits.(figs. 31, 32 & 33). Eleven adits were dug prior to July 1962 and five additional adits, JA-12 to JA-16 were dug between October 1962 and February 1963, in order to investigate cracks on the abutments. Adits JA-12, -13 and -14 were at the base of the left abutment and within the valley floor section. Adits JA-15 and -16 were in the right abutment. None of these adits were below the water table. All were dug by hand and

supported by timber when necessary. They were watched for crack development and logged daily as excavation progressed (see plate 18).

Boreholes (fig. 26). The purpose of the drilling was to:

1) Supplement the trench investigation and mapping of exposed bedrock;
2) To establish the dip of the beds; and
3) To recover samples from depth.

Forty-six boreholes were drilled in the valley floor; they were laid out on six north-south lines, in all the total footage drilled was 7,602'. They were approximately 100' apart and of varying depths from 60' to 200' to give some overlap for correlation of strata. Chicago Pneumatic CP-8 rigs were used to drill the bedrock with NX or BX corebits, but a Reich drill with a 3.5/8" tricone bit was used first to penetrate the alluvium.

The core from these boreholes was logged and generally sampled as follows:

(i) On $2\frac{1}{2}$' centres for insitu moisture, density and liquid limit tests;
(ii) At close centres, i.e. 0.5', in portions of clay, silty clay and clayey silt selected by inspection. Estimates of liquid limits were made before sampling.

Average core recovery was 55%. Greatest core loss occurred in sandstones and gravel where core recovery was consistently low regardless of the method used. Drill cuttings were usually obtained from the sandstones, but generally the

exact nature of the material and stratigraphic boundaries were in doubt. Core recovery in clays was usually good and towards the end of the programme recovery in clays and siltstones was nearly 100%.

Plate 30 shows two diamond drill rigs surrounded by a sea of mud during the 1962 monsoon season.

Well Permeameters (fig. 26). Well permeameter tests were made at various locations to ascertain the permeability of near surface bedrock. They were carried out following the procedures given in the United States Bureau of Reclamation Manual (1963).

Borehole Pump-out Tests (fig. 26). Nine borehole pump-out tests were performed to ascertain bedrock permeabilities below the water table at depths greater than tested by the well permeameters. They were performed by continuously recording the rising water level in a borehole section that had been pumped dry. Both the boreholes and well permeameters gave similar results; for sandstones of the order of $K = 10^{-4}$ cms/sec, and silts/clays $K = 10^{-6}$ cms/sec.

Field Tests

(i) Permeability tests as described above;

(ii) Disintegration tests on clays and sandstones. Approximately 1 kilo. samples of fresh clay or sandstones were immersed in water and the time taken for it to disintegrate and nature of the disintegration was recorded;

(iii) 'Liquefaction tests' on sandstones, small pits approx. 1' cube dug in sandstone at the elevation of water table and the collapse of the pit sides observed.

(b) Bedrock in the Abutments

Trenches (figs. 31, 32 and 33). Several north-south trenches were proposed for the abutments to obtain a detailed continuous log of the strata. However, the rough terrain limited the number of completed trenches to seven (plates 13 and 14). No samples were taken. Three trenches, R-S, T-U and V-X were located on the right abutment and four, A-X, A^1-X^1, B-X and C-X on the left abutment.

All the trenches were located in the sides of nullahs and were excavated by D-7 bulldozers.

Adits (fig. 26). Adit JA-16 and -17 were dug in the right abutment to investigate cracks. Their construction was the same as for adits in the valley floor.

Field Tests. Disintegration tests on clays and sands were performed. Times on approximately 1 kilo. lumps of clay for complete disintegration varied between 2 mins. and 48 hours. Time was not recorded after 48 hours.

RESULTS OF FIELDWORK

Results from the field were presented under the following headings:

a) Trenches

b) Boreholes

c) Geology;

(i) Maps,

(ii) Cross Sections,

(iii) Structure

In general the study of trenches, adits and outcrops gave most of the data additional to the site exploration information. The boreholes were disappointing because of low core recovery, due more to the nature of the bedrock, than to deficiencies in equipment and procedure. A slight improvement in core recovery was obtained as experience was gained by the drillers.

a) Trenches

Examples of the summaries of both estimated and measured liquid limit values obtained for trench samples are given on figs. 27, 28, 29 and 30, together with details of the exposed geology. Tested and estimated percentages of material type were made for each trench and are given in summary on Table III.

Two basic methods of sample location were used. In two trenches (DE and JK) which were cleaned up cliff face exposures (plate 22), samples were taken from vertical scrapes, while from the remaining trenches the samples were taken along a roughly horizontal line. In order to achieve uniformity of presentation of the test results, the vertical scrape results were projected down dip onto a theoretical horizontal sampling line. In this way results from all the trenches could be inspected on the same basis.

Inspection of the trenches indicated shear zones and thin zones of high liquid limit existed parallel to the bedding. These zones were later found at depth from drillhole cores. In addition shear zones were traced east/west along the strike of the bedrock in trench BD.

In computing the percentages of the so called 'high liquid limit' clay*, the thickness of such clays was scaled off the drawings and given as a cumulative thickness on Table III. The relative percentages of material types were obtained from this.

b) Boreholes

Layout of boreholes is shown on figs. 26, 31, 32 and 33. Geological sections with liquid limit results were produced to give a general picture of the relation of liquid limit to sub-surface geology.

The holes were concentrated in the valley floor upstream from the proposed dam axis in areas of potential upstream slip failure. They penetrated to depths intercepting potential critical failure planes through the foundation. Liquid limit results from these depths are shown on the sections; they show a similar distribution pattern to the liquid limits of the trenches. Drillers reported that it was easier to recover in the core barrel the lower liquid limit clays than the higher. Therefore, weak clays, shear zones and high liquid limit clays may be missing on the sections. Nevertheless, some high liquid limit material was recovered and sheared clay was noted occasionally in the cores. It is considered from evidence seen on the walls of the trenches and from the cores, that zones of high liquid limit were a bedding phenomenon extending down dip with the beds, and not just a surface

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* Any clay with a liquid limit of over 55% (not necessarily all shear zones). An arbitrary definition made in the Engineer's London office†.

weathering phenomenon. The sections have been labelled 'diagrammatic' because much of the geology was interpolated where gaps in the core occurred.

Fig. 34 shows a special series of holes, both vertical and inclined to investigate a zone of high liquid limit clay found in the area during the sampling of Pit J-223 (see fig. 26 and Fookes[2] 1963). Section No. 23 - 23' shows boreholes in conjunction with trench F^1 - G^1, and boreholes in Section 24 - 24' were initially laid out with trench F - G which was abandoned because of the difficulty of maintaining clean sections of the trench for inspection. This trench was damaged by monsoon rains and by the high water table. Boreholes shown on Section 25 - 25' were in the nullah floor where trenching was impractical. Boreholes shown on Section 26 - 26' were in conjunction with trench ABC and A^1 - B^1.

c) Geology

(i) Maps. Three geological sheets on 1" to 200' scale were produced to cover the abutments and main dam; viz. right abutment fig. 31 (sheet 1), main dam (the valley section), fig. 32 (sheet 2) and left abutment fig. 33 (sheet 3). Three further sheets (see Fookes[2] 1963) cover the same area and show location of boreholes, pits and trenches used to supplement the mapping. These are not shown here.

The Main Dam (the valley section) geology is also shown on a geotechnical map at a 1" to 100' scale fig. 26. Alluvium maps in the region of the Main Dam and the alluvial areas upstream and downstream of the Main Dam are given in Fookes[2] (1963).

The bulk of the mapping was carried out under the supervision of Dr. C. Willis of Harzint* (whose services were loaned to Binnie & Partners) 1961 to 1962 on a 1" to 200' scale using a plane table and telescopic alidade. The topography was obtained from Hunting Aero Surveys' maps and it is considered that 85% of the topographic contours on the final geological maps have an error of less than ½ a contour interval. The geological mapswere supplemented during the site investigation by the boreholes, pits, trenches just described and further mapping in a few small areas. This work resulted in changes and additions to the original mapping on both abutments; most additions were made in the vicinity of the trenches. In the valley section completely new detail was added for the bedrock below the alluvium. All changes are shown on the final maps, figs. 31, 32 and 33.

The original map prepared under the direction of Dr. Willis made distinction between sandstones, gravel and clays and only beds thicker than 5' were mapped. Much of the abutments are covered with slope wash, so that the maps even with the addition of trench and borehole information are not complete in every detail. Sandstones and gravel beds were usually fairly well exposed as they formed ridges between which the slope wash accumulated. It was assumed for the purposes of mapping that the material between sandstone ridges was clay, and this was generally borne out by observations in trenches and drill cores.

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* Harza International Co. Inc., Chicago.

The beds 'lens-out' or are subject to facies changes which are shown on the maps where there was definite field evidence.

The bedrock below the alluvium in the valley was interpolated from trenches and boreholes. As some of the interpolation was in a strike direction over distances of several hundred feet the accuracy suffers accordingly. It was known from abutment mapping that with facies changes, 'lensing-out', thickening and thinning of beds; correlation across the valley would be difficult, and errors of ± 20' could exist on the sub-alluvium bedrock map. A more accurate bedrock map could only have been obtained by stripping the alluvium.

(ii) Sections (located in plan on figs. 31, 32 and 33). Geological sections 1 - 1' to 21 - 21' were drawn up using the information shown on 1" to 200' geological maps. The limitations of the geological maps also apply to the sections. The dip of the bedrock was obtained directly from the map and occasionally checked in the field where exposure permitted. As some of the attitudes shown on the map were found to be in error, additional dips for the sections were obtained from trenches, further field observation, from consideration of the local fold pattern and from three point measurement of beds in boreholes. Some of the dips shown on the maps may stillbe in error as they could be dips of lenses or incorrect field measurement due to the difficulty of

finding the strike from the limited number of outcrops.

(iii) Structure. The damsite lies on the southern limb of the Mirpur syncline at the south-eastern end of the Mirpur basin. The abutments are formed by strike ridges running approximately parallel to the regional strike of the strata. At the extreme western limit of the right abutment the strike is west-north-west/east-south-east. It gradually swings to east-west along the abutment until at the centre of the damsite it is about parallel to the dam axis. In the left abutment the strike maintains this direction until the eastern limit of the abutment where it swings west-south-west/east-north-east.

The dip is northerly and dips varying from 20° to 55° from the damsite or abutments have been recorded. It is fairly constant along strike directions but varies considerably in dip directions owing to gentle flexures in the flanks of the main fold. Lensing of beds and minor slumping further complicate the structure. Three minor reverse faults are recorded.

Bedrock

The beds are Upper Siwalik in age and of freshwater origin; a fuller geological description is given in Part I.

Sandy Silts/Siltstones. These are firm to hard, yellow brown in colour and grade to fine sandstone, or to clayey silt.

Clayey silts. These are firm to hard, brown to dark brown and sometimes maroon in colour. They grade either to silty clay or sandy silt.

Clays. The majority of clays are slightly silty. They are on average weaker in terms of effective shear strength, than those of Mangla. They are generally firm to hard, brown to dark brown and occasionally red brown, overconsolidated and fissured. No shales were found.

Tectonic Structures in the Clays

The beds are folded, and are accompanied by minor thrust faulting, also shear zones along bedding planes which are common and occur every 20 to 30'. These shear zones do not form open cracks although they may be opened subsequently near the ground surface. Thrust (shear) joints have developed with folding. These joints generally form a diamond pattern in section; this pattern is only seen clearly in the clays but does occur in some sandstones.

Open Fissures and Cracks

The fissured clays which were extensively examined in adits both in the abutments and valley floor, contained cracks produced by recent erosion and weathering phenomena. At the time of the investigation there was concern on the possibility of reservoir leakage through cracks. Stress release near the ground surface, penetration of roots and chemical changes produce cracks, parallel and normal to the ground surface both in the sandstone and clays. A crazed pattern of cracks is strongly developed on the drying of clays and is weakly developed in sandstones. These open cracks and joints do not normally occur deeper than 15' below the ground surface though roots

have been observed penetrating them to ca 50' depth. The opening of surface cracks occurs every few feet; no surface cracks more than 1" wide were observed. Borehole permeability tests have borne out the observation that cracks are tight below ca. 15' in the abutments and valleys.

Small vertical neptunian (clastic) dykes up to 1' wide and generally infilled with buff or pink silt or silty sand were found in trenches R - S and ABC. Longest dyke found was traced laterally for 53' and vertically for 19'.

Engineering Geology of the Foundations

By the end of the investigation* the clay bedrock forming the foundations of the valley and abutments was shown to contain zones and layers of materials which were weaker than the 'average' clay bedrock, and of lower shear strength than that originally assumed for the design of the embankment slopes (at the end of the site exploration 1961). It was concluded they were attributed to three causes:

(i) Bedded layers or zones of clay of high liquid limit;

(ii) Zones of 'sheared' clay, which may or may not be of high liquid limit. These zones were parallel or nearly parallel to the bedding.

(iii) Fissures in clay.

The effect of each of these phenomena on the overall stability of the dam foundations as considered at the end of the investigation, is discussed following:

* Spring 1963.

The various figures and tables show the distribution of sandstones and clays and some of the trench sections show actual sheared zones. The relative proportion of sandstone and clay/silt was 1 to 3 and is shown in detail on the drawings and Table III.

(i) High Liquid Limit Clays

In this category is clay bedrock of liquid limit above 55%. These clays often have a lower dry density and generally contain a high percentage of clay sized particles. The effective shear strength (in terms of Ø' ult.) is lower than 24°, so areas of high liquid limit clay imply areas of weak clay.

The weak clays are generally found in relatively thin layers, which may, or may not, be continuous over large areas and which lie parallel to bedding planes. The prevailing dip of the beds of the damsite averages about 45° upstream so that failure of the foundations underlying the downstream or upstream slope would mean some portion of the failure plane must cut across the bedding planes. In the case of a downstream failure, the portion of a potential failure surface which rises towards ground level might follow a weak layer parallel to the bedding.

(ii) Sheared Clay *

The same comments as (i) apply as the geometry of the shear zones is similar to the high liquid limit zones. They occur in relatively thin layers of up to 3' width and parallel to bedding. Shear zones were noted every

* Findings from this and subsequent investigation are discussed in detail on pages 146 and 153.

20 - 30' in clay beds and some were traced in detail for at least 300' along the strike of the bedding. One exceptional zone was found which apparently cut across the bedding planes and dipped downstream. This 'cross-cutting' shear zone was subsequently found to be a local near-surface feature which when traced in depth was shown to be a part of a normal bedding shear zone.

(iii) Fissures in Clay*

Fissures occur in the clay bedrock. Some form patterns parallel to bedding, although a large number of smaller fissures are randomly orientated. Some of the major fissures are 'joints' and are continuous over large areas; the larger fissures constitute further potential planes of weakness.

It was found that clay scraped from the outer skin of a fissure surface had a higher liquid limit than that of the parent clay bedrock. Since the higher liquid limit clays have lower shear strength, this could mean that fissure surfaces represent planes of weakness.

LABORATORY TESTS‡

History. Laboratory tests on the samples from the initial exploration to determine effective shear permeameters for Jari Dammwere begun in January 1961. A complete programme

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* Fissure orientation studies made at Jari during the site investigation are discussed in Fookes (1965) included in the end pocket and on page 140.

of tests, including dry density, moisture content, Atterberg limits and grading, and a number of unconfined compression tests on fresh samples could not be finished at the time due to lack of suitable apparatus. However, density and moisture content measurements were made on site, on fresh samples from boreholes, to a maximum depth of 260'.

The dry densities were found to be about 120 to 130 lb/cu.ft. generally; and occasionally as high as 136 lb/cu.ft. or as low as 105 lb/cu.ft.

Between February and April 1961 an initial set of twelve triaxial samples from clay bedrock cores were tested‡ using standardised techniques for saturation, consolidation and shearing under fully drained conditions. A subsequent set of five core samples were chosen from apparently softer than average bedrock.

From samples which had low dry densities a further fourteen samples were tested. The results showed that these clays had liquid limits higher than average.

The results of the thirty-one tests are given in Table IV; the range of measured values are summarised below:

	Liquid limit Range	Ø'(ult) Values Range	Mean
First 17 samples 1961	34 - 57%	20 - 42°	31°
Later 14 low dry density samples 1961	45 - 65%	12 - 25°	18°

When the strengths (Ø' (ult)) were plotted graphically against liquid limit (fig. 26), it became evident:

(i) Below liquid limit 50% there was considerable scatter in $\emptyset'$ (ult) values which were, however, consistently higher than 28°.

(ii) Above liquid limit 50% the range of $\emptyset'$ (ult) values narrowed considerably to within closer limits.

(iii) These values showed a marked fall in $\emptyset'$ (ult) to between 20° and 16° for clay of liquid limit higher than 60%.

The results seemed to indicate that clay of higher liquid limit could have even lower values of $\emptyset'$ (ult) though this was not shown at that time.

In the site investigation programme (1962-63) it was, therefore, necessary to continue and intensify the triaxial testing with emphasis on clays of liquid limit greater than 60% and to determine the highest liquid limits (and possibly the lower limit of $\emptyset'$ (ult)) for clay bedrock on the whole damsite.

The earlier testing had been carried out on core samples from boreholes. Samples were now taken from pits, adits, wells and trenches (both from above and below water table) from which reliably undisturbed specimens could be trimmed by hand, as it was considered possible that the process of drilling may have disturbed the material sufficiently to affect its strength properties and also weak clay may not have been brought up in the core barrel.

Laboratory testing was extended to include consolidated-drained triaxial tests on remoulded clay samples, i.e. on the triaxial specimens re-compacted to the original density and moisture content. Samples were also reconsolidated to a

higher effective cell pressure after reaching the 'ultimate' condition, and re-sheared; these are referred to as 'reconsolidated' tests.

Attempts were made to trim specimens containing natural fissured surfaces on a potential plane of failure, but only one such sample was successfully trimmed. In addition, one specimen was prepared containing an artificial fissure, i.e. an intact clay specimen was first sliced along a typical failure plane, and the two halves placed in contact when setting up the triaxial cell.

SOIL PROPERTIES

Results obtained from laboratory triaxial tests and associated classification tests on clay samples are summarised in Tables V and VI. On adding the exploratory work (Table IV) some 70 samples in all were tested and 61 values of $\emptyset'$(ult) given. Suspect results have been discarded+. Values of $\emptyset'$ (peak) are also tabulated and for samples tested from April 1962 onwards (39 samples), together with values of $\emptyset'$ for reconsolidated and remoulded tests.

Sandstone test results are given in Appendix II.

Discussion of Laboratory Results and Tables

The discussion is based on Tables IV, V and VI and on the graphical relationships derived from the results given in them; some conclusions were modified later when more work was done in the foundation investigation stage. Nevertheless the ideas prevalent at the time are given here so that the development of the investigation can be followed.

The most significant change made in later correlations of strength and index property was by plotting $\emptyset'$ with a correction to make $c' = 0$. In the following $\emptyset'$ is plotted without correction.

(i) Strength versus Liquid Limit (see figs. 25 and 35)

In these diagrams values of $\emptyset'$ (ultimate) and $\emptyset'$ (remoulded) are plotted against liquid limit (average for the whole triaxial specimen). No correction is made for c'. Five different types of samples are indicated:

Borehole samples (trimmed from NX cores);

Adit samples (trimmed by hand from block samples taken from adits);

Well samples (from hand dug wells, below water table);

Open pit samples (blocks from open pits, above water table);

Shear zone samples (trimmed from small blocks taken from the wall of Trench HI).

The graph suggests a definite relationship between undisturbed $\emptyset'$ ultimate and liquid limit even though there is appreciable scatter. The heavy broken lines indicate the envelope bounding the majority of accepted results. The greatest scatter occurs below liquid limit 52%, but here the majority of $\emptyset'$ values exceed 20°. Below liquid limit 45%, $\emptyset'$ values generally exceed 25°. Between liquid limit 50% and 70% the $\emptyset'$ values decrease from an average of 23° to about 19°. The range of values also

narrows to 1° approximately either side of the mean. Above liquid limit 70% up to 100%, $\emptyset'$ (with one exception) falls consistently between 17° and 20°.

Results of triaxial tests on remoulded samples are plotted in fig. 35 and the envelope of the majority of results are indicated by the dotted lines and are superimposed as faint continuous lines on fig. 25. They show a trend similar to undisturbed values except that results tend to be slightly lower by 1° or 2°. It is significant that where unusually high or unusually low values of $\emptyset'$ (ult) have been obtained from undisturbed samples, the remoulded result invariably falls within the envelope (indicated by broken lines). Samples showing a higher than average undisturbed strength give a much lower remoulded strength, and those with an unusually low undisturbed strength show an increased strength on remoulding.

It is possible that unusually low undisturbed strengths may be due to small structural weaknesses (fissures or joints) within the material, which were eliminated in the process of remoulding. Abnormally high undisturbed strengths may be due to the presence of a cementing agent, the effect of which is destroyed on remoulding. Small variations in the quantity of calcareous material within the matrix could conceivably affect the cementation of the silty clays to an appreciable extent.

Fig. 25 shows the somewhat lower remoulded strengths of clay from a shear zone in Trench HI. Three of the six remoulded values fall on the lower line, and two of the remainder show reductions of $5\frac{1}{2}^{o}$ and $12\frac{1}{2}^{o}$ from undisturbed to remoulded which are appreciably greater than for most 'unsheared clay' samples. These were the only shear zone samples tested at this time. The graph also shows that the low strengths obtained from pit J223 (figs. 26 and 34) were associated with a zone or bed of high liquid limit clay. Attempts were made to trace the geometry of clay but this was never successfully concluded. It was established by digging a pit that the zone was not related to weathering and therefore must have extended only in a strike direction.

A lot of the fieldwork in preparation for the strength sampling programme consisted of search either by eye or by classification samples, for weak clay. The success of the pits, adits and trenches and the boreholes is clearly shown by the graph (fig. 25). The more or less random selection of specimens from cores (of early 1961) produced a good scatter of results but did not produce the low strengths on which later designs were based. When low strength material was deliberately searched for, firstly by classification tests (low density 1961, and liquid limit 1962/3 and clay fraction 1965) and secondly by eye when experience was gained (1962 and 1965), only then were the low strength materials found. Because of

the possibility of missing this material from core loss in drillholes; pits, trenches and adits were the more successful. In addition, they were cheaper and block samples (less disturbed than cores(?)) and three dimensional logs, could be obtained from them. Their limitations were only on depth, which depended on the water table or the equipment. Deepest trenches were about 10' into bedrock.

The strength test results from Jari covered about 1,000' of the stratigraphical column, and although it was carefully looked for at the time no relation appeared between position in the stratigraphical column and test result.

(ii) Strength versus Dry Density (fig. 36)

Values of Ø' ult. undisturbed are plotted against dry density of the whole triaxial specimen. The scatter of points is so great that there is little to conclude from this graph except that material of low dry density could be expected to have a lower strength than material of high dry density. For this reason, low dry density was abandoned in favour of liquid limit as an indication of strength, early in 1962.

(iii) Clay Fraction versus Liquid Limit (fig. 37)

The clay fraction of the whole triaxial specimen is plotted against mean liquid limit. Superimposed on the graph are lines of equal 'activity values' (defined as the ratio of Plasticity Index % to Clay Fraction %).

It was found from the hundreds of Atterberg tests, that when plotted on the Plasticity Chart, the great majority of points lay just above the 'A' line approximately parallel to it, defined by

$$PI - 0.73 (LL - 15)^*$$

It is from this relationship that the 'activity' lines were plotted.

It can be seen that most of the tested clays have activity values between 0.6 and 0.85, i.e. of 'low activity'. There are, however, a few notable exceptions with 'activities' between 0.85 up to about 1.8. Included in this group are:

4 No. borehole samples of selected 'low density' material;

5 No. samples from Pit J.223 (taken from a unique high liquid limit zone);

1 No. borehole sample from near Pit J-223;

3 No. borehole samples selected on the basis of high liquid limit;

7 No. classification test samples (for comparison with triaxial samples) taken from pit J-223.

The graph illustrates the extent of variation in the Jari clays, and also that unusual clays have been successfully identified and distinguished from the 'normal' clays by inspection.

(iv) Plasticity Chart and Particle Size (fig. 38)

The great majority of material behaving as clay lies between 20 and 65% clay fraction; higher values were

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* (derived by K.H. Head).

recorded but were rare. Nearly all clays on the plasticity chart lay just above the 'A' line. It is interesting to note that the only high liquid limit clays came from block samples not from drill cores, substantiating the suggestion that high liquid limit clays were lost during the drilling.

The portion of the clays just above the 'A' line (mainly clayey silts (inorganic) CL, clays (inorganic) of medium plasticity CI, and clays (inorganic) of high plasticity CH, of Casagrande's classification) occur in a similar position on the chart to glacial clays from Boston, Detroit, Chicago and Canada (Terzaghi 1955). On a casual inspection there would appear no geological relation, but a closer study may prove interesting as the glacial clays were the product of non-marine, cold deposition from particles scoured from a variety of hard rock types. Similarly the Upper Siwaliks were non-marine, cold or cool(?) deposition from particles scoured from a variety of hard rock types. Activities suggest the clays are mainly illitic.

(v) Ratio of Ultimate to Peak Effective Shear Strength

Values of $\frac{\tan \phi' \text{ (ult)}}{\tan \phi' \text{ (peak)}}$ are summarised in Tables IV, V and VI but are not plotted graphically. The relationship appears to be meaningless.

(vi) Ratio of Ultimate to Remoulded Effective Shear Strength

Values of $\frac{\tan \phi' \text{ (ult)}}{\tan \phi' \text{ (peak)}}$ shown in Table VII do not appear to be related to other properties.

If the above values are averaged, the following emerges:

T A B L E VII

	$\frac{\text{Tan } \emptyset' \text{ (u)}}{\text{Tan } \emptyset' \text{ (p)}}$	$\frac{\text{Tan } \emptyset' \text{(u)}}{\text{Tan } \emptyset' \text{(RM)}}$
Total No. of results	55	27
Average for all available results	0.77	1.16
Average for all results excluding shear zone	0.76	1.11
Average of 6 No. shear zone samples	0.92	1.36

This illustrates the greater decline in strength on remoulding for shear zone material; and also that 'sheared' clay has an ultimate strength closer to peak strength than has 'unsheared' clay, which could be expected if the clay has already been subjected to remoulding by a shearing action in situ.

Later work has since shown this paragraph to be erroneous (Foundation Investigation 1965).

Conclusions from 1962/3 Laboratory Tests

(i) Tests on hand trimmed specimens from block samples gave similar strength characteristics to those on core samples for a given type of clay. Although core recovery in clay was good, high liquid limit (weak) clays were probably not recovered by the drilling.

(ii) Almost the same ultimate strength was obtained from a limited number of sliced or fissured samples as from intact clays.

(iii) Reconsolidation and re-shearing gave $\emptyset'$ (ult) values only 1 or 2 degrees lower (in most cases) than undisturbed ultimate values, after applying the appropriate corrections for distortion of the specimen under continued shear.

(iv) In tests on remoulded samples a plastic type of failure occurred without a pronounced peak deviator stress. However, the maximum stress was almost the same or slightly below the ultimate undisturbed value.

(v) Selection of 'weak' material could be made in the field on the basis of inspection (with sufficient experience) on liquid limit result. An approximate correlation between liquid limit and strength was established. No corrections were made for c' in presenting effective strength results.

(vi) Generally Jari clays were of low activity (0.6 - 0.85) though higher (up to 1.6) existed.

JARI
SITE INVESTIGATION 1962-63
SUMMARY OF MATERIAL TYPES & HIGH LIQUID LIMIT CLAYS FROM THE TRENCHES

Exploratory Trench	Length of trench exposed ft.	Total Sandstone in trench ft.	Total Sandstone in trench %	Total Silt in trench ft.	Total Silt in trench %	Total Clay in trench ft.	Total Clay in trench %	Clay/Silt tested & estimated ft.	Clay/Silt tested & estimated %	Clay with LL above 55% ft.	Liquid limit above 55% Trench Length %	Liquid limit above 55% Clay/Silt %	Liquid limit above 55% Clay/Silt tested %
A - B	850	220	25.9	357	42.0	273	32.1	450	71.5	66.5	7.8	10.5	14.8
A_1-B_1	300	66	22.1	171	57.0	63	20.9	Not sampled					
B - C	220	43	19.5	143	65.0	34	15.5	139	78.5	15.0	6.8	8.5	10.8
D - E	637	121	19.0	226	35.4	290	45.6	80	15.5	18.8	3.0	3.6	23.5
F_1-G_1	695	204	29.4	285	41.0	206	29.6	364	74.0	41.0	5.9	8.4	11.3
F_2-G_2	185	67	36.3*	86	46.5	32	17.3	111	94.0	24.0	13.0	20.3	21.6
F_3-G_3	230	70	30.4*	123	53.5	37	16.1	37	23.1	34.0	14.8	21.2	92.0
H - I	814	219	27.0**	373	45.9	222	27.1	245	41.2	108.0	13.3	17.4	42.2
J - K	437	90	20.5	161	36.8	186	42.7	147	42.5	14.9	3.4	4.3	10.1
P - Q	303	64	21.1	160	53.0	79	25.9	74	31.0	6.0	2.0	2.5	8.0

NOTES:- * = Includes approx 5% gravel
** = Includes approx 1% gravel

TABLE III.

JARI
SITE EXPLORATION 1961
SUMMARY OF TRIAXIAL RESULTS ON CLAY BEDROCK.

B.H./Pit No.	Sample No.	Depth ft-in.	Dry density lb/cu.ft.	L L %	Clay Fraction %
J 97	7918 B	51-8	121	49.1	44
J 155	7760 A	46-6	126	42.0	25
	B	46-6	125	34.3	24
	C	46-6	124	39.5	26
J 112	7711 A	191-3	130	43.0	30
	B	191-3	123	46.4	29
J 155	7909 A	125-5	128	37.7	18
	B	125-5	125	40.9	28
	C	125-5	126	35.2	17
J 111	7759 A	107-8	125	46.0	29
	C	107-8	122	51.3	34
	7761 A	115-10	128	55.2	37

TABLE IV (i)
(Continued on IV (ii))

TABLE IV (ii)
(Continued from IV (i))

Sample No.	ø' 1 Peak	ø' 2 Ult.	ø' 3 Reconsolidation.	ø' 4 Remoulded	tan ø' (Ult) / tan ø' (peak)	tan ø' (Ult) / tan ø' (Rem)	Remarks
7918 B	30.2°	-	Reconsolidated and remoulded tests not carried out.				Borehole Samples (NX cores)
7760 A	42.1°	38.7°			.887		
B	36.6°	(34.4°)			-		
C	34°	34°			1.0		First Set
7711 A	57.3°	42.6°			.922		
B	44.1°	34.4°			.680		Feb-Apr 1961
7909 A	37.2°	36.5°			.975		
B	30.3°	27.7°			.900		
C	39.2°	33.6°			.813		
7759 A	49.7°	34.0°			.572		
C	32.3°	21.2°			.613		
7761 A	25.0°	19.4°			.755		

B.H./Pit No.	Sample No.	Depth ft-in.	Dry density lb/cu.ft.	L L %	Clay Fraction %
J 194	8373 A	262-8	122	59.5	45
J 131 A	9007 A	85-11	122	56.7	45
J 131 A	9014 A	138-0	117	50.7	39
J 195	8268 A	218-0	126	41.1	29
	B	218-0	130	38.2	26
J 88	8216 A	174-5	114	50.6	21
	B	174-5	110	45.1	30
J 105	8435 A	116-8	112	64.4	43
J 88	8222 A	223-0	107	52.8	34
J 87	8241 A	197-2	115	-	28
	B	198-2	116	59.8	34
J 105	8433 A	103-2	109	52.5	29
J 100	11467 A	183-10	116	63.1	56
J 87	8233 A	138-7	115	54.2	-
J 100	11467 B	183-10	117	62.5	45
	10149 B	177-10	110	59.7	39
J 118	10136 A	114-6	120	52.1	36
	10136 B	115-0	115	49.2	-
J 169	8389	182-8	113	50.7	31

TABLE IV (iii)
(Continued on IV (iv))

TABLE IV (iv)
(Continued from IV (iii))

Sample No.	ø' 1 Peak	ø' 2 Ult.	ø' 3 Reconsolidation.	ø' 4 Remoulded	tan ø' (Ult) / tan ø' (Peak)	tan ø' (Ult) / tan ø' (Rem)	Remarks
8373 A	-	-	Reconsolidated and remoulded tests not carried out.		-		Second Set Apr-May 1961
9007 A	-	-			-		
9014 A	26.5°	21.6°			.792		
8268 A	33°	30.3°			.890		
B	50.4°	32.0°			.299		
8216 A	26°	(21.9°)			.824		Third Set (low dry densities)
B	29°	(27.4°)			.936		
8435 A	20°	-			-		
8222 A	27°	18.8°			.667		
8241 A	33°	23.9°			.683		May-Sept 1961
B	28°	15.5°			.521		
8433 A	37°	24.8°			.613		
11467 A	26°	18.9°			.700		
8233 A	29°	17.8°			.580		
11467 B	15.3°	-			.612		Fourth Set (low dry densities)
10149 B	27.4°	17.6°					
10136 A	35°	(29.5°)			.810		
10136 B	23.2°	19.1°			.807		
8389	36.2°	20.6°			.514		Sept-Dec 1961

Average of 24 results = .723

Total 31 tests in 1961.

JARI

SITE INVESTIGATION 1962-63

SUMMARY OF TRIAXIAL RESULTS ON CLAY BEDROCK

B.H./Pit No.	Sample No.	Depth ft-in.	Dry Density lb/cu.ft.	L L %	Clay %
J 156	10051 B	110-6	114	64.6	55
JA 4	10211 A (1)	28-0	134	81.4	59
	10211 A (2)		136	67.2	63
JA 4	10211 B (1)		127	60.0	57
	10211 B (2)		125	74.0	-
JW 2	0916 (1)	38-6	115	-	
	(2)		108	55.9	42
	(3)		126	52.0	43
	(4)		122	60.1	53
	(5)		121	57.0	51
J 223	0919B (1)	11-5	118	50.1	27.5
J 223	0919B (2)		125	89.4	50
J 223	1258 (D)	9-3	113	88.7	49.5
J 223	1258 (E)		111	74.7	-
J 223	1258 (F)		119	87.7	29
J 223	1260 E	10-10	114	99.8	52
"	0919B (3)	11-5	122	93.9	42
"	0919B (4)	11-5	119	97.0	-
"	1366 A	17-8	115	44.9	32
"	1366 B	17-8	118	46.1	36
"	1366 C	17-8	116	52.3	40

TABLE V (i)

(Continued on V (ii))

TABLE V (ii)
(Continued from V (i))

Sample No.	ϕ' 1 Peak	ϕ' 2 Ult.	ϕ' 3 Reconsolidation.	ϕ' 4 Remoulded	$\frac{\tan \phi' \text{ (ult)}}{\tan \phi' \text{(peak)}}$	$\frac{\tan \phi' \text{ (ult)}}{\tan \phi' \text{ (Rem)}}$ ("Sensitivity")	Remarks
10051 B	21.6°	20.8°	-	21.6°	.960	.96	Special investigation of high LL clays, March-Sept 1962
10211 A (1)	27.0°	17.3°	-	14.7°	.610	1.18	
10211 A (2)	26.4°	18.8°	18.0°	17.2°	.685	1.10	
10211 B (1)	33.5°	23.0°	-	25.5°	.640	0.89	Block samples from Adit (except 10051)
10211 B (2)	24.8°	-	-	-	-	-	
0916 (1)	28.7°	22.5°	23.7°	-	.758	-	Block samples from Well
(2)	42.7°	32.0°	23.9°	22.8°	.702	1.49	
(3)	-	36.0°	-	31.0°	-	1.21	
(4)	47.4°	34.6°	22.5°	22.8°	.636	1.64	
(5)	33.6°	21.5°	19.1°	19.6°	.593	1.11	
0909 B (1)	36°	33.4°	27.4°	28.7°	.908	1.20	Block samples from Open Pit
0909 B (2)	23°	19.7°	18°	18.2°	.945	1.09	
1258 (D)	27.1°	20.3°	18.2°	18.3°	.723	1.12	
1258 (E)	21.4°	17.8°	18.9°	16.5°	.820	1.08	
1258 (F)	24.0°	18.0°	15.6°	16.5°	.730	1.10	
1260 E	24°	17.6°	17.3°	17.2°	.712	1.02	
0919 B (3)	26.6°	20.3°	16.8°	15.5°	.738	1.34	
0919 B (4)	21.7°	13.5°	17.4°	17.2°	.603	0.78	
1366 A	29.3°	25.9°	23.2°	-	.865	-	
1366 B	25°	23.8°	23.0°	-	.946	-	
1366 C	21.2°	-	-	-	-	-	
Average from 18 samples =					0.748	1.14	

JARI

SITE INVESTIGATION 1962-63

SUMMARY OF TRIAXIAL RESULTS ON CLAY BEDROCK.

B.H./Pit No	Sample No.	Depth ft-in.	Dry Density lb/cu.ft.	L L %	Clay %
J 223 BC	42441	84-5	119	65.5	30
J 235	30613	76-4	114	65.9	56
"	30614	80-1	122	63.8	50
J 237	34360	41-0	118	57.8	24
J 239	34316	48-10	122	49.6	27
"	34317	51-7	123	50.0	42
J 240	30653	35-4	119	63.5	48
"	30658	49-2	111	59.4	41
"	30662	66-8	119	52.5	40
J 256	42326	60-6	116	68.7	25
Trench HI.	44673	-	111	76.0	56
"	44675 (Sheer	-	113	73.1	59
"	44677 A Zone)	-	119	75.9	58
"	44677 B	-	115	68.4	55
"	44678 A	-	116	72.0	51
"	44678 B	-	112	74.9	58
Trench HI.	44679	-	119	68.4	50
	44680	-	112	68.6	57

TABLE VI (i)

(Continued on VI (ii))

TABLE VI (ii)
(Continued from VI (i))

Sample No.	Ø' Peak	Ø' Ult.	Ø' Reconsolidation	Ø' Remoulded	tan Ø' (Ult) / tan Ø' (Peak)	Tan Ø' (Ult) / tan Ø' (Rem) ("Sensitivity")	Remarks
42441	-	-	19°	16.5°	-	-	1962 (continued)
30613	21.4°	21.9°	23.3°	18.8°	(1.02)	1.18	
30614	21.5°	20.3°	-	18.9°	.94	1.08	Borehole Samples (NX cores)
34360	26°	-	19.1°	-	-	-	
34316	37.8°	16.5°	23.3°	23.0°	0.38	0.70	
34317	24.7°	23.7°	21.2°	-	0.95	-	
30653	25°	21.5°	21.3°	18.2°	0.845	1.20	
30658	22.3°	20.2°	20.0°	-	.898	-	
30662	21.1°	16.5°	17.7°	-	.767	-	
42326	22.8°	21.5°	14.9°	19.3°	.938	1.19	
44673	23°	22°	20½°	16½°	.953	1.37	Block samples from sheared clay zone exposed in Trench HI. Oct-Nov 1962.
44675(Shear	19°	17½°	17°	15°	.915	1.17	
44677 A zone)	-	15½°	16½°	15°	-	1.03	
44677 B	21°	20°	20°	15½°	.948	1.31	
44678 A	22½°	20°	18½°	19°	.878	1.06	
44678 B	33°	31°	26½°	18½°	.925	1.79	
44679	14.6°	14.6°	14.2°	-	(1.0)		Tube Samples from same shear zone tested March 1963
44680	21.2°	21.5°	15.8°	-	(1.0)		
Average from 13 samples (179-260)					0.866	1.19	
Average from 6 shear zone samples (250-260)					0.924	1.36	

PLATE No. 28 July 1962

Bulldozer trench ABC Jari, panoramic view looking east, the middle terrace alluvium overlying the bedrock is clearly shown on both photographs and on the lower photograph the 4" cross section, continuous sampling groove (arrowed), in the clay and silt bed stratigraphically below the $alpha_2$ sandstone. The shear zone by the red cross in the lower photograph was the first found at Jari and was traced (where exposure permitted) from its original exposure in adit JA 5 (near Kakra).

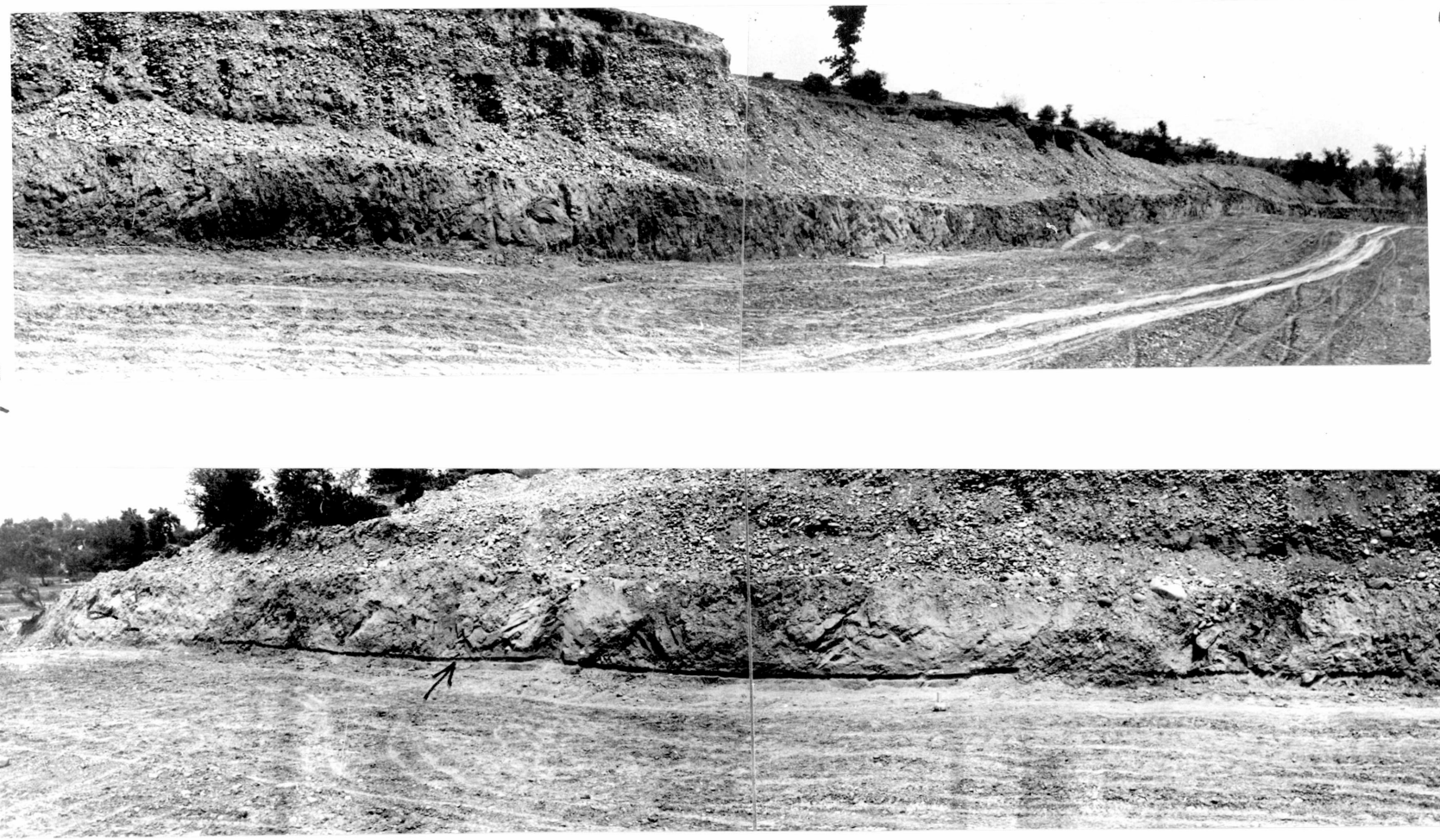

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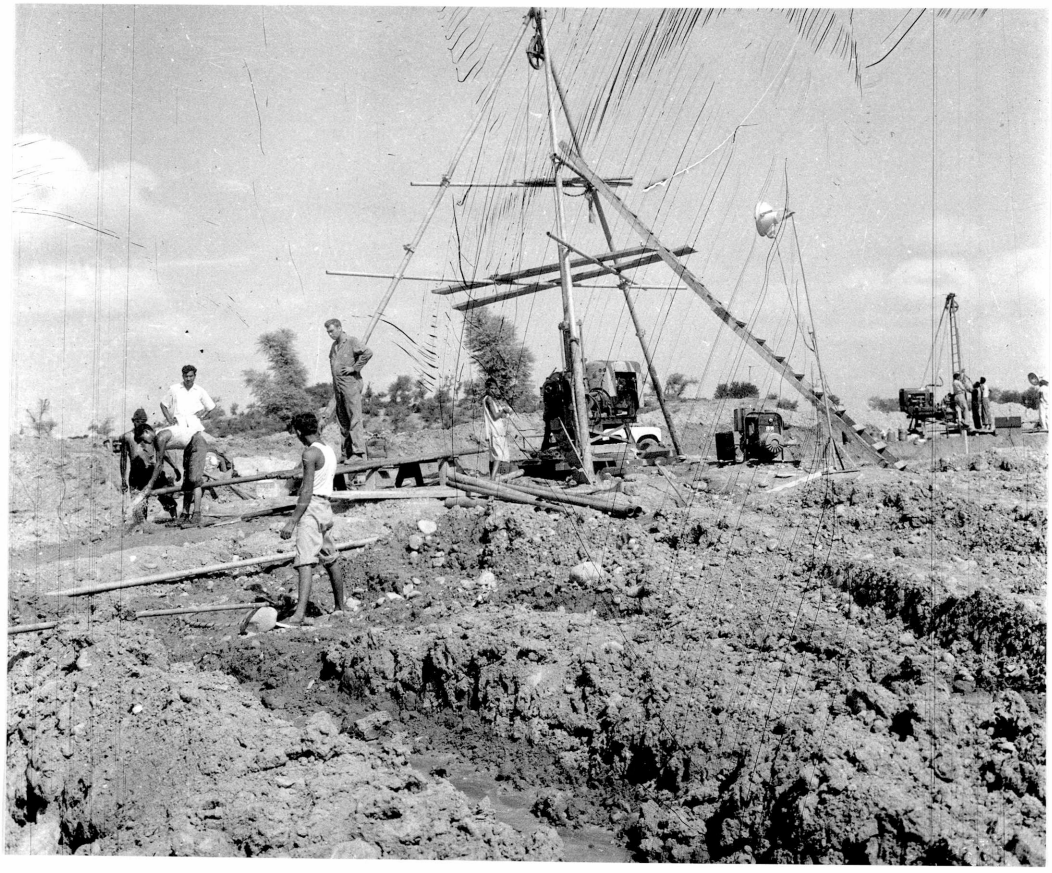
PLATE No. 29 August 1962

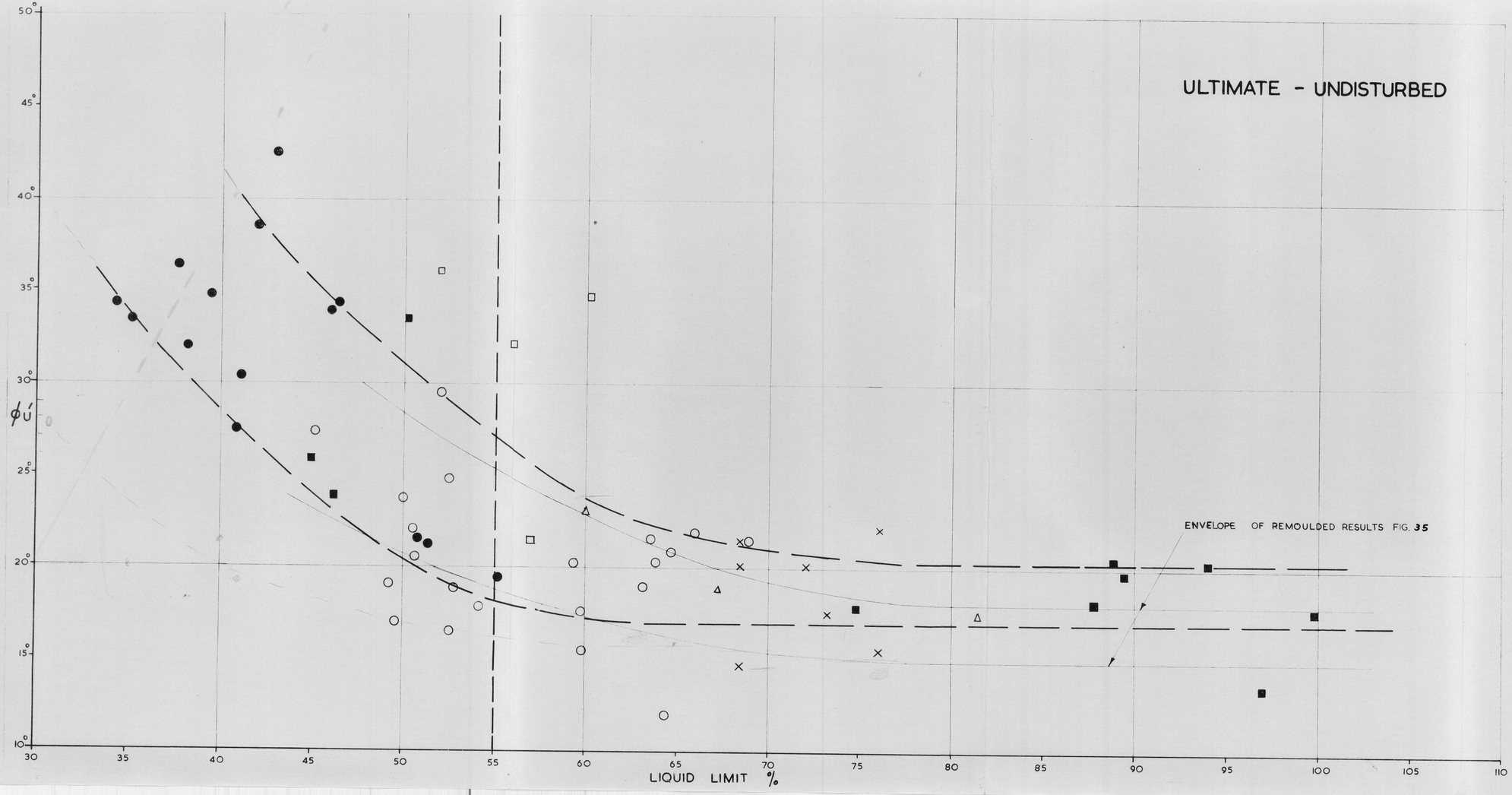
A B32 backhoe digging part of trench HI during the Jari site investigation. The logging and sampling teams on the side of the trench are waiting for the digger to reach bedrock beneath the lower terrace alluvium before commencing; water entered this trench shortly after the photograph was taken and it collapsed, delaying the work for several days. The junior geologist (in the check shirt) was trapped by the trench collapse; he was fortunately rescued but had to leave his boots stuck in the debris. It is believed they now form part of the upstream shoulder foundations of the dam.



PLATE No. 30 August 1962

Two Chicago Pneumatic CP8 diamond drill rigs in muddy conditions during the monsoon, lower terrace alluvium Jari site investigation. The light was fitted for night work. Rigs were skid mounted with a temporary tripod for hauling the drill string, later, rigs were usually truck mounted.





LEGEND

CORE SAMPLES FORM BOREHOLES :—

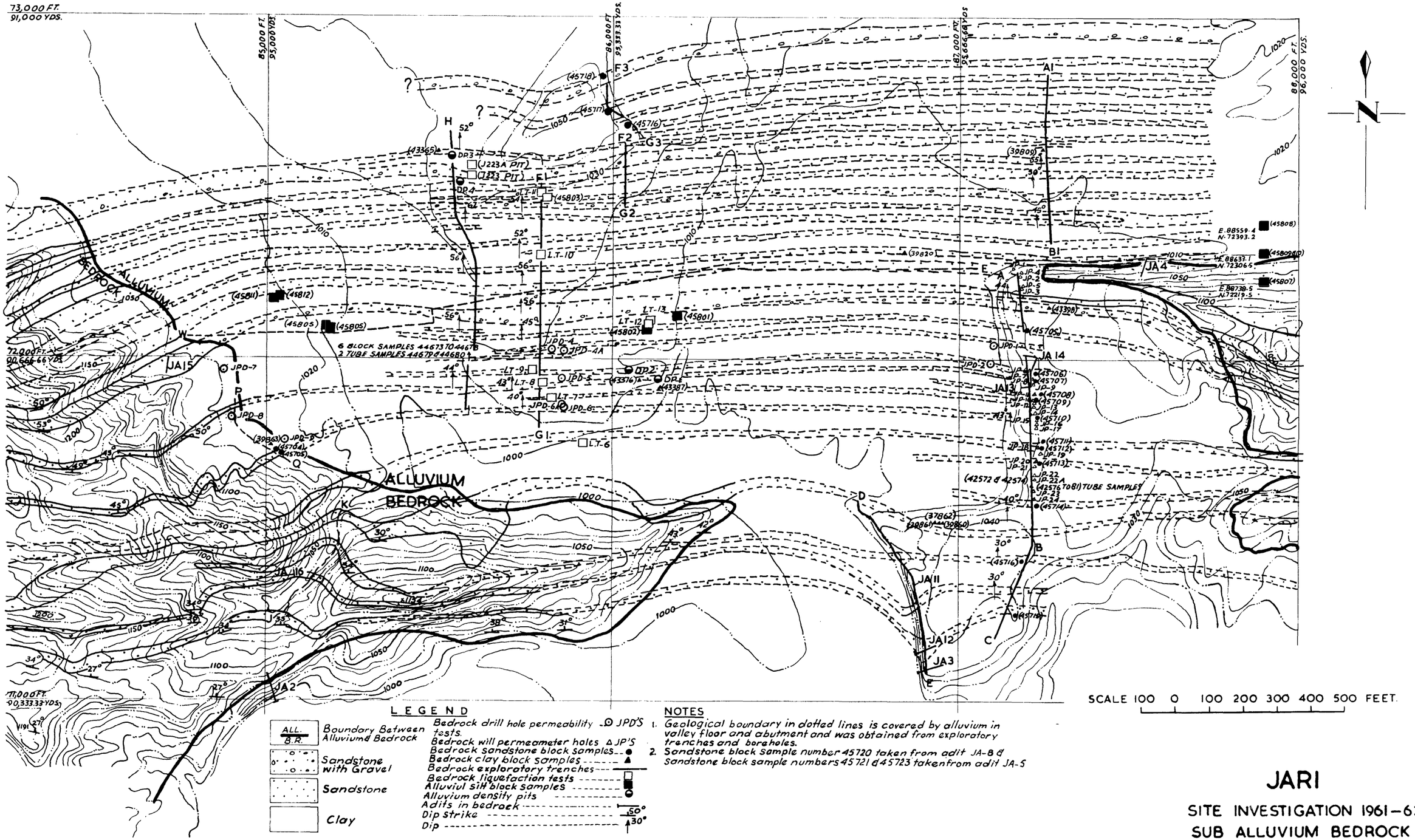
- EARLY 1961 ●
- 1961–62 (LOW DENSITY) ○

BLOCK SAMPLES FORM :—

- ADITS △
- WELL (BELOW WATER TABLE) □
- OPEN PIT J–223 ■
- TRENCH (SHEAR ZONE) ×

JARI

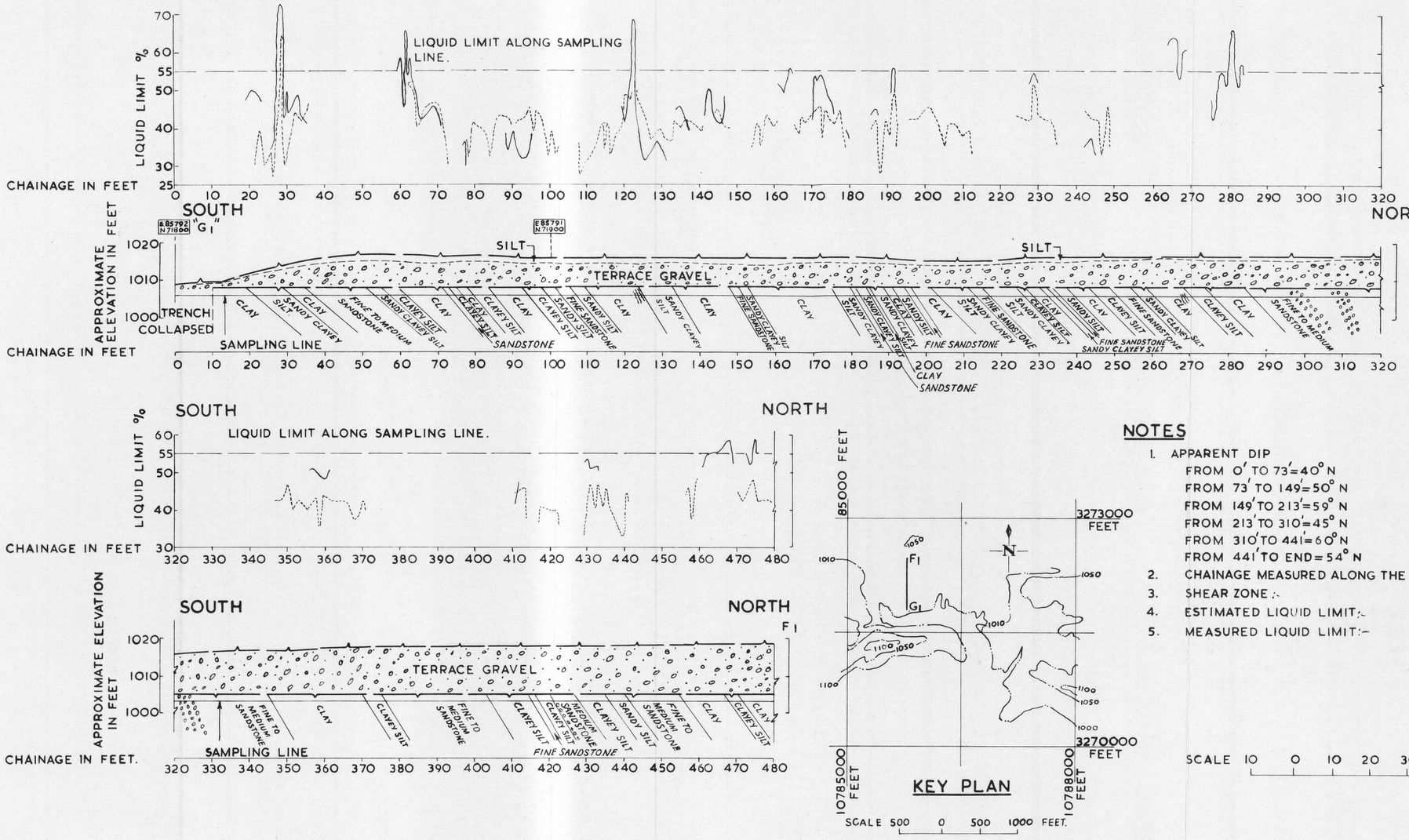
SITE INVESTIGATION 1961–63
SHEAR STRENGTH (ULTIMATE)
VS LIQUID LIMIT
FIG. 25.



JARI

SITE INVESTIGATION 1961–63
SUB ALLUVIUM BEDROCK
GEOLOGY

FIG. 26.



NOTES

1. APPARENT DIP
   - FROM 0′ TO 73′ = 40° N
   - FROM 73′ TO 149′ = 50° N
   - FROM 149′ TO 213′ = 59° N
   - FROM 213′ TO 310′ = 45° N
   - FROM 310′ TO 441′ = 60° N
   - FROM 441′ TO END = 54° N
2. CHAINAGE MEASURED ALONG THE SAMPLING LINE
3. SHEAR ZONE :-
4. ESTIMATED LIQUID LIMIT:-
5. MEASURED LIQUID LIMIT:-

SCALE 10 0 10 20 30 40 50 FEET

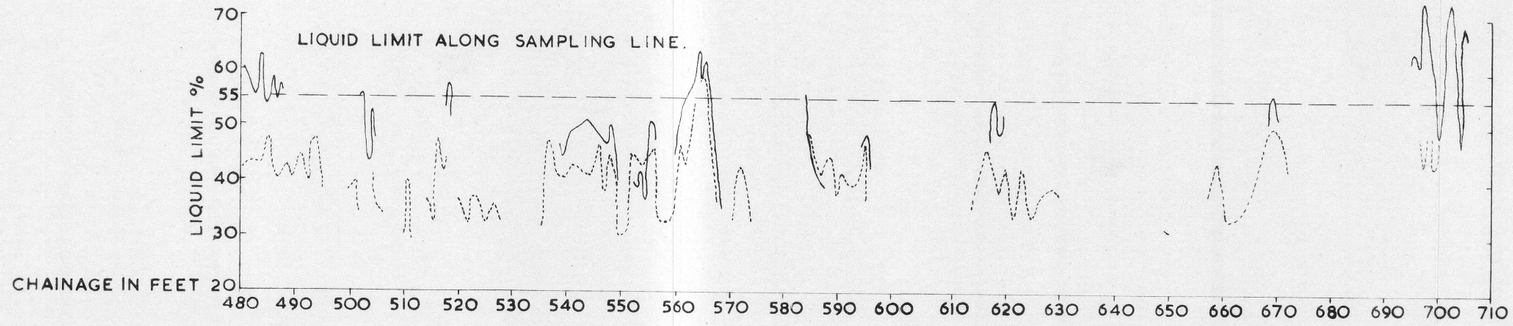
JARI

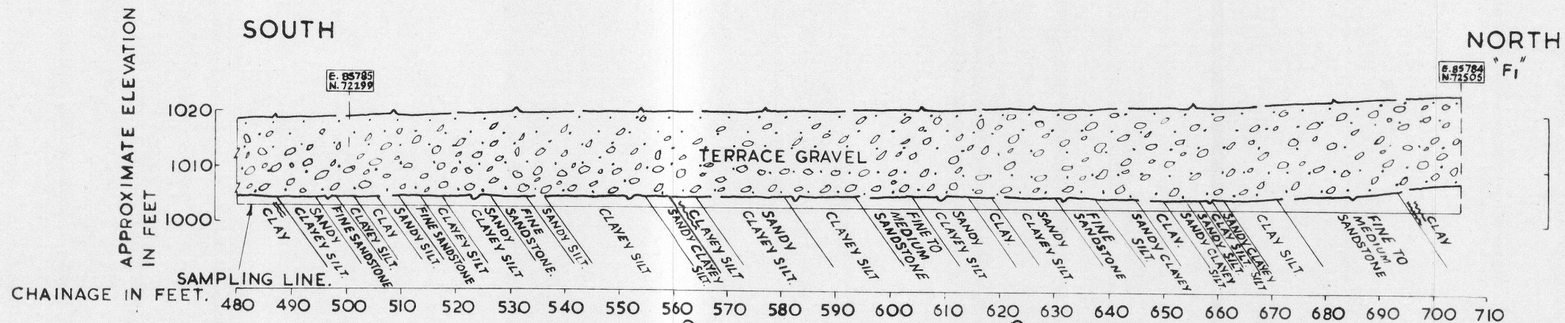
SITE INVESTIGATION 1961 - 63

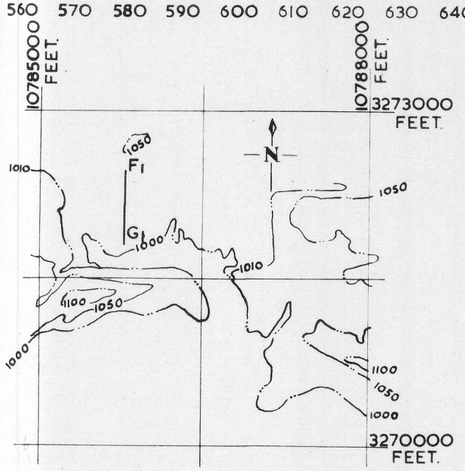
TRENCH F1-G1

(SHEET 1 OF 2)

FIG. 27.







KEY PLAN

SCALE 500 0 500 1000 FEET

NOTES:—

1. APPARENT DIP 54° N THROUGHOUT.
2. CHAINAGE MEASURED ALONG THE SAMPLING LINE.
3. SHEAR ZONE.
4. ESTIMATED LIQUID LIMIT.
5. MEASURED LIQUID LIMIT.

SCALE 10 0 10 20 30 40 50 FEET

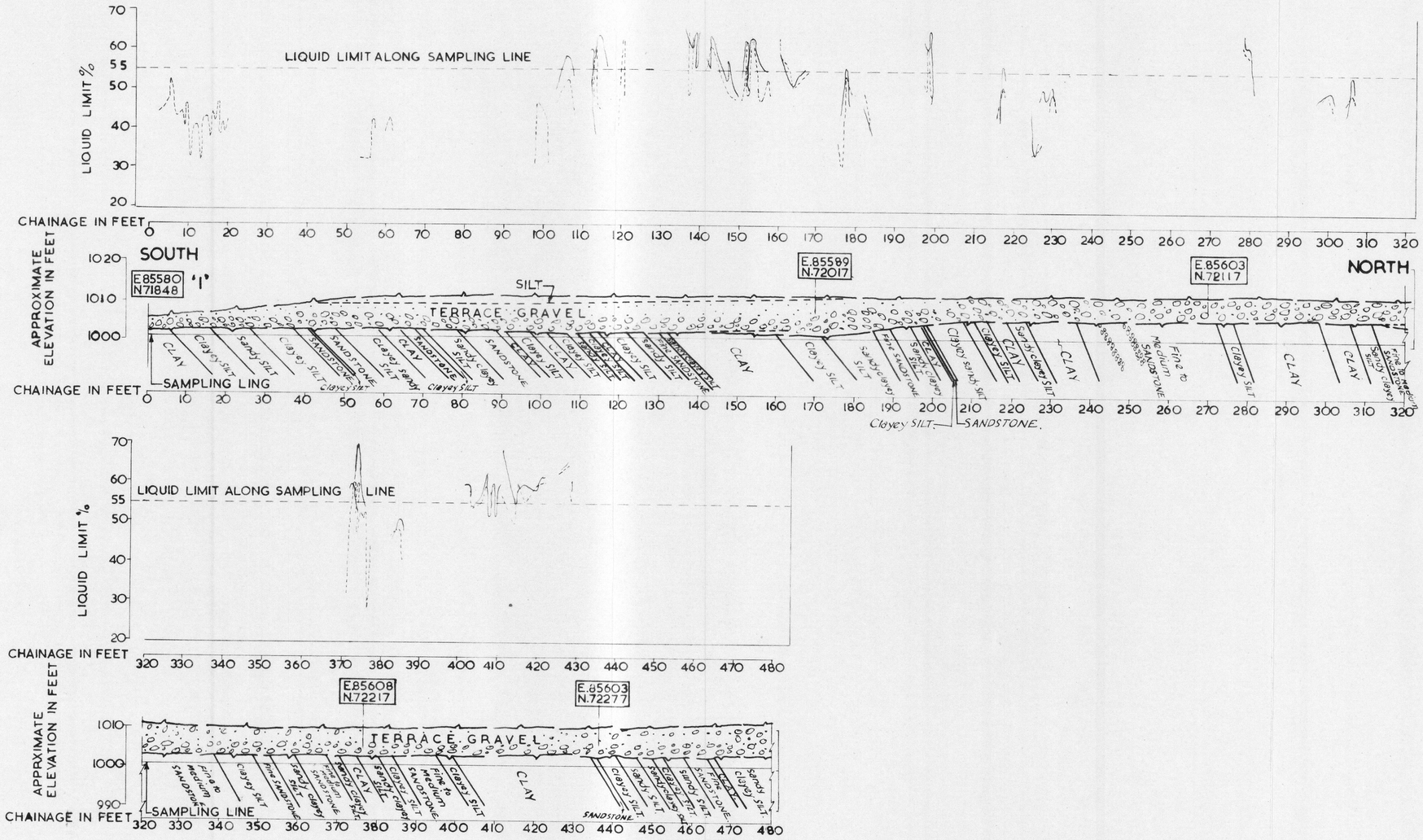
JARI

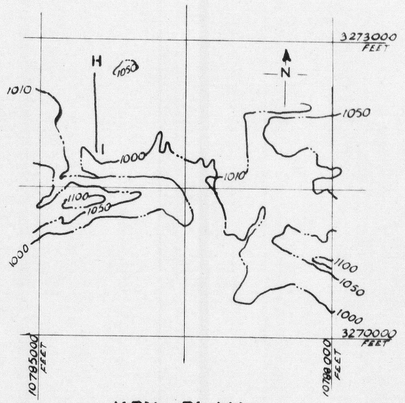
SITE INVESTIGATION 1961-63

TRENCH F1-G1

(SHEET 2 OF 2)

FIG. 28.





KEY PLAN

SCALE 500 0 500 1000

NOTES:

1. APPARENT DIP FROM
   0° TO 185° — 44°N
   185° TO 238° — 60°N
   238° TO 360° — 68°N
   360° TO 396° — 58°N
   396 TO 480° — 56°N
2. CHAINAGE MEASURED ALONG WITH SAMPLING LINE.
3. SHEAR ZONE.
4. ESTIMATED LIQUID LIMIT.
5. MEASURED LIQUID LIMIT.

FEET 10 5 0 10 20 30 40 50 FEET

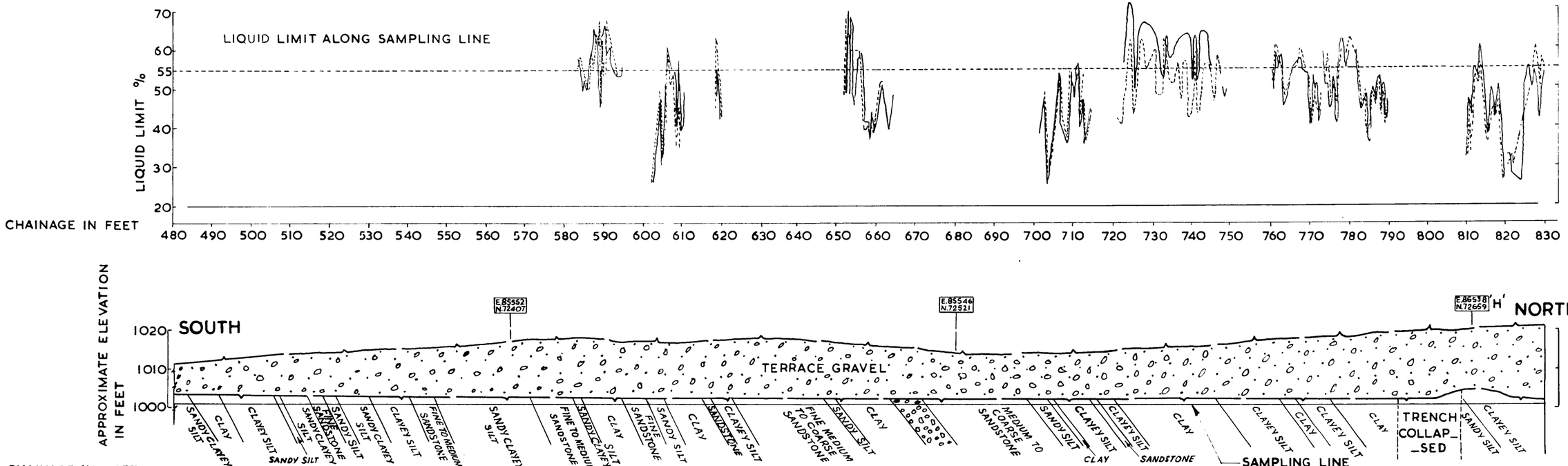
JARI

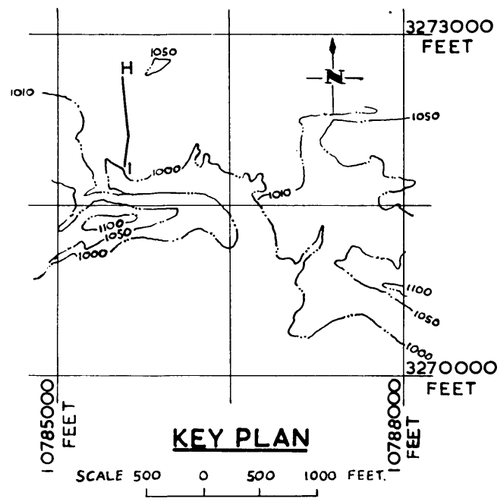
SITE INVESTIGATION 1961-63

TRENCH H-I

(SHEET 1 OF 2)

FIG. 29.





NOTES

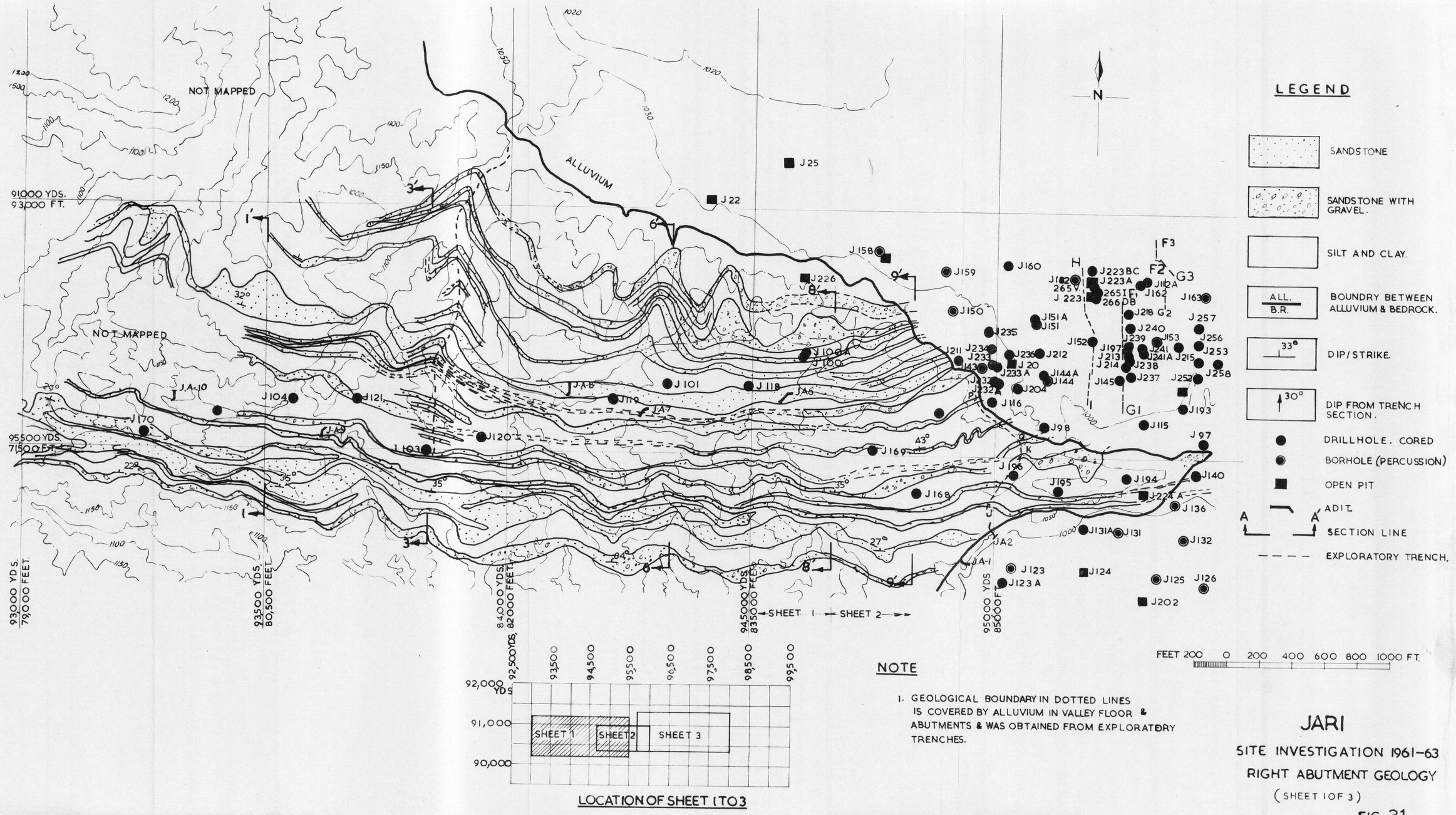
1. APPARENT DIP FROM 480′ TO 515′=56° N
   FROM 515′ TO 541′=62° N
   FROM 541′ TO 699.6′=65° N
   FROM 699.6′ TO END=52° N
2. CHAINAGE MEASURED ALONG THE SAMPLING LINE
3. ESTIMATED LIQUID LIMIT:-
4. MEASURED LIQUID LIMIT:-

SCALE 10 0 10 20 30 40 50 FEET

JARI

SITE INVESTIGATION 1961-63
TRENCH H-1
(SHEET 2 OF 2)

FIG. 30.



LOCATION OF SHEET 1 TO 3

NOTE

1. GEOLOGICAL BOUNDARY IN DOTTED LINES IS COVERED BY ALLUVIUM IN VALLEY FLOOR & ABUTMENTS & WAS OBTAINED FROM EXPLORATORY TRENCHES.

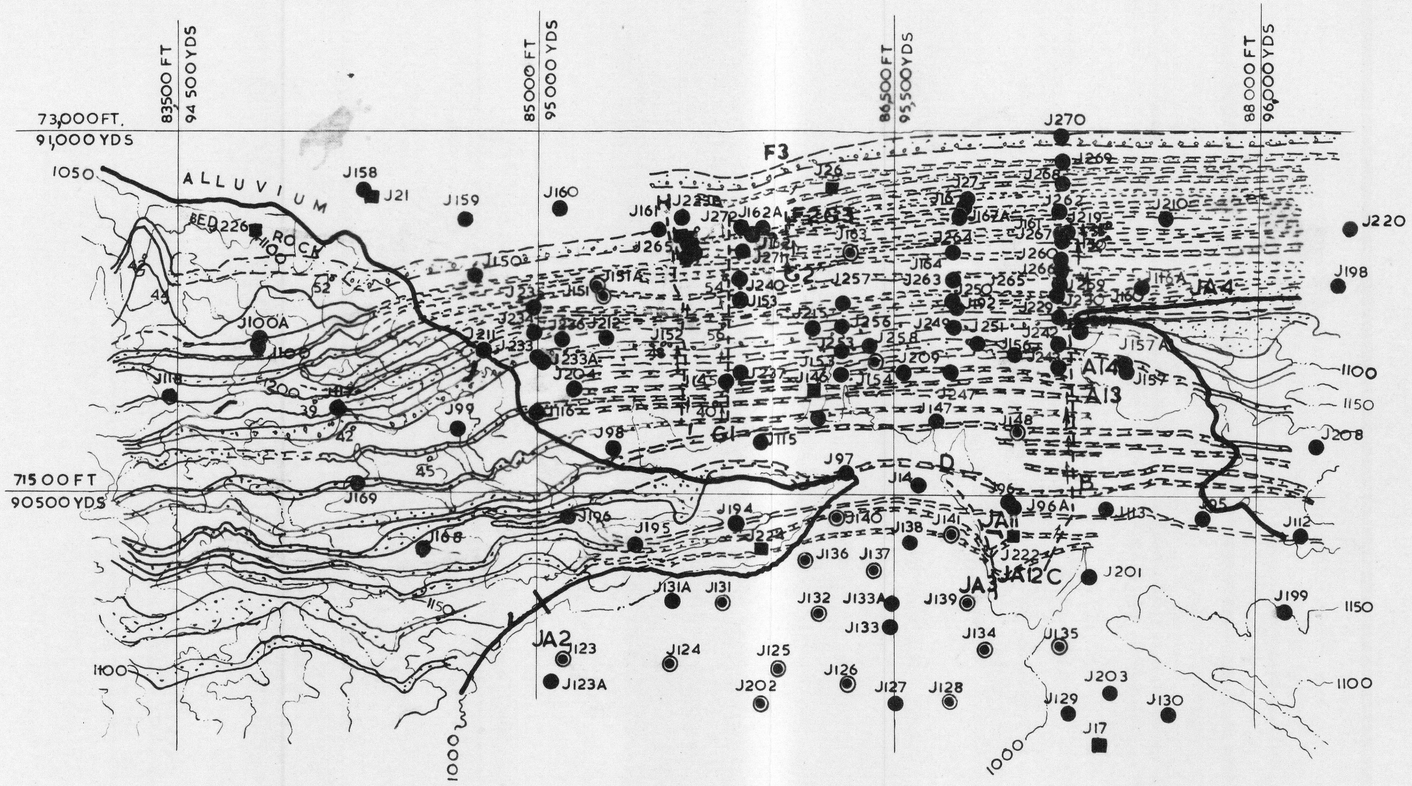
JARI

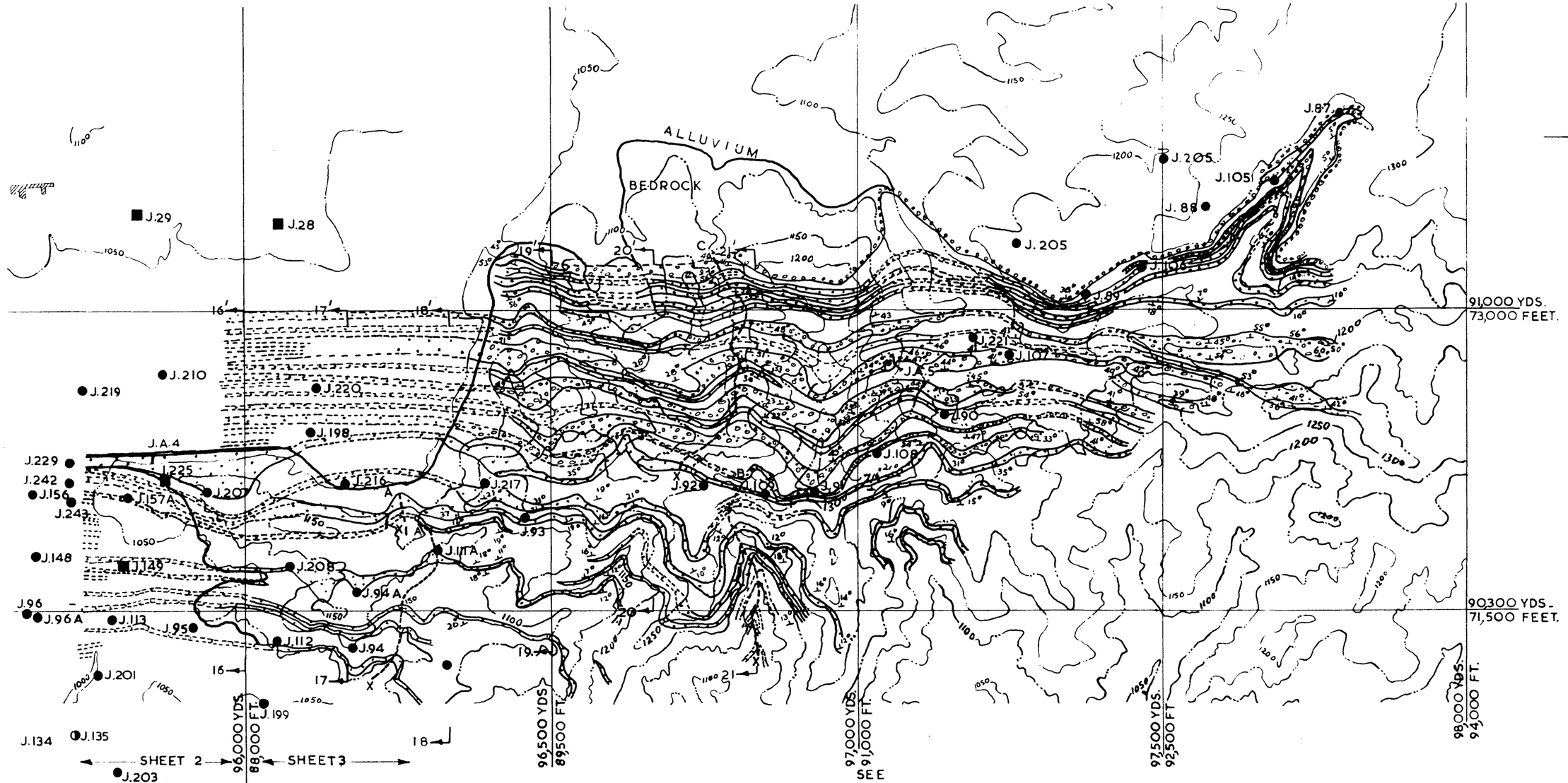
SITE INVESTIGATION 1961–63

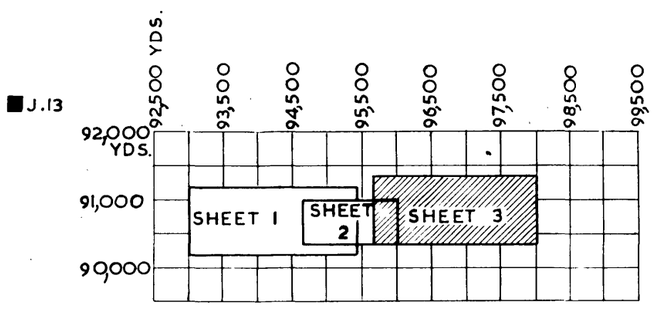
RIGHT ABUTMENT GEOLOGY

(SHEET 1 OF 3)

FIG. 31.


73,000FT.
91,000YDS
83500 FT
94 500YDS
85000 FT
95 000 YDS
86500 FT
95,500YDS
88000 FT
96000YDS
71500 FT
90500YDS
ALLUVIUM
BED ROCK
F3
F2
F1
G2
G1
H
D
B
JA1
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LEGEND

- GRAVEL
- SILT & CLAY
- DRILLHOLE CORED
- BOREHOLE PERCUSSION
- OPEN PIT.
- SANDSTONE
- 46° DIP STRIKE
- ADIT
- EXPLORATORY TRENCH.
- SANDSTONE WITH GRAVEL
- ALLUVIUM / BEDROCK — BOUNDARY BETWEEN ALLUVIUM & BEDROCK.
- 16 16' SECTION LINE

SCALE 200 0 200 400 600 800 1000 FEET.

NOTE

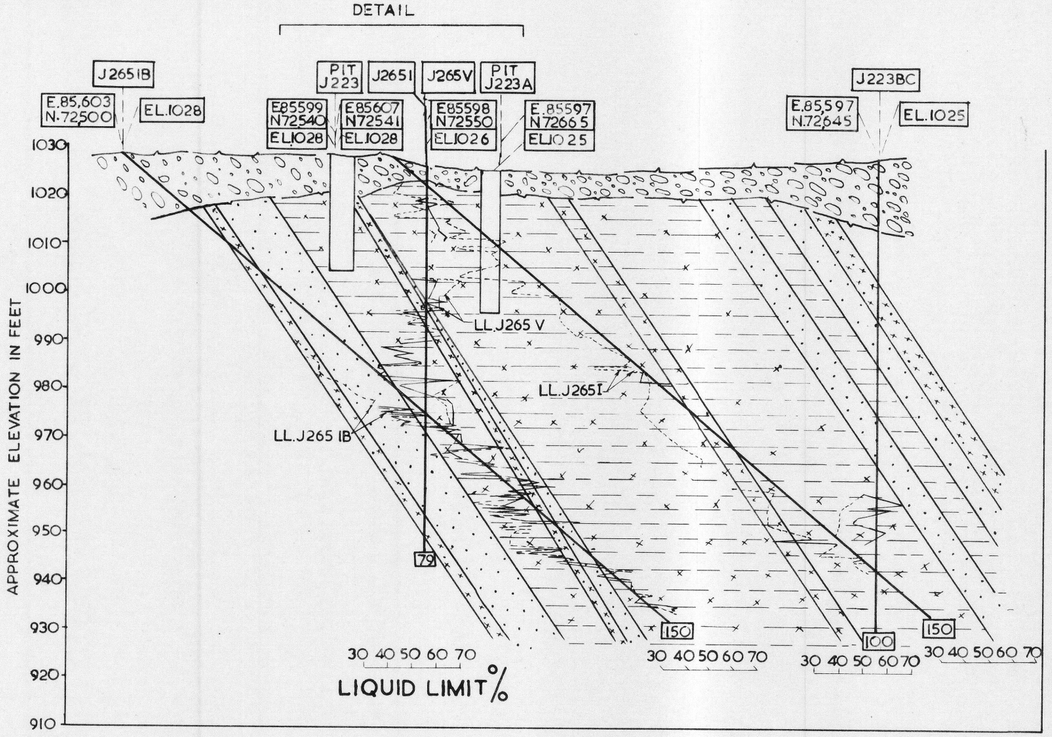
1. GEOLOGICAL BOUNDARY IN DOTTED LINES IS COVERED BY ALLUVIUM IN VALLEY FLOOR AND ABUTMENTS AND WAS OBTAINED FROM EXPLORATORY TRENCHES.

JARI

SITE INVESTIGATION 1961-63
LEFT ABUTMENT GEOLOGY
(SHEET 3 OF 3)

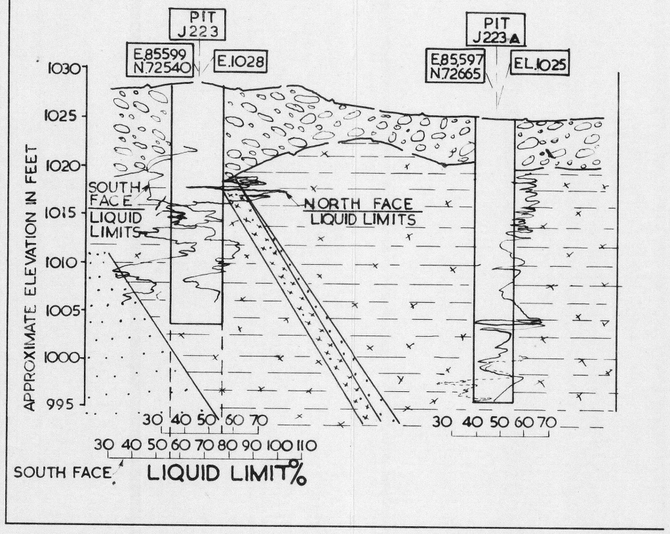
FIG. 33.

SOUTH



SECTION 22–22'

NORTH



DETAIL OF PITS J223 & J223A

NOTES:

1. GEOLOGY IS APPROXIMATE OWING TO LOW CORE RECOVERY.
2. LIQUID LIMITS VALUES ARE PLOTTED GRAPHICALLY FOR BOREHOLE OR PIT USING THE BORE-HOLE CENTRE LINE OR PIT FACE AS BASE OF THE GRAPH. WITH INCLINED BORE-HOLES THE ABSCISSA IS HORIZONTAL.
3. THE LL. SCALE IS POSITIONED SO THAT THE LL. VALUES LESS THAN 55% FALL TO THE LEFT AND VALUES GREATER THAN 55% FALL TO THE RIGHT OF THE BEDROCK LINE OR PIT FACE.
4. ESTIMATED LIQUID LIMIT.
5. MEASUREMENT LIQUID LIMIT.

LEGEND

- ALLUVIAL GRAVEL
- SANDSTONE
- SANDY SILT
- CLAYEY SILT
- SILTY CLAY
- CLAY

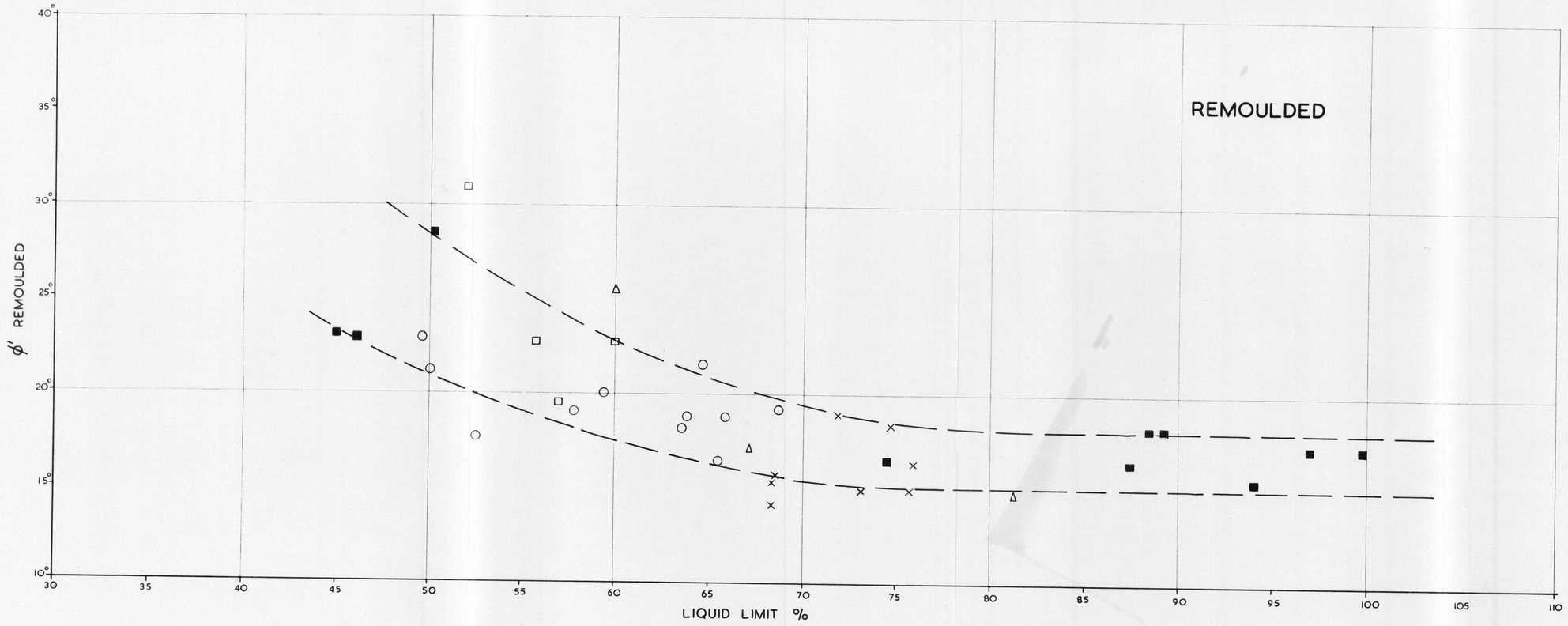
FEET 10 0 10 20 30 40 50 FEET

JARI

SITE INVESTIGATION 1961–63

PIT J-223

FIG. 34.



LEGEND:

CORE SAMPLES FROM BOREHOLES.

1961-62 (LOW DENSITY) ○

BLOCK SAMPLES FORM.

ADITS △

WELL (BELOW WATER TABLE) □

OPEN PIT J-223 ■

TRENCH (SHEAR ZONE) ×

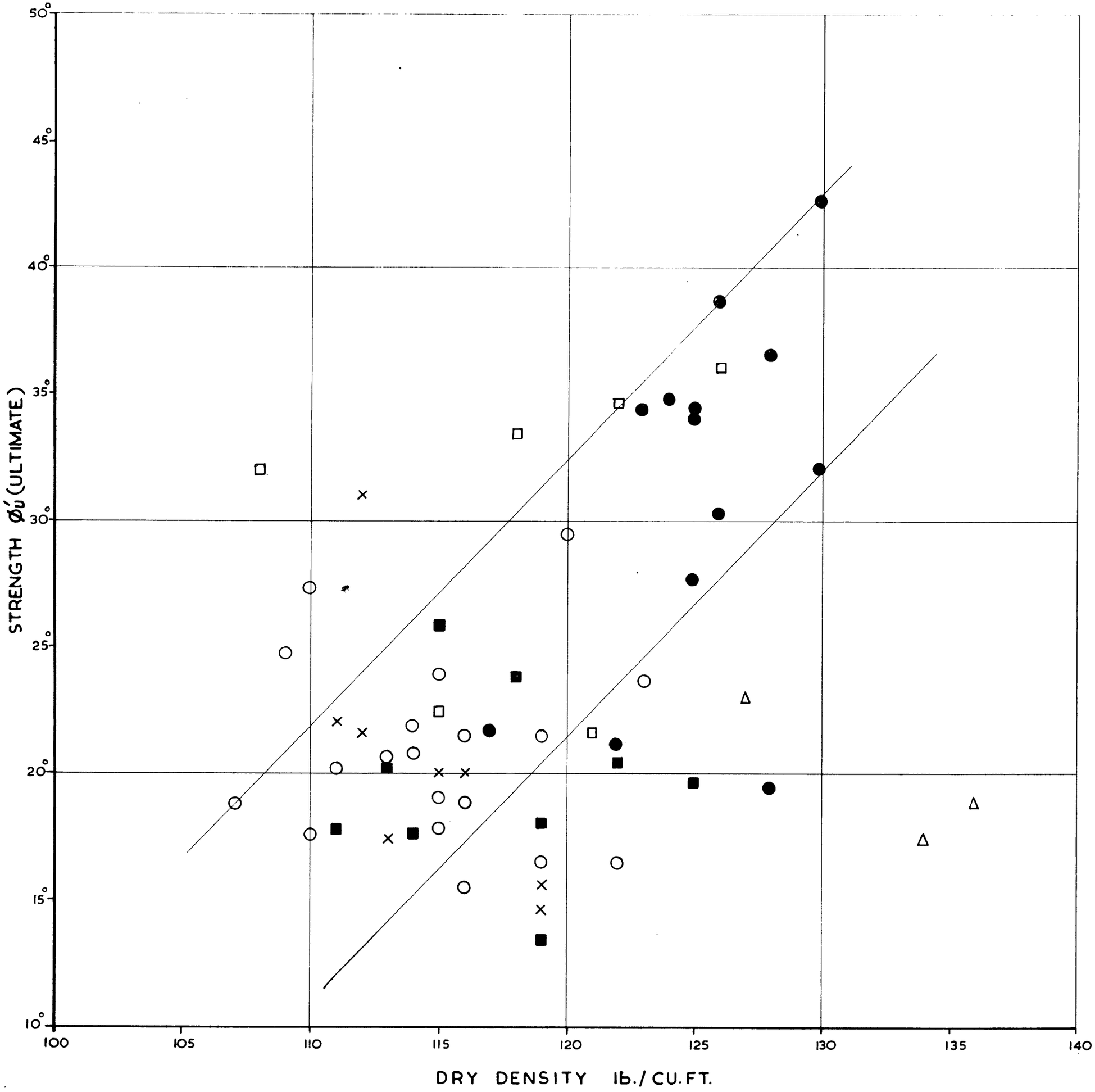
JARI

SITE INVESTIGATION 1961-63

SHEAR STRENGTH (REMOULDED)

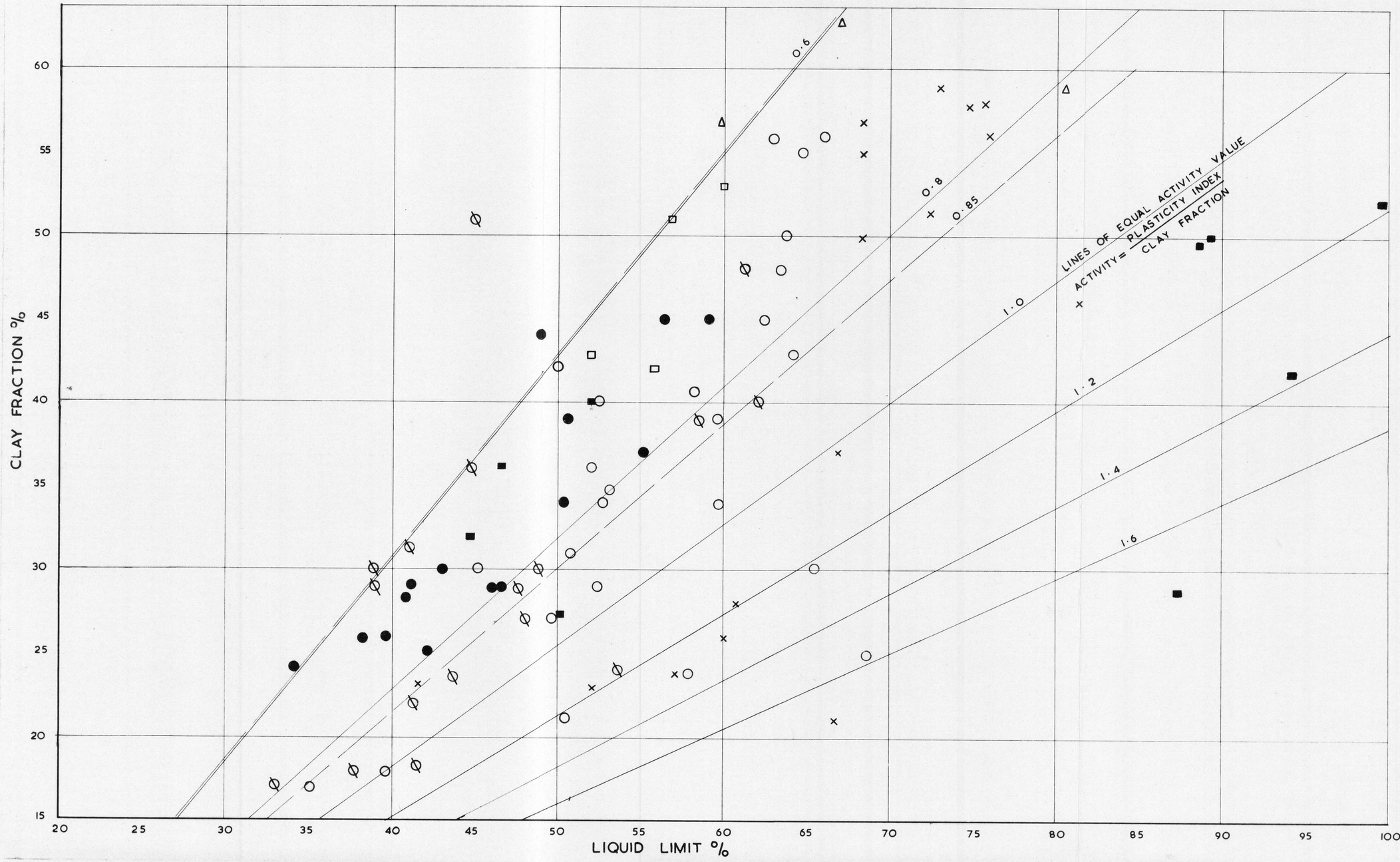
VS LIQUID LIMIT

FIG. 35.



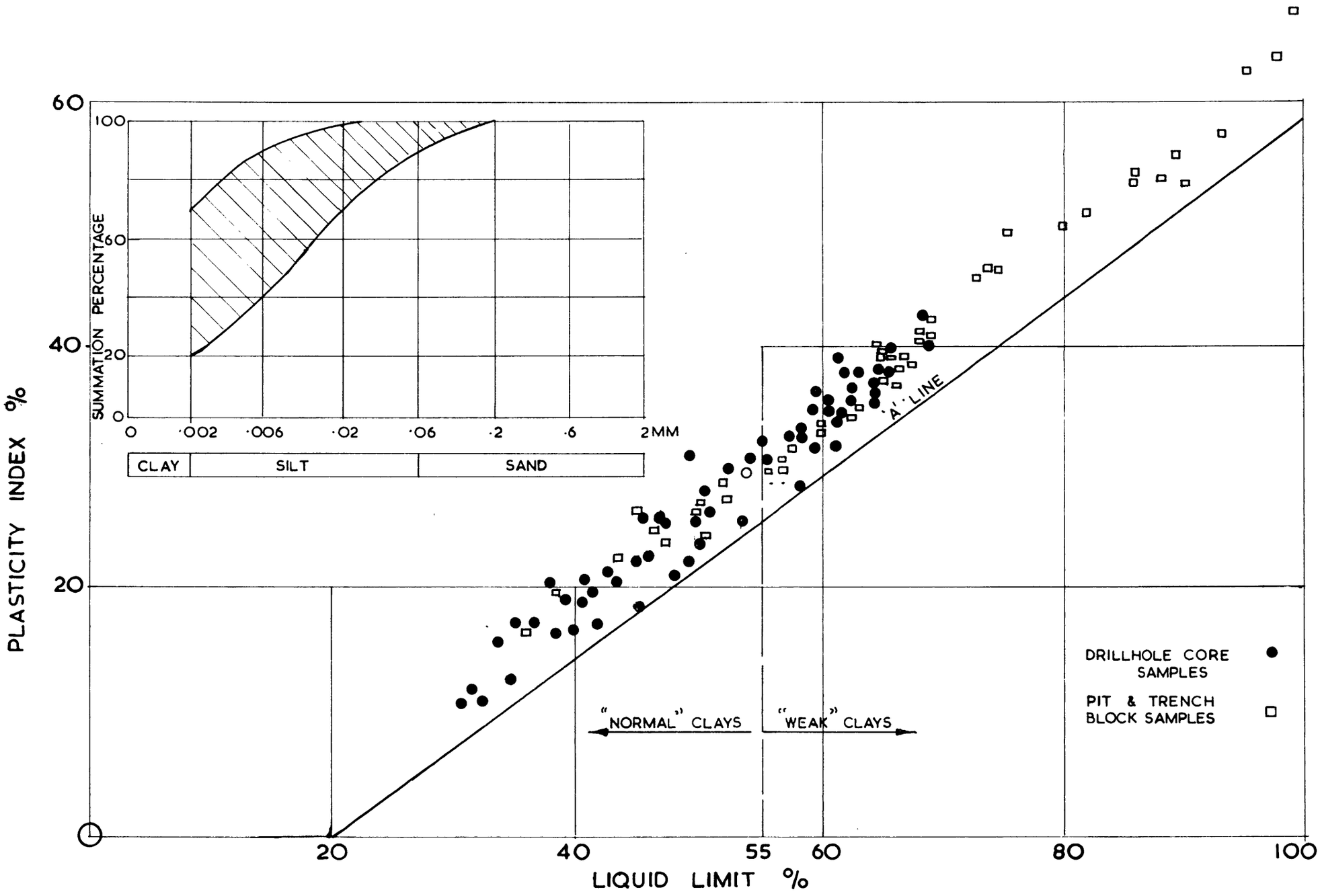
JARI
SITE INVESTIGATION
1961–63
Ø' ULT. VS. DRY DENSITY ALL TRIAXIAL SPECIMENS

FIG. 36.



JARI
SITE INVESTIGATION 1961-63
CLAY FRACTION VS LIQUID LIMIT

FIG. 37



JARI

SITE INVESTIGATION 1961-63

PLASTICITY CHART AND PARTICLE SIZE

FIG. 38.

SITE INVESTIGATION OF SUKIAN

LOCATION AND DESCRIPTION OF SITE

Sukian Dyke is the third largest dam of the Project. It follows the crest of a ridge for a distance of $3\frac{1}{2}$ miles eastward from Mangla to Bala Gala. Its western end starts 1 mile east of the Mangla Fort and continues along the low ridge that separates the high terraces of the Jhelum river to the north and the hinterland of the Jabba Nullah system to the south. The eastern end ties in with the Bala Gala ridge, which forms the southern rim of the Mirpur basin (see figs. 3 and 4 and plate 5).

The ridge crest has an average elevation approximately 1180' and forms an almost unbroken watershed between the small nullahs draining northward into the Jhelum River and the nullahs draining southward into Jabba Nullah which eventually leads into the Jhelum. Some of the nullahs join or nearly join across the ridge and form short low lengths along the ridge. The topography of the ridge crest is fairly smooth but the flanks of the ridge are rough and sculptured by the nullahs (plate 12).

The whole area is underlain by alternating beds of clays, silts, siltstones, sandstones and gravel of the Siwalik formation. The eastern end of the site is blanketed by drift deposits of silts, sands and gravels whose grading becomes coarser northward towards the thick bedrock gravel beds of Bala Gala.

The Dyke takes its name from the village of Sukhiban half a mile west of its eastern end.

INVESTIGATION PROCEDURES

Introduction

Detailed site investigation started in February 1963 when mapping teams became available from the Jari investigation programme. Prior to this, owing to the pressure of work elsewhere the site exploration had been confined primarily to mapping and drilling and no laboratory tests had been done to determine the strength of the bedrock. For the original design in the Tender documents, it was assumed that the bedrock was similar to that of Mangla and Mangla design parameters were at that time used for the current design work at Sukian. However, the detailed work at Jari showed the need for an extremely thorough systematic geological and soils investigation at Sukian. The investigation techniques developed at Jari were then successfully used and further developed at Sukian. The work at Jari had shown that weak clay beds with strengths lower than had been assumed for design were present, so search for weak beds formed an important part of the Sukian investigation.

Exploratory work prior to February 1963 was as follows:

1.‡ Geological mapping on a 1" to 500' scale carried out during 1958-59 by the Geological Survey of Pakistan.

2.‡ 12 boreholes, drilled at widely spaced intervals along the proposed dam centreline. This work was carried out by

the Swissboring Company during 1961-62. Water pressure tests were made and generally showed similar results to those obtained at Mangla and Jari, i.e. an average figure for silts/clays of k = 10^{-6} cm/sec. and for sandstones k = 10^{-4} cm/sec. Also Lefranc water tests were made on the bedrock gravel at the extreme north-eastern end of the site. These gave figures of k = 10^{-3} to 10^{-4} cm/sec.

3.‡ Geological mapping on a 1" to 500' scale completed about the end of 1961. This work extended from the south-western end of the site westwards to chainage 235, where the alluvial cover prevented any further mapping without sub-surface aids.

4. A programme of laboratory sampling and testing during 1961-1962. This work concentrated on locating and sampling the so-called 'bentonite' seam found at approximately chainage 316. It was found that the 'bentonite' appeared to be lens-like in distribution and of variable lithologic character and liquid limit. The highest liquid limit recorded was 140%.

Site Investigation

The site investigation started with new geotechnical mapping on a scale of 1" to 200'. To supplement the mapping in areas where the bedrock was only poorly exposed or completely unexposed, numerous trenches were dug and four NX boreholes were drilled through the alluvium into bedrock (see figs. 10, 11 & 12).

A few liquid limit tests were performed on samples from each bed systematically exposed by the trenches as mapping proceeded. From the liquid limit/effective strength relationship established at Jari, these tests were used to give a

general impression of the strength of the beds. When this impression was established detailed investigation started with continuous groove sampling from selected areas, followed by trenches in which block samples were taken for triaxial tests and classification sampling and testing. Extensive areas of suspected weak clays were found and the investigation was programmed on a day to day basis to establish the extent, geometry and properties of these beds.

In addition to the special problem of weak clays, weathering, fissuring, field density, disintegration permeability as well as the geology of the bedrock was studied.

The alluvium was only briefly investigated. No study was made of the borrow areas.

FIELD TECHNIQUES

Only the site investigation commencing February 1963 is discussed.*

(i) Mapping

Geological mapping was carried out on a scale of 1" to 200' (figs. 10, 11 and 12) by plane table and telescopic alidade. Geological sections normal to the proposed centreline, were drawn from this mapping and are shown in Fookes (1964).

1" to 200' topographic sheets were made for the mapping, close to the proposed centreline, from the 1" to 40' construction quantity survey grid, by reduction on a pantograph to a scale of 1" to 200'. Within the area covered by the grid

* As with the Jari investigation, interpretation current at the time is given.

the contour accuracy is estimated to be ± 3'. Topography outside this area was constructed by enlargement of the Survey of Pakistan 1" to 500' map by pantograph. The accuracy of the maps prepared by these techniques must, therefore, suffer accordingly. Where possible spot checks were made on the 1" to 200' sheets from local control stations during the mapping.

The mapping was supplemented by boreholes SK 717 to SK 720 and trenches SK 1 to SK 20.

Many trenches were dug as they were found to be more useful than boreholes in exposing bedrock. In general, bedrock up to chainage 260 was already reasonably well exposed but beyond chainage 260 it was covered with drift of variable thickness (plate 12). Everywhere except on the strike ridges and in the nullahs, the bedrock was covered by cultivated soil, so that the majority of geological boundaries are shown dotted on the drawings as they were not actually observed. The sandstone beds usually formed low strike ridges that emerged through the soil cover.

Boundaries were drawn between sandstones, gravels and the clays/silts (which were grouped together). Beds greater than 3' thick are shown on the maps except where they are found to be of a limited lateral extent. Occasionally beds were proved to thicken or thin, lens out or to change facies so that with the extensive cover of drift and cultivated soil, discrepancies were to be expected when the foundations were exposed during excavation.

(ii) Boreholes

Three groups of boreholes were drilled. All groups were drilled using NX coring bits and Chicago Pneumatic C-P 8 rigs. Location of holes is shown on figs. 10, 11 and 12.

a) The first group of 4 holes, SK 717 to 720 were for core recovery to supplement the bedrock mapping. No samples were taken and no water pressure tests were made.

b) The second group of 30 holes, SK 721 to SK 738, SK 741 to SK 749, SK 751 to SK 753 were for water pressure tests on sandstones. Tests were made from within 30' of the bedrock surface. The holes were laid out so that each sandstone bed was drilled and tested at least once and thick beds tested twice. In general the testing procedure was satisfactory but trouble was experienced with caving sandstones and several holes were re-drilled.

Test results are given in Appendix II.

c) The last group was of three special holes numbered RE 739B, 740 and 750, located to obtain core from the same beds, at depth (viz. fig. 22), that had been sampled in detail from the trenches. The core was taken to test the effect of depth on index and strength properties of the bed. Location of the boreholes, bedrock and results are shown in figs. 12 and 39.

Average core recovery from group a) was 86% and group c) was 64%. Mud drilling was used for both these groups.

The groundwater table was not met in any of the boreholes.

(iii) Trenches

Trenches were extremely useful and convenient in revealing bedrock below the drift and soil covering. The latter was largely a result of cultivation together with weathering. Two groups were dug:

a) The first group of trenches was to supplement the geological mapping. These trenches were numbered SK 1 to SK 15 and SK 17 to SK 21. Their locations are shown on figs. 10 and 11. Geological sections of each trench on a 1" to 20' scale are given in Fookes (1964). Where liquid limit samples were taken from trenches the results are shown on the geological sections. The trenches were either dug by D8 bulldozer, or B-51 or B-38 backhoes. They were only dug as deep as required to establish the geological boundaries between beds which was generally of the order of 1-2' below the base of the soil covering. 10,600' run were dug by the bulldozer and 3,010' run by backhoe. Where the Contractors' haul road to Jari immediately south of the Dyke cut good exposures in the bedrock, the exposures were given trench numbers (SK 22 to SK 25, fig. 12). These exposures were used to supplement trenching and to take 'continuous' groove liquid limit samples* which together with selected block samples for strength tests helped to establish the liquid limit/strength properties at the eastern end of the site.

b) The second group of trenches, SK 12A, 12B; SK 17A, 17B, SK 20 and SK 26, SK 26A, were used primarily for bedrock

* See page 46.

sampling. These trenches were aligned either at right angles to the strike of the bedrock or parallel to the strike. All the trenches were dug by a B-38B backhoe and generally extended to 10-15' into bedrock, the maximum depth below top of bedrock was 36'. Location of the trenches is shown on figs. 11 and 12 and the details of the geology and sampling on 1" to 4' scale geological sections given in Fookes (1964). In addition one pit SK 2045 was used to supplement work on trench SK 6 (fig. 40).

In the closing stages of the investigation, exposures made by the foundation excavation of the dam, were also used for sampling.

(iv) Sampling

Sampling proceeded with the detailed geological logging of the trench or exposure. Four types of sample were taken as described in Part I. All samples were taken from freshly exposed material.

Apart from occasional individual liquid limit samples, all the liquid limit samples were taken at close centres, as described in Part I, from a continuous groove of approximately 4" x 4" cross section. Liquid limit results from these samples are plotted as a graph on the geological sections of the trenches (discussed later) or as a graph of liquid limit against chainage (see Fookes 1964). The object of this close centre sampling was to obtain the liquid limit values for a large number of beds in detail, which when correlated with

effective strength results would enable a strength picture of the beds to be ascertained. The results of this correlation are shown on fig. 41.

Samples for comprehensive classification testing, viz. liquid limit, plastic limit, moisture, density and unconfined compression strength, were taken in trenches SK 17A, SK 20, SK 12A, SK 12B, SK 26, and pit 2045, for detailed study in comparison with triaxial tests. The samples were taken from both horizontal and vertical grooves and are described later.

Block samples were cut about 1' cube and immediately waxed with 3 coats of paraffin wax. Locations of block samples were either chosen by eye or by reference to liquid limit results. As the time available for the investigation programme was limited, block samples were generally taken from what appeared to be low strength material. The method of selection of each sample is indicated in the tables summarising the triaxial test results (Tables VIII to XII).

In trenches SK 20, SK 12A and SK 26 (figs. 42, 43 and 44), block samples were taken from the same geological horizon in a single bed but at differing depths down dip so that variation of strength with depth below top of bedrock could be ascertained. In addition special boreholes SK 739B, 740 and 750 were drilled to obtain deep triaxial samples down dip and on the same bedding plane as samples taken from trenches (see fig. 39). The variation of strength along the strike of beds was investigated in trenches SK 17A and SK 26A where block samples were taken at different locations along the strike of the same bed (for example see fig. 45).

(v) Field Tests

The following tests were carried out in the field:

(i) Permeability of sandstones from boreholes;

(ii) Field density;

(iii) Disintegration.

Field density tests were made by sand replacement on freshly exposed unweathered material of every bed exposed.

The location of these tests and the range of results for each bed is given in Fookes (1964). Where results were in doubt, repeat tests were made.

Disintegration times are shown on Tables VIII to XII. Disintegration tests were made by immersing a 1 kilo. undisturbed sample in water and recording the time and fashion of disintegration. Details in Fookes (1964).

GEOLOGY

The oldest beds are found at the western (Mangla) end of the Dyke and an apparently uninterrupted succession occurs dipping towards the eastern (Jari) end. At the Mangla end the beds strike north 55°W and dip approximately 12°NE. The dip and strike remains fairly constant across the site, although minor variations occur. At the extreme eastern end the influence of the Mirpur syncline to the north-east is apparent and the strike of the beds swings a little to the west apparently in line with the structural axis. Dips from 10° to 16°NE were recorded in the field mapping; variations of the dip were due to local minor flexures or to lensing

of beds. A geological section for the whole length of the Dyke is shown on fig. 46. This section shows the thickness of the various beds; the sandstone beds range from approximately 20' to 150' in thickness from top to bottom of the bed and the clay/silt beds from approximately 5' to 100'.

The geological succession consists of a series of clay/silt and sandstone beds. The beds at the western end are of similar age, thickness and lithology as the beds of the Intake and Main Dam, and although they have not been mapped in the field, they have been walked over and are considered to be continuations of the same beds. At the eastern end of the Dyke, the beds are of similar lithology to the beds of the Jari Damsite. The beds at both the eastern end of Sukian and at Jari underlie the Bala Gala gravel succession and are, therefore, considered to be of similar age. See the columnar section fig. 6 and discussion in Part I.

The sandstones are generally silty fine to medium grained, although silty fine grained and fine to coarse grained varieties do occur. They consist mainly of sub-rounded to sub-angular quartz, together with mica, feldspar, mafic and accessory minerals. Sandstone bed 7 (fig. 10) contains a few more mica flakes than typical; sandstone beds 15, 17 and 24 have more rounded grains and lower densities. The deposition history of this latter three may be associated with the red clays described following. The sandstones are described in more detail in Part I and laboratory test results on them are given in Appendix II.

The clays and silts at Sukian were mapped as one unit and are conveniently discussed as one unit. The term silt is preferred to siltstone for the clayey silts as they did not ring to the hammer and have cohesive properties which are classified in the field as 'soft', 'stiff', 'firm' or 'hard', in a similar manner to the clays. Occasionally very thin beds of true siltstone occur; these are generally sandy.

All the clays and silts are overconsolidated and most of the clays are fissured; at the Mangla end some 5,000' of bedrock has been eroded and this figure decreases uniformly west to east and is about 2,000' at the Jari end. These figures are based on geological evidence and are roughly confirmed by consolidation test results (pers.comm. N. Ambrayses, K. Head 1962). Three colour groups of clays and silts have been recognised, the 'black', 'red' and 'brown' groups. Most beds are brown, the typical colour of the Project's clays and silts. The black clays are the smallest numerically and the bentonitic clays are usually contiguous with them. The groups are considered to be associated with geological deposition cycles. Three main cycles are recognised, the 'Mangla Brown' cycle of chainage 180 - 250, the 'Sukian Red' of chainage 250 - 320 and the 'Jari Brown' of chainage 320 - 360. Minor colour rhythms occur within each cycle.

The red group may have been deposited from sediments brought from eroding red beds elsewhere (extensive red beds were undergoing erosion on the Deccan Plateau during Siwalik times and their erosion products may have reached as far as

Sukian by a slight northward shift of the axis of the Indo/Gangetic geosyncline?). The fine, rounded grained sandstone beds alternating with the red beds may have been transported over long distances and the grains rounded in the process.

The separation into groups proved of great use in the field during investigation for assessing the general strength characteristics of the clay and silt beds, and for location selection of block samples. From the three main groups the Mangla Brown, the Sukian Red and the Jari Brown, three 'strength' zones were recognised and related to the chainage. These zones are discussed later.

The boundaries between the clay and silt beds and the sandstones are usually sharp. Occasionally minor erosion planes occur at the top of a bed which often take the form of shallow washouts. Transition zones of silt between a clay and a sandstone bed are rare although grading within beds, either clays or sandstones, from coarse to fine, are common. Often a zone of clay balls or clay lenses occurs at the base of a sandstone bed. The clays contain shear zones, thrust (shear) joints and other minor structural features discussed later. Further general details of clay beds are given in Part I.

Bentonitic Clays

Five or six* 'bentonitic' clay seams were found and are shown on figs. 11 and 12 and on section fig. 46. The mode

* The inability to trace these seams exactly could not be avoided during investigation due to inadequacy of exposures. In the foundation mapping during construction six seams were found.

of occurrence of these clays is variable. All of them occur with clay and silt beds and sometimes they occur together with a grey ashy volcanic breakdown product which on examination under the microscope reveals the inclusion of volcanic glass and debris (pers.comm. S. Masood 1961; Taquib Ali 1962). This volcanic material varies from a few inches to a few feet in thickness. It is generally local and has not been traced for more than 300'. The beds of bentonitic clay are usually thinner and range from 1" to 1' in thickness. They have been traced over several hundred yards and recovered at depth from boreholes (e.g. SK 708). The clay beds between sandstones 14 and 15 contain various thin lenses of bentonitic clay and volcanic material of silt to sand grading.

It is considered that the bentonitic clays have been formed from volcanic dust deposits that have been mixed with the local clays as they were deposited. At times when volcanic activity increased or was nearer to Sukian the proportion of volcanic dust would increase in the sediments and give rise to the thicker beds of grey ashy material.

At the start of the investigation, as a multiple working hypothesis, it was thought that the form of the bentonitic deposits could exist as any one of the variations a) to d) given on fig. 47. Investigation consisted of tracing the surface expression of the material which was a khaki colour on the ground with occasional 'popcornlike' occurrences, together with trenching, pitting and boreholes. It was concluded from this work that the form of the material was like

c) (i) or (ii)(fig. 47). Full exposure later during construction showed it was intermediate between c) (i) and (ii) (pers. comm. D. Wilson 1965). The largest lens exposed was over 350' long with a maximum width of true bentonitic material of ca. 2½'.

Use of the term 'bentonitic clay' is in agreement with Tourtelot (1964) quote:

> 'Bentonite - Bentonite is a rock consisting virtually of clay derived from the alteration of volcanic ash (Twenhofel, 1937, p.99; Knechtel and Patterson, 1955; 1956, p.1.) Bentonite differs from the other rocks composed of clay-sized particles with which it ordinarily is associated by not containing any organic material; and, hence, it weathers to very light colours, commonly shades of yellow and orange. The material commonly occurs in well-defined extensive beds. Most bentonite consists predominantly of montmorillonite, but it has a wide range of physical properties that seem to depend upon complexly related chemical and crystallographic features of the material. Some bentonite is referred to as swelling bentonite because it swells during weathering and produces a frothy popcornlike crust on the surface of the outcrop. Other bentonite lacks this characteristic and is referred to as non-swelling bentonite.
>
> 'Bentonitic - Bentonitic applies to light-grey to dark-grey claystone that differs from bentonite chiefly in colour. Swelling bentonitic claystone consists of a

mixture of swelling bentonite and detrital clay minerals; the amount of swelling seems to depend largely on the proportions of these constituents. Some bentonitic claystone has a characteristic frothy popcornlike surface similar to that of nearly pure bentonite. Non-swelling bentonitic claystone forms a gumbo-like cap as much as half a foot thick upon weathering but lacks the frothy, popcornlike surface.'

The existance of bentonite was first noticed when the village women were found digging shallow pits to win blocks of the material for use locally in the nearby villages (the material is coverted for its fulling properties). At that time its nature, mode of occurrence and distribution were unknown.

At about the same time that the site exploration commenced, the Geological Survey of Pakistan (Buream of Mineral Resources), was investigating deposits of bentonite on a regional basis. They later reported (Taquib Ali 1962) that the length of the outcrop of the principal seam found at Sukian was about 18 miles and that its averare thickness was from 3" to 10". They also considered the bentonite seams (in general) occurring in the Siwaliks were found at the base of volcanic ash beds (of from 2' - 4' in thickness) and microscopic studies of heavy minerals from samples selected from various areas showed the presence of zircon, apetite, hornblende and magnetite; together with quartz, feldspar, biotite and shreds of volcanic glass. The grains of these minerals were angular and fresh

and it was considered that their source was not too far distant from their place of deposition, and they concluded that the deposits were formed either by single volcanic ash fallout or falls that had been repeated one after the other in rapid succession and deposited into shallow calm waters.

Table XIII shows chemical analyses of bentonites found near Sukian compared with Wyoming bentonite, USA.

T A B L E XIII

Chemical Analysis of Pakistan and Foreign Bentonites

	Wyoming USA	Rohtas Fort Jhelum Dist Pakistan	Bhimbar Azad Kash-mir	Samwal Azad Kash-mir
Silica (SiO_2)	57.98	54.89	51.50	59.74
Alumina (Al_2O_3)	22.46	12.78	18.23	13.34
Iron oxide (Fe_2O_3)	3.80	2.57	1.64	1.95
Titanium oxide (TiO_2)	Not det-ermined	0.23	0.21	0.07
Lime (CaO)	1.92	4.27	3.26	2.29
Magnesia (MgO)	3.24	4.50	4.56	1.07
Sodium oxide (Na_2O)	1.35	0.55	-	0.25
Potassium oxide (K_2O)	-	-	-	-
Moisture at 110°	8.68	9.78	-	1.60
Sulphur	-	-	-	-
Loss on ignition	-	-	-	-
Chemically held water	-	0.51	19.63	9.78
$\frac{SiO_2}{Al_2O_3}$ Ratio	2.58	4.29	2.88	4.48

The table was summarised from Taquib Ali (1962)

LABORATORY TESTS ‡

Laboratory testing techniques are divided into two categories which are discussed separately, viz. classification tests (the determination of index properties) and strength tests (the measurement of effective shear strength and related properties). The small amount of testing carried out prior to the investigation which started in February 1963 is not discussed.

a) Classification Tests

The greatest number of the laboratory classification tests consisted of liquid limit tests on samples taken systematically from continuous grooves. As with the Jari investigation the one-point liquid limit test using air-dried samples, was extensively employed. On approximately one sample in every ten, Standard Atterberg tests for liquid limit and plastic limit (B.S. 1377:1961) were carried out ; occasionally some field moisture contents were measured.

Small undisturbed samples were taken at 0.5' or 1' intervals from certain selected grooves for measurement of unconfined compressive strength, for comparison with other index properties.

All triaxial samples were systematically subjected to classification tests. A one-point liquid limit test and particle size analysis were carried out on each individual specimen and both Standard Atterberg limit tests were carried out either on representative trimmings from each block sample or on the combined remains from the triaxial specimens.

Unconfined compressive strengths of each block sample was measured by trimming a separate $1\frac{1}{2}$" dia. x 3" high specimen. Densities and moisture contents were measured before and after testing.

b) Triaxial Tests

Standard consolidated-drained triaxial compression tests were carried out on $1\frac{1}{2}$" dia. x 3" high samples after saturation under controlled back pressure. The usual procedure based on the techniques of Bishop & Henkel, as described in Part I, was followed. Filter-paper side drains were fitted to all samples. The laboratory did not consider it necessary to make allowance for either side drains or rubber membrane in calculating deviator stresses. The rate of strain was typically 0.9% per hour, and was never more than half that calculated by the usual method from the c_v value measured in the consolidation stage.

Most samples were tested in sets of three hand-trimmed specimens from the undisturbed block. With one exception (sample 58124) sample axes were vertical. Effective cell pressures for each set were standardised at 20, 60 and 120 lb/sq.in. except for a few special tests and the tests on samples from the bentonitic clay. A back pressure of at least 10 lb/sq.in. was maintained whilst shearing and a continual check of the pore pressure made at the base of the sample. To see if the envelope to the Mohr circles behaved differently at higher or lower cell pressures, one sample No. 58139 was tested at 5 and 300 lb/sq.in. in addition to the

usual 20, 60 and 120 lb/sq.in. The resulting circles showed no unusual features and they gave a normal envelope.

Shearing was continued past the peak deviator stress until the ultimate (residual) condition was reached. The area correction which was developed for Jari tests was then applied to calculate the true ultimate deviator stress. Mohr circles were drawn for both peak and ultimate conditions and a straight line envelope was drawn by eye to each set of circles. From this values of c', Ø' (peak) and Ø' (ultimate) were derived.

SOIL PROPERTIES

The following describes and discusses the results and interpretations used at site on a day to day basis to develop the investigation.

Sample Selection

Clay samples for triaxial tests were selected in the field according to seven different requirements as follows:

a) Random samples within a bed or part of a bed;

b) Average samples, i.e. samples representative of a given bed or part of a bed which appeared to be fairly homogenous;

c) Weak clay samples, selected either by eye or from liquid limit results;

d) Strong clay samples, selected either by eye or from liquid limit results;

e)‡ Samples requested by the Consulting Engineers, London;

f) Samples associated with bentonitic clay;

g) Bentonitic clay samples.

Table XIV summarised the sample selection compared with the ranges of results obtained:

T A B L E XIV

Sample Selection	No. of tests	Ø' (ult) values
a) Random	7	$12\frac{1}{2}^{o}$ to $29\frac{1}{2}^{o}$
b) Average	4	17^{o} to 28^{o}
c) Weak	18	15^{o} to 23^{o}
d) Strong	5	26^{o} to $31\frac{1}{2}^{o}$
e) ‡Requested from London	6	14^{o} to $22\frac{1}{2}^{o}$
f) Associated with bentonitic clay	2	17^{o} to 25^{o}
g) Bentonitic clay	2	15^{o} to 23^{o}

Ø' (ult) values are not corrected for c' = 0, each result has a small C'.

Index properties

Atterberg properties of all triaxial samples are plotted on the Plasticity Chart in fig. 48. All the clays with liquid limits ranging from 35% to 75% (classification CI - CH) lie in a zone just above and parallel to the 'A' line. The equation to its centreline is approximately defined by:

$$PI = 0.73 (LL - 15)^{*}$$

The similarity of this line and that for the Jari clays (fig.38)

* (Derived by K.H. Head.)

is immediately clear. Black clays are all of fairly high plasticity and tended to provide the weakest strength samples. Brown clays were of little lower plasticity and gave (in general) slightly stronger samples. It is of interest to note that the approximate position of the Black, Red and Brown clays on the plasticity chart was predicted during mapping and logging in the early part of the investigation.

Two of the bentonitic clays lie below the 'A' line, but the others lie close to a line defined by:

$$PI = 0.73 (LL - 5)^*$$

Bentonitic clays below the line undoubtedly are of only partly decomposed ashy material.

The clay fraction is plotted against plasticity index in fig. 49, on which lines of given activity values are drawn. To accommodate the bentonitic clays in the drawing the plasticity index is reduced above P.I. = 50. Most of the samples are of low to moderate activity (up to 1.6). Clays of each colour group show similar scatter of activity values. The bentonitic clays, as expected, have higher activities, ranging from 1.5 to 3.2 (mostly over 2.0), apart from these, the clays show similar activity to the Jari clays.

Colour Groups

The local colour classification was developed in the field to give an estimate of the strength of the clay. Clay beds were coloured according to their groups, brown, black or red, by visual classification and are shown in plan by

* (Derived by K.M. Head.)

Fookes (1964). The colour technique was of considerable use in the early part of the investigation, but with increasing experience it was replaced by a direct visual estimate of the strength.

In the field each colour group was subdivided into 'clayey' or 'silty' by feel and texture. The groups were further subdivided into ' hard' and 'soft', not necessarily on the basis of apparent strength but according to 'waxiness' of appearance and touch. 'Soft' clays* had a waxy character which is difficult to describe but was fairly easy to recognise with field experience; scraping with a blade readily produced a shiny surface. These effects were not present in the 'hard' clay.

There is considerable overlapping of the properties of one group with another, as shown in table XV showing test results of 45 block samples. The table gives the colour grouping but does not subdivide the groups into 'hard' or 'soft', 'clayey' or 'silty'. Colour classification was made in the field at the time of sampling by visual inspection.

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* This term 'soft' is at variance with the term as defined in C.P. (2001) 1957 'Site Investigation' and its use was later dropped.

T A B L E XV

	Brown	Red	Black	Bentonitic
Liquid limit range	30 - 60	42 - 64	46 - 73	93 - 140
Clay fraction range	16 - 47	18 - 53	19 - 52	29 - 49
Average 'clayey' CF	36	40	45	33
Average 'silty' CF	20?	25	25	-
Ø' (ult) clayey	16 - 18°	14 - 23°	12 - 23°	
Ø' (ult) silty (one result)	27 - 32°	23 - 28°	(27°)	
c' lb/sq.in* (one result)	5 - 10(18)	0 - 11	0 - 18	

The colour grouping was an attempt to map actual engineering parameters. No further work has been done on colour groups as they were replaced by actual test results during the course of the investigation; further specific work on them together with mineralogical analysis might prove interesting. Although only a rough indication, the similarity of activity of each of the groups might show the colour changes are solely reflection of the oxidation states of the iron compounds, not differences of the basic clay minerals.

Correlation of Effective Shear Strengths

The relationship between effective stress parameters and clay fraction is plotted in fig. 50, as in fig. 41 again the site technique of plotting both the c' and Ø' values derived from each set of triaxial tests are used. The correlation of index properties shown by the graphs is poor so the site

* These figures are the site interpretation and are not corrected to c' = 0.

laboratory (K.H. Head) developed a technique of plotting ultimate deviator stress ($\sigma_1 - \sigma_3$/ult for each triaxial specimen against the index property of the appropriate effective cell pressure of the test. At (for example) 35%, 50% and 65% liquid limit, deviator stresses were read off from each curve. From the values of σ_3' and σ_1' derived, three sets of Mohr circles were drawn representing the mean, upper and lower limit circles for each liquid limit. Envelopes drawn to these circles gave the effective stress parameters used to draw correlation curves with the liquid limits. These are shown as drawings nos. RE 1448 (sheets 1-2) and RE 1649 in Fookes (1964). The median correlation curve showed that ϕ' (ult) decreased from 30° at liquid limit 35% to 14° at liquid limit 65%. The scanty evidence from changes at liquid limit greater than 65% suggests that the strength does not decrease much more at higher limits providing the clay is not weathered. No samples were from shear zones as only two moderate shear zones were found during the investigation. Many more were found later during the foundation mapping in the construction of the core trench. Fig. 41 shows a somewhat similar picture but was thought that the scatter of points was too great to permit an envelope to be drawn, so only a median line was attempted. This indicates some decrease in strength with increase of liquid limit. No such line was drawn for the clay fraction curve, fig. 49.

Bentonitic Clays

Mohr circles for the three bentonitic clay samples were plotted in two groups according to the type of failure surface observed+ after triaxial testing. These are indicated as 'rough' and 'smooth' in Table VIII(ii). The 'rough' surfaces, which collectively gave $\emptyset'$ ult of 23°, were fibrous, rough and uneven. The 'smooth' surfaces ($\emptyset' = 15^{\circ}$) were highly polished and almost planar; it was considered they were due to pre-existing fissures or planes of weakness within the material. The samples came from partly decomposed ashy material and were not waxy in appearance like the true completely bentonitic end product.

STRENGTH OF THE BEDROCK

Introduction

The programme of investigation was designed to study the variation of the effective shear strength of the clays and silts both along the length and breadth of the site and with depth. A limited investigation on the strength of the sandstones was also carried out.

From the colour classification of beds and from the liquid limit scrapes, the site was divided into three zones of bedrock strength. During the investigation zone 1 was called after the 'Mangla brown clays', zone 2 the 'Sukian red clays' and zone 3 the 'Jari brown clays'. Table XVI gives details of the liquid limit distribution in the clay beds of each zone.

T A B L E XVI

Clay/Silt* Bed number	Range of Liquid Limits				% clay & silt beds in bedrock
	Below 40%	40-50%	50-60%	Above 60%	
Zone 1 ch.117-210					
0/1	53.6	41.1	5.3	0	
1/2	48.1	27.6	4.3	0	
2/3	95.7	4.3	0	0	
Average for the zone	70%	26%	4%	0%	48%
Zone 2 Ch. 210-329					
3/4	0	15	53.7	31.2	
5/6	21.1	29.6	48.5	1.8	
11/12	16.1	73.6	10.2	-	
14/15	0	9.3	58.7	32	
16/17	2.8	32.2	57.2	7.8	
17/18	18.6	32	42.4	29	
18/19	5.1	68.3	26.5	0	
19/20	5.2	82.2	12.6	0	
20/21	16.0	80.6	3.4	0	
22/23	25.0	52.5	22.5	0	
23/24	20.4	47.3	31.5	1	
Average for the zone	14%	47%	35%	4%	38%
Zone 3 Ch. 329-351					
25/26	55.8	39.2	5.0	0	
26/27	50.0	50.0	0	0	
28/29	36.7	51.3	12.0	0	
30/31	0	34.8	48.8	16.2	
31...	53.4	33.8	12.7	0	
Average for the zone	48%	40%	11%	1%	67%

Average of liquid limit distribution for all zones:

Below 40%	:	37%
Between 40-50%	:	41%
Between 50-60%	:	20%
Above 60%	:	2%

Notes:

a) *Clay beds are indicated by numbers 0/1; 1/2; 2/3 etc. These are the sandstone bed numbers above and below the clay bed. Sandstone bed numbers are shown on figs. 10, 11 and 12.

b) All percentages shown are calculated by measurement on the true stratigraphic thickness of the beds.

c) A total of 38% of all the clay/silt bedrock, as measured along the centreline, was tested (some 5,800 liquid limit samples); the remainder was estimated.

d) Zone 2 extends over approximately 70% of the length of the dam.

e) Silt/clay: sandstone bed ratio ca. 1:1.

Variation of Strength with Depth

To investigate the variation of effective shear strength with increasing depth, four independent sets of clay bedrock samples were taken from representative red* and black* beds as follows:

1) Samples 55379 and 55381 from Trench SK 20 (figs. 51 & 52);

2) Samples 55388, 55389 and 55390 from Trench SK 12A (Fookes 1964);

3) Sample 58121 together with NX core samples MDC 786, 787 from borehole 750; (fig. 39);

4) Samples 58132, -28, -29, -31, -33 from Trench SK 26 (figs. 42, 43 and 44).

The test results are given in summary in Tables VIII to XII.

In each of the above sets the samples were taken from a single geological horizon, down dip at increasing depths. The boreholes were located so as to recover samples from the appropriate beds at 35' to 45' depth. Unfortunately owing to poor core recovery together with loss of samples on trimming, the results from boreholes were not considered reliable enough for firm conclusions to be drawn from these depths. Repeat holes were not drilled.

* These colour beds were considered at the time likely to produce the weakest samples.

Results from the sets of tests in the trenches showed that below the weathered zone there was no significant increase in effective shear strength with increasing depth. In some cases there was a slight increase in c', without much change in Ø', but the evidence was not conclusive. Values of c' and Ø' are plotted against depth below original ground surface in fig. 39.

Trench SK 26 was studied in greatest detail; results show a marked drop of Ø' (to 14°) in the weathered zone, compared with an average value of 19° below the zone down to the tested depth of 36'. The most marked drop occurred in the first 5' below top of bedrock, then a decreasing drop for the next 5' to 10' after which there was no significant change.

Weathered clay can be seen by eye in the field. The first 5' appears to be markedly weathered and has a crumbly texture. Iron staining on fissure planes is common and sometimes there is a total colour change to a khaki/brown. From 5' - 15' the crumbly texture is not apparent and the colour change is not apparent or is patchy, but iron staining on fissure surfaces is still common. Even at depths of 36', some iron staining on fissures can be observed. The term 'weathered zone' was reserved for clay which has a crumbly texture and occurring immediately below the bedrock surface*. On some geological sections (e.g. fig. 45) the depth of the weathered zone has been shown. Over the site generally the black clays have weathered a little more than the red or brown clays.

*Note discussion on weathered London Clay, Skempton (1964) p.93

Although the number of results on index tests were relatively few no significant changes of property related to weathering were apparent. The small changes that occurred (with the exception of sample 58121, BH 750, fig. 39) in Atterberg limits could be related to original clay fraction and the decrease of density near surface could be related to appearance of the crumbly characteristics in the near surface soil. The soil chemistry was not investigated.

It is of interest to compare these findings with those of Tourtelot (1962) on the massive Pierre Shale (loc.1.) whose plastic and liquid limits have fairly similar ranges to the Upper Siwalik clays. In addition to index properties detailed mineral analyses were carried out. In summary, Tourtelot reported that three zones could be recognised; a soil (a foot or so thick), partly weathered brownie gray (sic) shale some 10' thick and a lightly weathered zone some 50' thick, of soft black shale in which joints and bedding planes were somewhat stained with iron oxides and coated with crystals of gypsum. The test data suggested that extreme weathering produced the soil and the liquid limit and plastic index of this zone was increased. Plastic limit remained uniform (at Sukian, little change occurred in any of the limits). The chemistry of the shales showed clear changes, sulphide sulphur in the fresh shale was oxidised to sulphate sulphur in the weathered material and was concentrated there by ground evaporation carrying soluble salts to the surface. Ferrous iron in the fresh material became ferric iron in the weathered

but there was little change in the total iron. Part of the sodium was lost by weathering and was partly replaced by calcium and magnesium in ion exchange reactions. Some calcium was added to the weathered material by accumulation of calcium carbonate near the surface. Total moisture remained about the same along the weathering profile (as at Sukian (?)) but the amount of H_2O + increased with weathering and the amount of H_2O- decreased. These changes are similar to others reported in the literature and as Tourtelot's colour changes upwards from black to brown/grey to a surface soil, and as the iron oxide coatings and calcite concretions are similar to the conditions observed at Sukian, it would not be unreasonable to conclude that the Pierre shale oxidation changes and the changes at Sukian are somewhat similar though less severe at Sukian. More work at Sukian to relate strength and weathering would be of interest.

It was concluded that the Sukian weathered zone with low effective strengths extends for approximately the first 5' below the top of bedrock and that some weathering affecting strength to a lesser extent occurs for the next 5' - 10'. Below this the effective strengths do not appear significantly affected.

The weathered zone was not found at Mangla or Jari and only occurs at certain limited localities at Sukian.

Variation of Strength along the Centreline

The results of investigation into the variation of soil properties along the length and breadth of individual clay beds are shown as follows:

a) As a graphical plot of index properties against geology shown for trench SK 12A; trench 12B; trench SK 17A, fig. 45; trench SK 17B; trench SK 20, figs. 51 and 52; trench SK 26, figs. 42, 43 and 44; trench SK 26A;

b) As effective shear strength results from samples along the same geological horizon, figs. 51, 52; 42, 43 & 44.

c) Details of these results are given in Tables VIII to XII, fig. 53 and Fookes (1964).

Inspection of the graphs show that variations of liquid limit are in agreement with the geological description of the bed, viz., silts have the lowest liquid limit and clays have the highest. Where one geological horizon was sampled (e.g. trench SK 20, SK 26 or 17A, fig. 45), the range of liquid limit results was narrow and generally within sampling and testing error. This testing error had been found by checks in the laboratory to be $\pm$ 5%. It was concluded that liquid limit properties along geologically continuous horizons within clay beds, over the distances examined, were similar.

A similar conclusion was reached for effective strengths. Inspection of results of samples from different locations along geologically continuous horizons (e.g. Trenches SK 12A, SK 20, or SK 26A and B) showed marked uniformity of results (where not affected by weathering). The longest distance of geologically continuous horizon within a clay bed that was tested was over 700' (in clay bed 14/15, fig. 11).

The thickness of this particular horizon was 4' - 5'; it was contained within a bed approximately 20' thick.

These conclusions from the testing data are confirmed to some extent by inspection of the geological maps and exposures in the field. The beds are of fairly consistent lithology in directions parallel to the bedding and deposition or structural discontinuities although certainly existing (e.g. washouts, plate 16) are clearly seen on 100% exposure of the beds. They gave investigation difficulties when establishment of continuity of beds depended only on drill evidence. Occasionally some beds did show significant changes in property along the bedding plane and on examination this was obviously due to disturbances of the material on deposition or soon after (by false bedding, clay ball zones or bottom structures). The presence of these irregularities serve to increase the strength of the beds in the bedding direction as their irregularity hinders development of planar failure surfaces. Further work on these lines and on relating strength features to the various sedimentary environments should prove rewarding and of importance in design where the strength of the bedding plane surface is taken into consideration.

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SUMMARY OF TRIAXIAL RESULTS ON CLAY BEDROCK

Trench No.	Sample No.	Coordinates ft.	Depth below	Grading Clay %	Grading Sand %	Liquid Limit %
SKB-2	47214 (B)	E 40232 N 78882 El. 1144.3	OGL. 20.4' TBR. 18'	22-35	10-25	45-54
SKB-2	47217 (B)	E 40232 N 78882 El. 1143.2	OGL. 21.5' TBR. 19	29-49	1-11	100-140
	47218 (B)	E 40232 N 78882 El. 1143.0	OGL. 21.7' TBR. 19'	33-35	12-15	93-117
	47220 (B)	E 40232 N 78882 El. 1142.3	OGL. 22.4' TBR. 20'	29-31	10-12	114-130
SKB-2	47221 (B)	E 40232 N 78882 El. 1141.3	OGL. 23.4' TBR. 21	19-34	1-4	46-52

TABLE VIII (i)
(Continued on VIII (ii))

TABLE VIII (ii)
(Continued from VIII (i))

Sample No.	Field Density lb/cu.ft.	Unconf. Compr. Strength (lb/sq.in)	Disinteg-ration Time	C' (lb/sq.in)	ø'	Remarks
47214 (B)	120	50		0 0	26° 25°	Peak Clay above Ult "Bentonite" Red Silty Soft
47217 (B)	105			0 5	36° 23°	Peak "Rough" Surface of Ult failure
47218 (B)	98			"Bentonite"		
47220 (B)	106			7 5	15° 15°	Peak "Smooth" Surface of Ult failure.
47221 (B)	127	200		28 0	27° 27°	Peak Clay below Ult "Bentonite" Black Silty Soft

TABLE VIII (iii)
(Continued on VIII (iv))

Trench No.	Sample No.	Coordinates ft.	Depth below	Grading Clay %	Grading Sand %	Liquid Limit %
SKG-2	49573 (R)	E 42800 N 82208 El. 1198.5	OGL. 22' TBR. 1'	25	5	50-55
SK-6	50940 (R)	Ch. 258.9 Off. 450 El. 1174	OGL. 5' TBR. 2'	29-32	6-8	60-66
SK-17	50944 (R)	Ch. 303.1 Off. 215 El. 1153	OGL. 10' TBR. 4'	20-24	4-7	47-50
SK-13	50945 (R)	Ch. 328.3 Off. 198 El. 1202	OGL. 6' TBR. 5'	35	1	52-61
SK-25	50952 (R)	Ch. 349.7 Off. 950 El. 1228	OGL. 6' TBR. 5'	47	3	56-60

E = Easting (Mangla
N = Northing Coordinates)

Ch. = Chainage (Sukian
Off. = Offset Coordinates)

El. = Elevation
OGL. = Original Ground Surface Level
TBR. = Top of bedrock

TABLE VIII (iv)
(Continued from VIII (iii))

Sample No.	Field Density lb/cu.ft.	Unconf. Compr. Strength (lb/sq.in)	Disinteg-ration Time	C' (lb/sq.in)	ϕ'	Remarks
49573 (R)	134	93	1 hr: 50%	8 7	$18\frac{1}{2}^{\circ}$ 18°	Peak Brown Clayey Ult. Soft
50940 (R)	125	87	2 hrs: 100%	8 6	14° 12°	Peak (Curved envelope) Ult. (Weathered) Black Clayey Soft
50944 (R)	130	97	30 hrs: negligible	20 11	23° 18°	Peak Red Clayey Ult. Hard
50945 (R)	131	123	2 hrs: 50%	20 4	$18\frac{1}{2}^{\circ}$ $14\frac{1}{2}^{\circ}$	Peak Red Clayey Ult. Soft
50952 (R)	130	43	2 hrs: 90%	7 5	20° 16°	Peak Topmost clay, next Brown Ult. to base of gravel Clayey (weathered) Soft.

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SUMMARY OF TRIAXIAL RESULTS ON CLAY BEDROCK

Trench No.	Sample No.	Coordinates ft.	Depths below O.G.L. & T.B.R.	Grading Clay %	Grading Sand %	Liquid Limit %	Field Density lb/cu.ft. (& M/C%)	Unconf. Compr. Strength lb/sq.in.	Disintegration time Mins.	Disintegration Class
SK-6	55347 (L)	E. 35029 N. 79699 El. 1172	OGL 7.9' TBR 5.9'	50	4	64-73	133	28	9	D
	55386 (A)	E. 35029 N. 79699 El. 1174	OGL 6.2' TBR 4.2'	43	8	61-64	126	29	9	D
	55387 (A)	E. 35029 N. 79699 El. 1172	OGL 8.1' TBR 2.1'	50	7	60-65	131	49	3	D
SK-22	55342 (R)	Ch.337+04 Off.460 El. 1169	OGL 16.6' TBR 14'	19	12	43-55	129	87	Negligible in 20 hours.	A⁻
SK-17A	55377 (W)	Ch.308+50 Off.260 El. 1154	OGL 9' TBR 5'	53	1	58-64	134	24	5% in 20 hours	A⁻
	55378 (W)	Ch.308+60 Off.258 El.1153	OGL 10' TBR 6.5'	43	2	56-58	136	147	10% in 20 hours	A⁻

TABLE IX (i)

(CONTINUED on IX (ii))

TABLE IX (ii)
(Continued from IX (i))

Sample No.	Shear Strength C' lb/sq.in.	ø'		Coeff of Consolidation sq.ft. per month at consolidation pressure. 20	60	120 lb/sq.in.	Visual Classification
55347 (L)	0	26°	Peak	34	4.0	0.54	Black
	0	22½°	Ult.				
	0	18°	Rem.				
55386 (A)	7	17°	Peak	96	2.3	0.48	Clayey
	5	17°	Ult.				
55387 (A)	9	24°	Peak	27	1.4	2.0	Hard
	0	23°	Ult				
55342 (R)	22	28°	Peak	19	-	8.2	Brown Silty soft
	8	29½°	Ult.				
	6	23°	Rem.				
55377 (W)	9	18½°	Peak	18	9.1	0.14	Red Clayey
	8.5	16°	Ult.				
55378 (W)	30	16°	Peak	27	1.7	0.28	Hard
	8	15°	Ult.				

Trench No.	Sample No.	Coordinates ft.	Depths below O.G.L. & T.B.R.	Grading Clay %	Grading Sand %	Liquid Limit %	Field Density lb/cu.ft. (& M/C%)	Unconf. Compr. Strength lb/sq.in.	Disintegration Time Mins.	Class
SK-20	55379 (W)	E. 41055 N. 79300 El. 1149	OGL 12.6' TBR 11.5'	33	2	54-57	134	114	120	B
	55381 (W)	E. 41045 N. 79270 El. 1159	OGL 4.0' TBR 1.8'	43	3	54-63	120	26	240	B
SK-12A	55388 (W)	E. 39560 N. 79100 El. 1053.5	OGL 16' TBR 13.0'	41	1	56-62	133	57	70	B
	55389 (W)	E. 39545 N. 79075 El. 1058	OGL 12' TBR 8.5'	48	1	58-63	137	122	Negligible in 20 hours	A^-
	55390 (W)	E. 39520 N. 79040 El. 1070.5	OGL 3.6' TBR 0.6'	39	10	51-55	155	22	1	D

TABLE IX (iii)
(Continued on IX (iv))

TABLE IX (iv)
(Continued from IX (iii))

Sample No.	Shear Strength C' lb/sq.in.	∅'		Coeff of Consolidation sq.ft. per month at consolidation pressure. 20	60	120 lb/sq.in.	Visual Classification
55379 (W)	24	22°	Peak	57	0.57	0.085	Red Clayey Soft
	6	21°	Ult.				
55381 (W)	4	20°	Peak	110	16	0.28	(Weathered)
	0	18°	Ult.				
55388 (W)	18	25½°	Peak	68	17	0.11	Red Clayey Soft
	5	18°	Ult.				
55389 (W)	14	24½°	Peak	11	0.23	0.18	
	6	17½°	Ult.				
55390 (W)	3	20½°	Peak	76 (1 circle).	2.8	0.14	(Weathered)
	0	16°	Ult.				

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SUMMARY OF TRIAXIAL RESULTS ON CLAY BEDROCK

Dyke Section	Sample No.	Coordinates ft.	Depths below OG.L. & T.B.R.	Grading Clay %	Grading Sand %	Liquid Limit %	Field Density lb/cu.ft. (& M/C%)	Unconf. Compr. Strength lb/sq.in.	Disintegration Time Mins.	Disintegration Class
(2)	55394 (W)	Ch.246+2' Off.20.7' U/S El. 1194.5	OGL. 7' TBR. 5'	52	4	50	137 (14.7)	82	10	C
(3)	55395 (W)	Ch.260+83.5' Off.60' U/S El. 1190.8	OGL. 5' TBR. 4'	44	9	57	128 (20.8)	31	50% in 24 hrs.	B
(2)	55396 (A)	Ch.245+21' Off.20' U/S El. 1196	OGL. 7' TBR. 5'	27	8	50	138 (13.2)	222	60	C
(3)	55398 (R)	Ch.271+90' Off.85' U/S El.1180.3	OGL. 4' TBR. 2'	23	20	42	136 (14.1)	11	480	C
(2)	55400 (A)	Ch.233+77' Off.8.5' U/S	OGL. 6' TBR. 4.5'	18	10	45	142 (14.0)	128		C
(2)	58108 (W)	Ch.226+20' Off.420' U/S El.1135	OGL. 7' TBR. 6'	36	2	53	142 (12.3)	336	5% in 24 hrs. + crack	B

TABLE X (i)
(Continued on TABLE X (ii))

TABLE X (ii)
(Continued from X (i))

Sample No.	Shear Strength C' lb/sq.in.	Ø'		Coeff. of Consolidation sq. ft. per month at consolidation pressure. 20	60	120 lb/sq.in.	Visual Classification
55394 (W)	13 8.5	20° 17°	Peak Ult.	3.4	0.19	1.0	Red clayey soft
55395 (W)	5 3.5	17½° 16½°	Peak Ult.	13	1.9	10.5	Black clayey hard
55396 (A)	12 0	35° 28°	Peak Ult.	14	9.1	1.7	Red silty soft
55398 (R)	(10 * (5	26°) 25°)	Peak Ult.	13	9.2	1.8	Red silty soft
55400 (A)	32 4	29½° 24½°	Peak Ult.	33	6.3	3.1	Red silty soft
58108 (W)	16 6	32° 22½°	Peak Ult.	27	19	14	Red Clayey hard

* Uncertain

Dyke Section	Sample No.	Coordinates ft.	Depths below O.G.L. & T.B.R.	Grading Clay %	Grading Sand %	Liquid Limit %	Field Density lb/cu.ft. (& M/C%)	Unconf. Compr. Strength lb/sq.in.	Disintegration Time Mins.	Class
(1)	58109 (W)	Ch.188+70' Off.90' D/S El. 1167	OGL. 5' TBR. 5'	34	1	57	141 (10.2)	525		
(3)	58121 (W)	Ch.264+00' Off.37.5' D/S El.1200.0	OGL. 12' TBR. 11'	30	4	62	131 (16.3)	304		
(3)	58112 (W)	(2.5' East of 55378) (one 4" dia sample)		35	2	53	134 (17.2)	-		
B.H. 750 (3) (W)	786 (M.D.C.) (W) 787 (W)	E. 35404 N. 79486 El. 1144	OGL. 44'	26	8	56	140 (12.9)	-		

TABLE X (iii)
(Continued on TABLE X (iv)

TABLE X (iv)
(Continued from X (iii))

Sample No.	Shear Strength C' lb/sq.in.	Ø'	Coeff. of Consolidation sq. ft. per month at consolidation pressure 20	60	120 lb/sq.in.	Visual Classification
58109 (W)	15	29° Peak	15	8.1	5.4	Brown silty soft
	7	22° Ult.				
58121 (W)	35	$21\frac{1}{2}^{\circ}$ Peak	27	16	10.5	Black clayey hard
	10	21° Ult.				
58112 (W)			-	-	0.11	Red clayey soft (same as 55378)
B.H. 750 (3) (W) 786 (M.D.C.) (W) 787 (W)	18	$27\frac{1}{2}^{\circ}$ Peak	53	-	0.8	Black clayey hard (Same geological horizon as 58121)
	18	$19\frac{1}{2}^{\circ}$ Ult.				

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SITE INVESTIGATION 1963-64
SUMMARY OF TRIAXIAL RESULTS ON CLAY BEDROCK

Trench No.	Sample No.	Coordinates ft.	Depth Below O.G.L.& T.B.R.	Grading Clay %	Grading Silt %	Grading Sand %	Liquid Limit	Field Density lb/cu.ft. (& M/C %)	Unconf. Compr. Strength lb/sq.in.
SK-26	58132 (L)	E. 35080 N. 79610 El. 1181.5	OGL. 4' TBR. 4'	52	41	7	60	128 (15.6)	64
SK-26	58128 (L)	E. 35105 N. 79655 EL. 1170.5	OGL. 14' TBR. 14'	47	46	7	57	136 (15.7)	136
SK-26	58129 (L)	E. 35120 N. 79690 El. 1163	OGL. 21' TBR. 20'	45	45	4	62	138 (16.3)	150
SK-26	58131 (L)	E. 35138 N. 79710 El. 1157	OGL. 27' TBR. 25'	48	45	3	58	135 (16.4)	200
SK-26	58133 (L)	E. 35150 N. 79730 El. 1146	OGL. 36' TBR. 36'	49	46	3	60	136 (14.3)	45
SK-26-A	58135 (L)	E. 35140 N. 79560 El. 1178	OGL. 10' TBR. 10'	41	48	11	52	133 (21.4)	91
SK-26A	58134 (L)	E. 35070 N. 79590 El. 1178	OGL. 5.5' TBR. 5.5'	35	46	16	49	126 (14.1)	33

TABLE XI (i)
(Continued on XI (ii))

TABLE XI (ii)
(Continued from XI (i))

Sample No.	Shear Strength C' lb/sq.in.	Ø'	Coeff. of Consolidation sq.ft.per month. at consolidation pressure 20	60	120 lb/sq.in.	Visual Classification
58132 (L)	14 9.5	14° Peak 13½° Ult.	0.76 (.040)	- -	0.74 -	Black Clayey Hard(Weathered)
58128 (L)	23 11	19° Peak 15° Ult.	6.8 (.022)	13.5 (.010)	17 (.009)	
58129 (L)	15 5	21½° Peak 20° Ult.	45 (.015)	14 -	8 (.008)	Black Clayey Hard
58131 (L)	13 4	21° Peak 19° Ult.	77 (.011)	8 (.012)	6.8 (.010)	Black Clayey Hard
58133 (L)	12 7	21° Peak 18° Ult.	11.3 (.032)	8 (.014)	0.12 (.009)	Black Clayey Hard
58135 (L)	22 12	20° Peak 20° Ult.	30 (.013)	18 -	14.5 (.008)	Black Clayey Hard
58134 (L)	11 8	20° Peak 19½° Ult. (2 circles)	57 (.023)	6.5 (.014)	6.5 (.007)	Black Clayey Hard

Trench No.	Sample No.	Coordinates ft.	Depth below O.G.L.& T.B.R.	Grading Clay %	Silt %	Sand %	Liquid Limit	Field Density lb/cu.ft. (& M/C %)	Unconf. Compr. Strength lb/sq.in.
(Axis horizontal)	58124 (W)	Ch.219 +44' Off.41' U/S El. 1152'	OGL. 7.5' TBR. 6.5'	34	63	3	55	143 (12.5)	214
(Axis vertical)	58126 (W)	Ch.219+46' Off.38' U/S El. 1151.5	OGL. 8.5' TBR. 7.5'	32	62	6	48	141 (12.4)	143
BH-740	781	E. 39644	Depths 36.0'	23	73	4	56	133(16.7)	-
M.D.C.	784 W	N. 79220	36.5'	45	53	2	54	137(14.8)	-
	785 W	OGL.1157 at B.H.	37.2'				53		
BH-740	782 REM	E. 39644	Depths 44.3'	22	71	7	45	136	
M.D.C.	783 W	N. 79220	47.0'				45	(14.9)	-
		OGL.1157 at B.H.							
BH-750	788 W	E. 35405	Depths 28.2'	45	50	5	55	135	-
M.D.C.	789 REM	N. 79486	29.0'				61	(13.7)	
	790 W	OGL.1188 at B.H.	29.5'				52		

TABLE XI (iii)
(Continued on XI (iv))

TABLE XI (iv)
(Continued from XI (iii))

Sample No.	Shear Strength C' lb/sq.in.	ø'	Coeff. of Consolidation sq.ft.per month. at consolidation pressure 20	60	120 lb/sq.in.	Visual Classification
58124 (W) (Axis horizontal)	29.5 13	25° Peak 19° Ult.	27 (.015)	8.5 (.013)	4.8 (.022)	Black Clayey Hard
58126 (W) (Axis vertical)	18 14	23° Peak 18° Ult.	74 -	27 -	13 (.008)	
781 784 W	Inconclusive		48 (.015)	-	6.8 (.011)	Red Silty Soft
782 REM 783 W	(Peak not determined) 12	23° Ult.	-	33 (.011)	1.3 (R) (.014)	Red Silty Soft
788 W 789 REM	Inconclusive		25 (.05)	-	21 (R) (.009)	Black Clayey Hard

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SITE INVESTIGATION 1963-64

SUMMARY OF TRIAXIAL RESULTS ON CLAY BEDROCK

Trench No.	Sample No.	Coordinates ft.	Depth below O.G.L.& T.B.R.	Grading Clay %	Silt %	Sand %	Liquid Limit	Field Density lb/cu.ft. (& M/C %)	Unconf. Compr. Strength lb/sq.in.
Section 1.	58139 (S)	Ch. 182+10' Offset 94' D/S El.1217'	OGL. 33'	25	57	18	37	146 (6.3)	735
	58140 (S)	Ch. 182+10' Offset 105' D/S El.1223'	OGL. 22'	16	59	25	37	145 (1.5)	608
	58141 (S)	Ch. 182+10' Off. 117' D/S El. 1227'	OGL. 10'	25	68	7	45	146 (6.6)	710
	58145 (S)	E 41434 N 78745 El:-1183.8		14	74	12	35	123 (11.6)	100
	58146 (S)	E. 42234 N. 80707 El: 1158.2		10	70	20	30	125 (9.0)	-

REM = Remoulded.

(R) = Random sample
(W) = Selected as weak
(S) = Selected as strong
(A) = Selected as average
(B) = Bentonitic material
(L) = Sample requested by London.

This key also applies to Tables VIII, IX, X and XI.

M.D.C. = Mangla Dam Contractors.

TABLE XII (i)

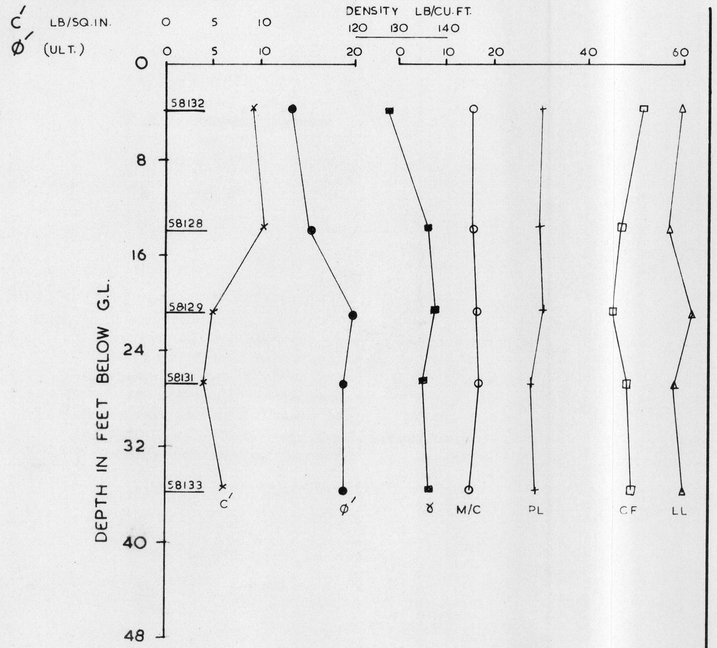
(Continued on Table XII (ii))

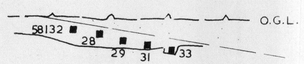
TABLE XII (ii)
(Continued from TABLE XII (i))

Sample No.	Shear Strength C' lb/sq.in.	ø'		Coeff. of Consolidation sq. ft. per month. at consolidation pressure. 20	60	120 lb/sq.in.	Visual Classification
58139 (S)	30 10	35° 27°	Peak Ult.	30 (.013)	34 (.009)	53 (.008)	Brown Silty Soft Clay
58140 (S)	25 6	36° 27½°	Peak Ult.	74 (.011)	35 (.007)	14 (.008)	- Do-
58141 (S)	32 10	30° 26°	Peak Ult.	15 (.030)	22 (.008)	17 (.010)	- Do-
58145 (S)	17	29°	Ult.	41 (.014)	92 (.008)	68 (.007)	Brown Silty Hard Clay.
58146 (S)	9	31½°	Ult.	56 -	81 (.007)	182 (.006)	- Do -

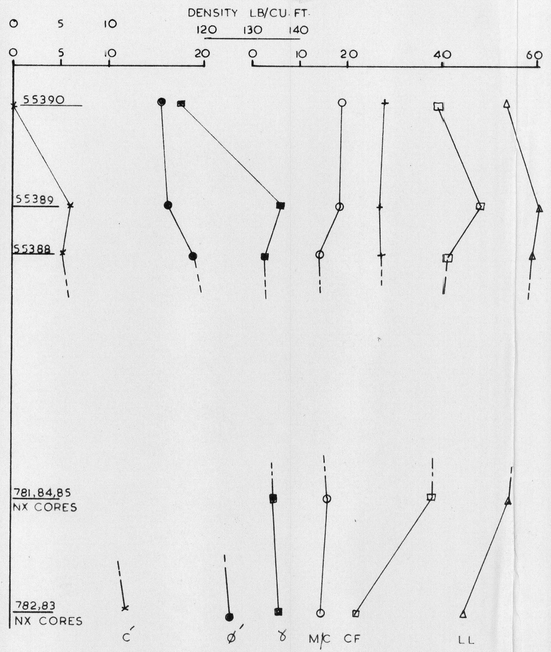
(Figures in brackets refer to my values in Cm 2/kg.)

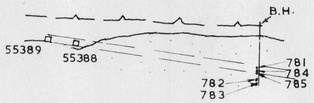
TRENCH SK-26



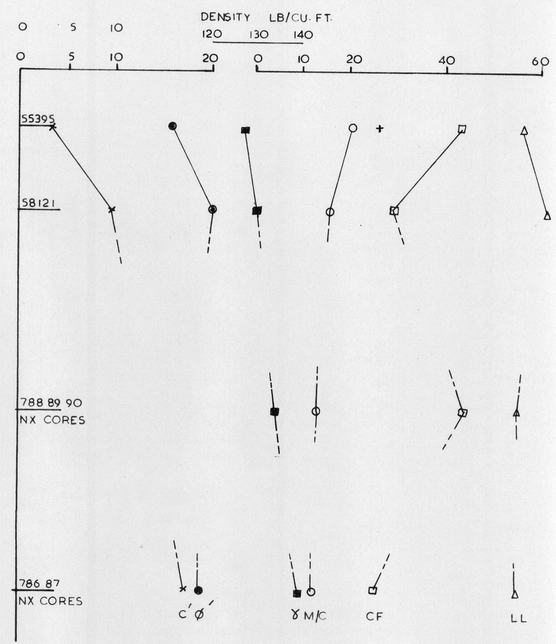


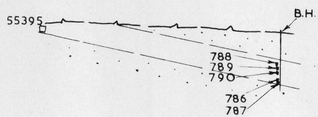
TRENCH SK 12A & B.H.740





B.H. 750 & EXCAVATION SAMPLES





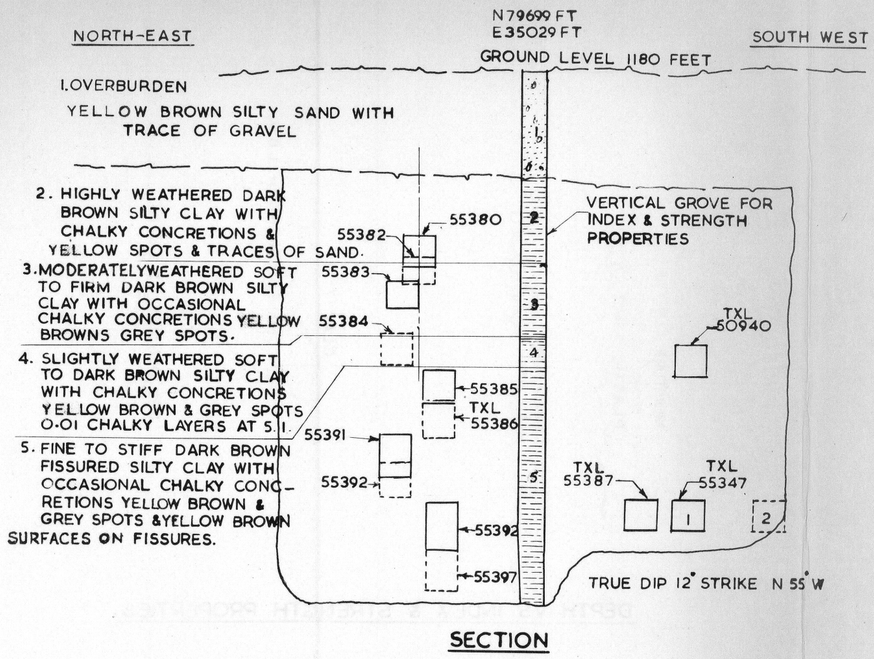
LEGEND

MOISTURE CONTENT	o
PLASTIC LIMIT	+
LIQUID LIMIT	△
DENSITY	■
CLAY %	□
C′	x
Ø′	●

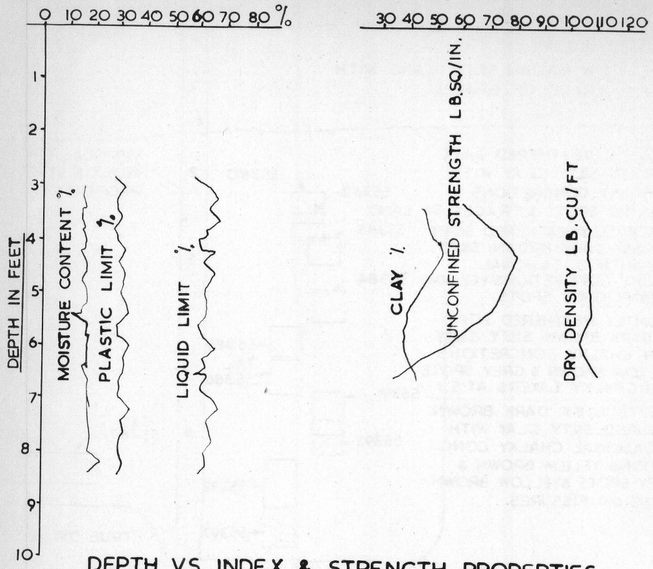
FOR LOCATION IN PLAN
SEE FIGS. 11 and 12.

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SITE INVESTIGATION 1963-64
SOIL PROPERTIES VS DEPTH
FIG. 39.



SECTION



DEPTH VS INDEX & STRENGTH PROPERTIES.

LEGEND

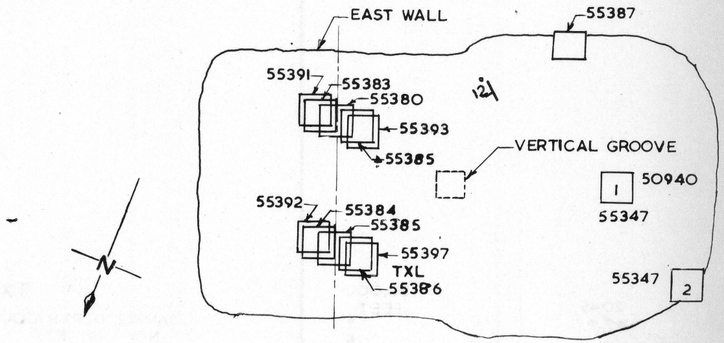
- OVERBURDEN.
- DIP STRIKE.
- SK-6 EXPLORATORY TRENCH.
- CLAY.
- 2045 OPEN PIT.

NOTES:-

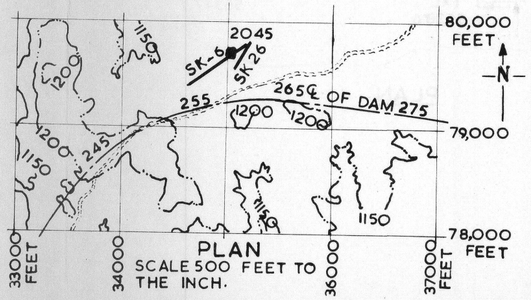
1 THE SECTION GIVES THE LOCATION OF TRIAXIAL BLOCK SAMPLES PROJECTED HORIZONTALY ON THE EAST WALL OF THE PIT.

2 THE PLAN GIVES THE LOCATION OF TRIAXIAL BLOCK SAMPLES. PROJECTED VERTICALLY ON THE BASE OF THE PIT.

3 THE ORDINATE AXIS OF THE GRAPH GIVES DEPTH OF SAMPLE BELOW ORIGINAL GROUND LEVEL. SAMPLES WERE TAKEN FROM THE VERTICAL GROOVE SHOWN ON THE PLAN & SECTION.



PLAN



PLAN
SCALE 500 FEET TO THE INCH.

TXL RESULT

SAMPLE NO	DEPTH IN FT	LIQUID LIMIT %	FIELD DENSITY	C'	φ'
50940	5	60–66	125	9	11°
55347	7·9	64–73	133	0	25·5°
55386	6·2	61–64	126	5	17°
55387	8·1	60–65	129	0	23°

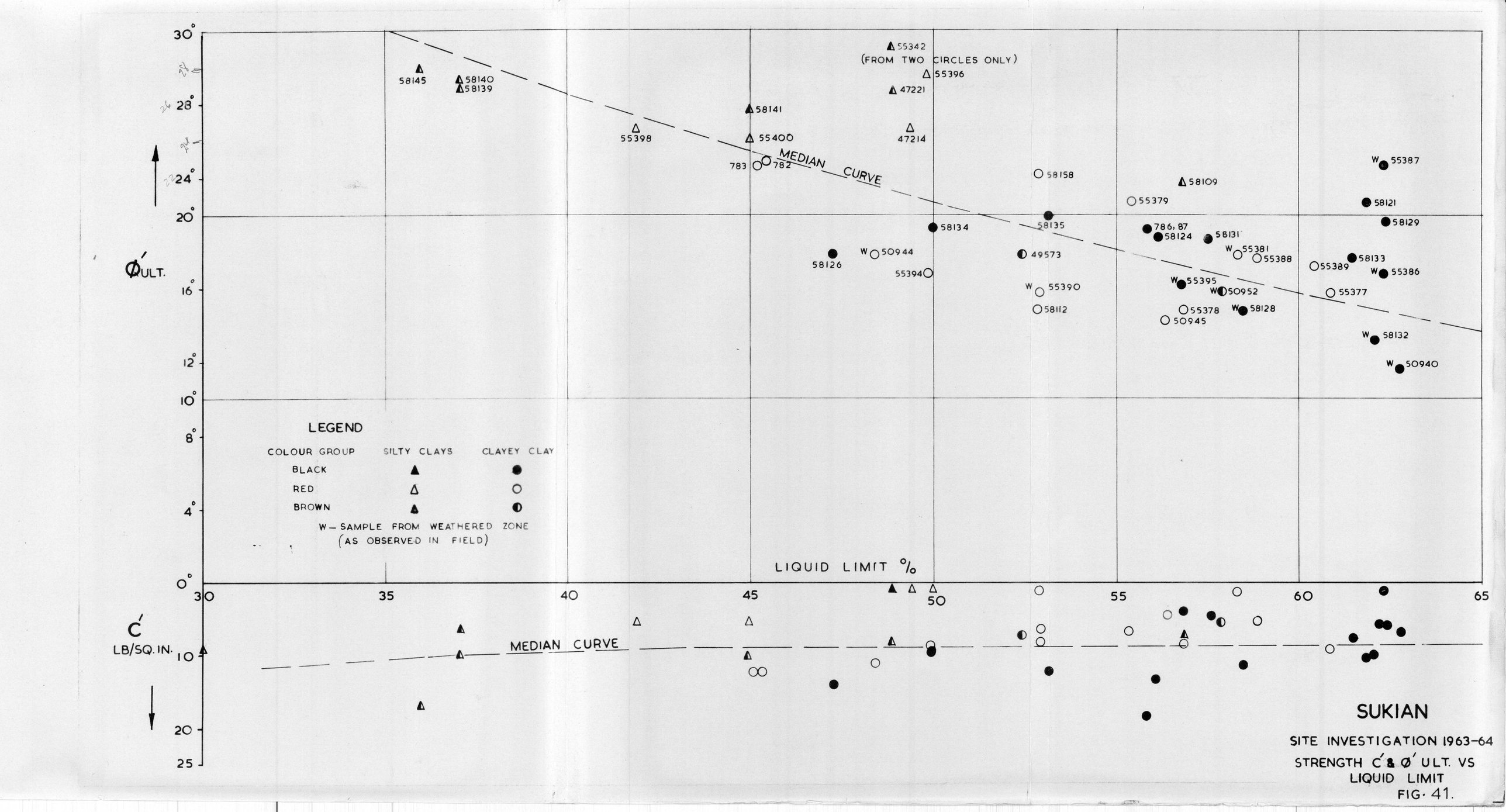
FEET 12 6 0 1 2 3 4 5 FT.

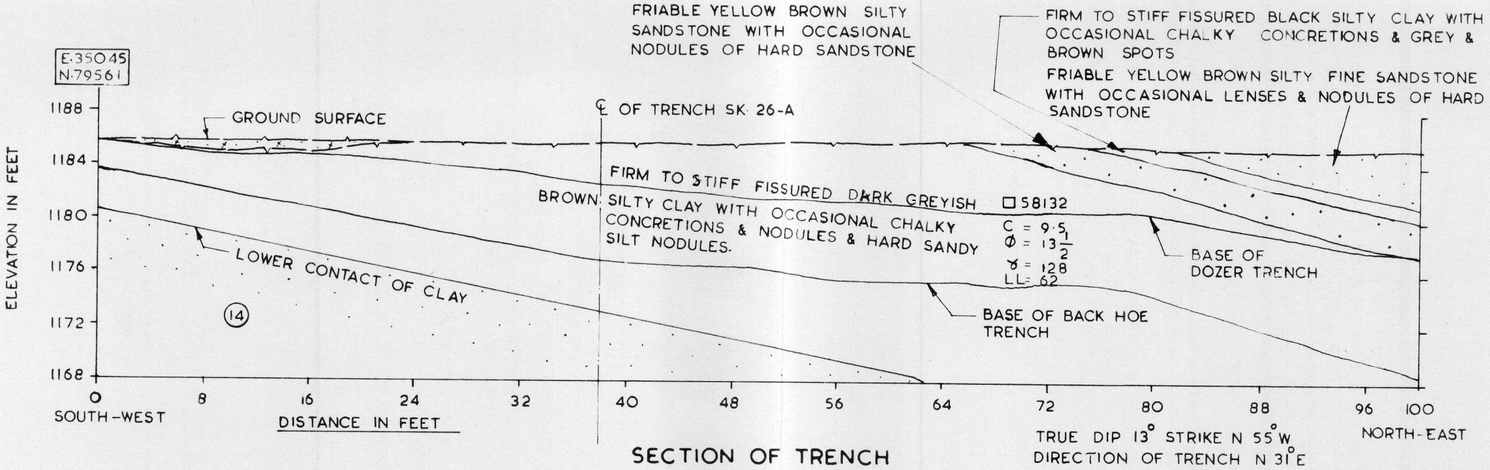
SUKIAN

SITE INVESTIGATION 1963-64

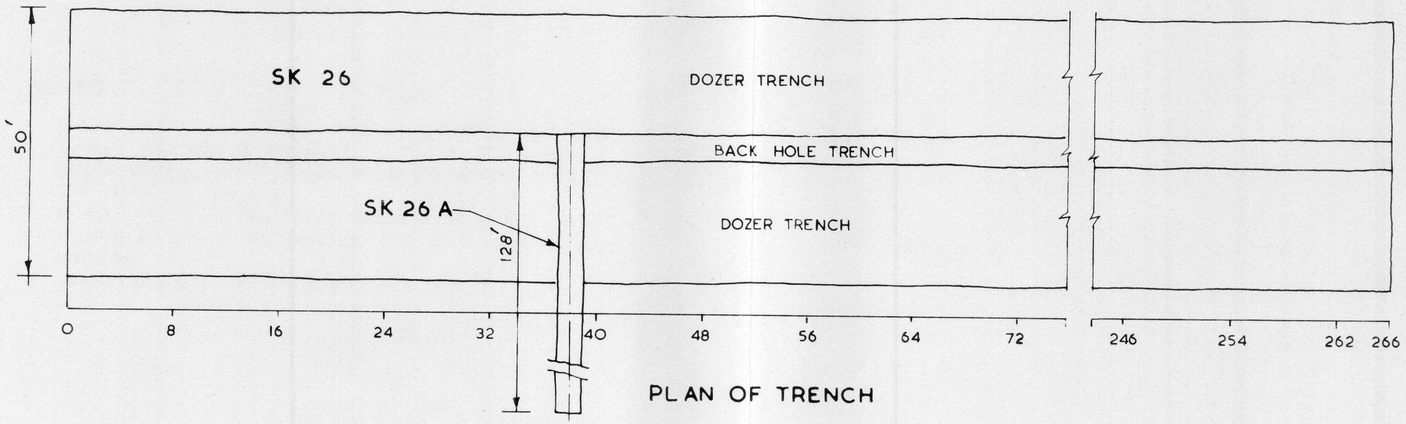
PIT. 2045

FIG. 40.

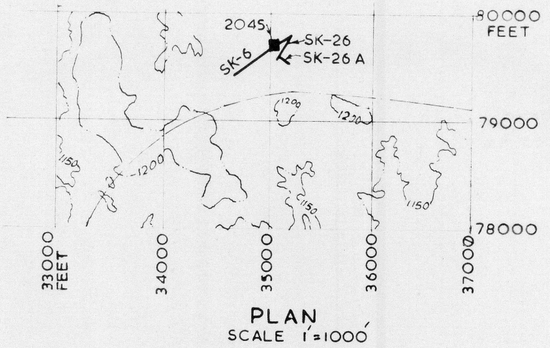

30°
28°
24°
20°
16°
12°
10°
8°
4°
0°
Ø' ULT.
58145
58140
58139
55398
58141
55400
783
782
55342
(FROM TWO CIRCLES ONLY)
55396
47221
47214
MEDIAN CURVE
58158
58109
55379
W 55387
58121
58129
58134
58135
786, 87
58124
58131
W 55381
55388
58133
55389
W 55386
58126
W 50944
55394
49573
W 55390
58112
W 55395
W 50952
55377
55378
50945
W 58128
W 58132
W 50940
LEGEND
COLOUR GROUP
SILTY CLAYS
CLAYEY CLAY
BLACK
RED
BROWN
W — SAMPLE FROM WEATHERED ZONE
(AS OBSERVED IN FIELD)
LIQUID LIMIT %
30
35
40
45
50
55
60
65
C'
LB/SQ. IN.
10
20
25
MEDIAN CURVE
SUKIAN
SITE INVESTIGATION 1963-64
STRENGTH C' & Ø' ULT. VS
LIQUID LIMIT
FIG. 41.



SECTION OF TRENCH



PLAN OF TRENCH



PLAN
SCALE 1"=1000'

LEGEND

- OVERBURDEN
- SANDSTONE
- CLAY

NOTES:-

1 BLOCK SAMPLES WERE TAKEN FROM WHAT WAS JUDJED BY EYE TO BE EXACTLY THE SAME GEOLOGICAL HORIZON

2 SANDSTONE BED NUMBER IS SHOWN THUS ····· (14)

SCALE 0 8 16 FEET

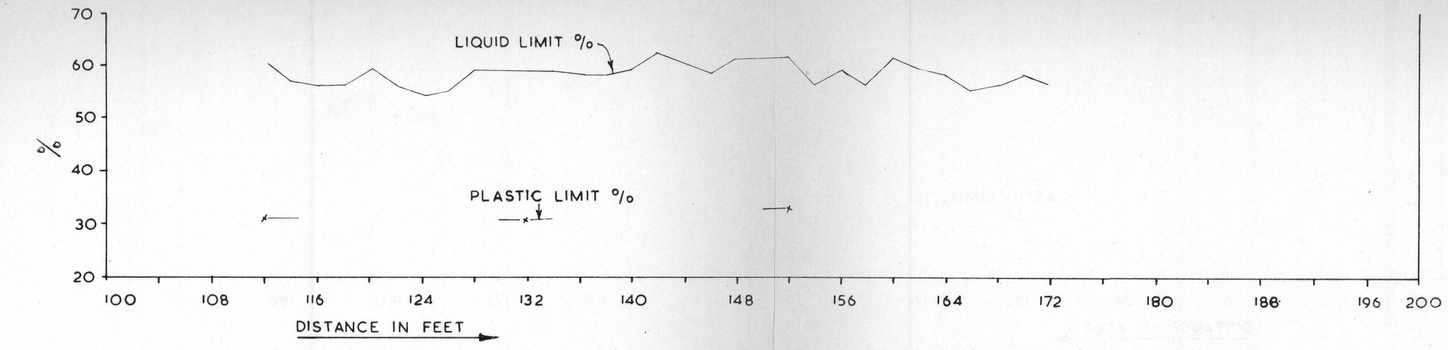
SHEET 1 DISTANCE 0- 100'
" 2 " 100·200'
" 3 " 200·266'

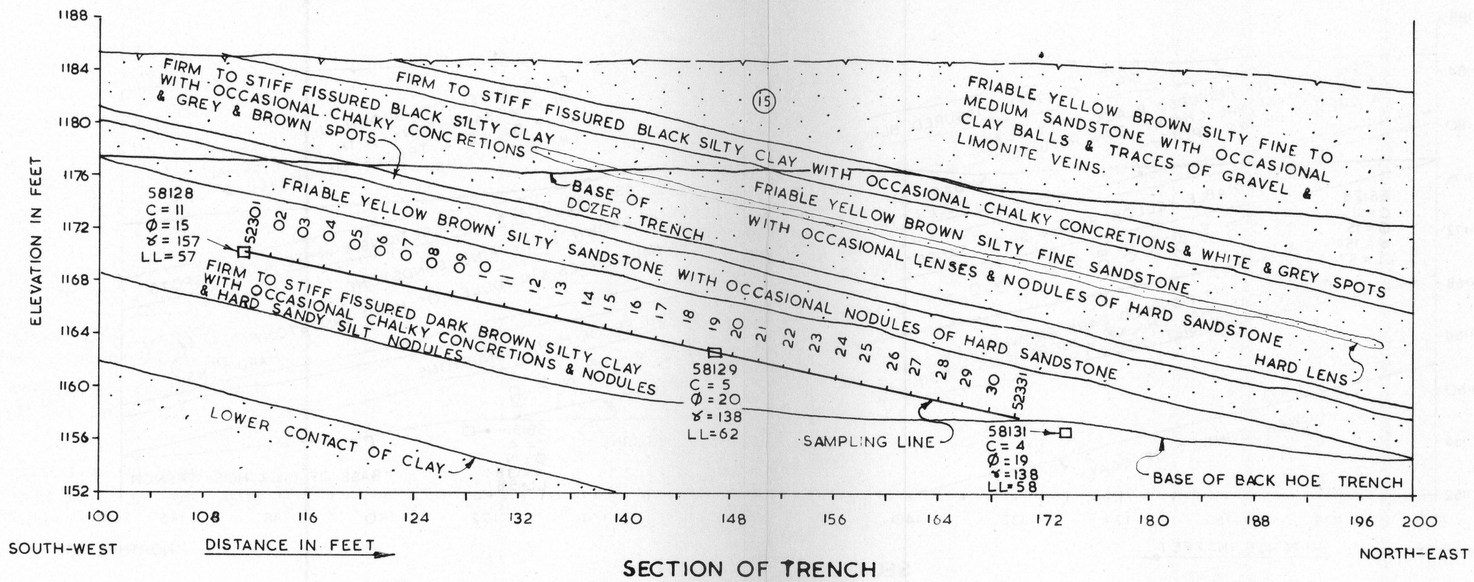
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SITE INVESTIGATION 1963-64
TRENCH SK 26

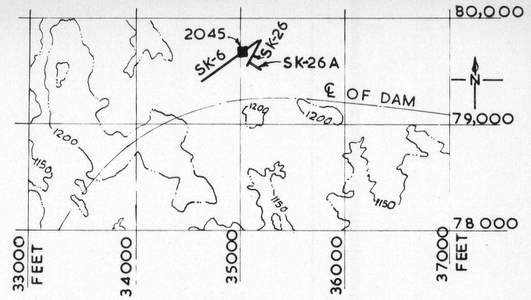
(SHEET 1 OF 3)

FIG. 42





SECTION OF TRENCH



PLAN
SCALE: 1" = 1000'

NOTES :-

1. LIQUID LIMIT TESTS WERE MADE ON SAMPLES TAKEN FROM 2 FEET CENTRES AS SHOWN.
2. BLOCK SAMPLES WERE TAKEN FROM LOCATION SHOWN ON THE LOCATION THUS: □
3. BLOCK SAMPLES WERE TAKEN FROM WHAT WAS JUDGED BY EYE TO BE EXACTLY THE SAME GEOLOGICAL HORIZON
4. SANDSTONE BED NO. IS SHOWN THUS (15)

LEGEND

SANDSTONE

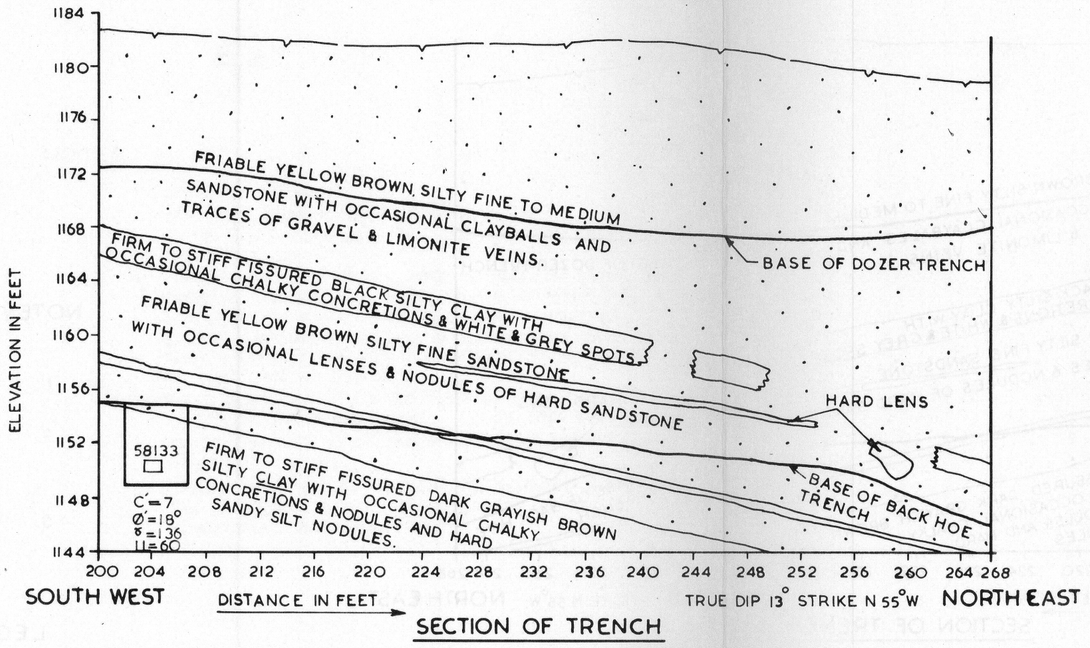
CLAY

SAMPLING LINE

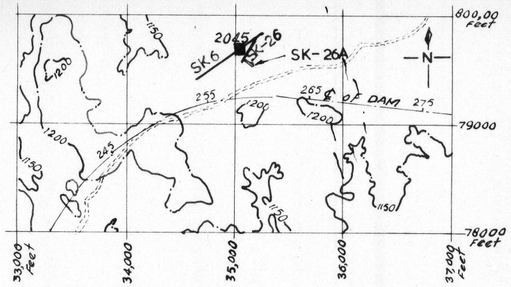
SUKIAN

SITE INVESTIGATION 1963-64
TRENCH SK 26
(SHEET 2 OF 3)

FIG. 43.



SECTION OF TRENCH



PLAN

NOTES:

1. LIQUID LIMIT TESTS WERE MADE ON SAMPLES TAKEN FROM 2 FEET CENTRES AS SHOWN.
2. BLOCK SAMPLES WERE TAKEN FROM LOCATION SHOWN ON THE SECTION THUS ..... □
3. BLOCK SAMPLES WERE TAKEN FROM WHAT WAS JUDGED BY EYE TO BE EXACTLY THE SAME GEOLOGICAL HORIZON.

LEGEND

CLAY

SANDSTONE

SCALE 0 8 16 FEET

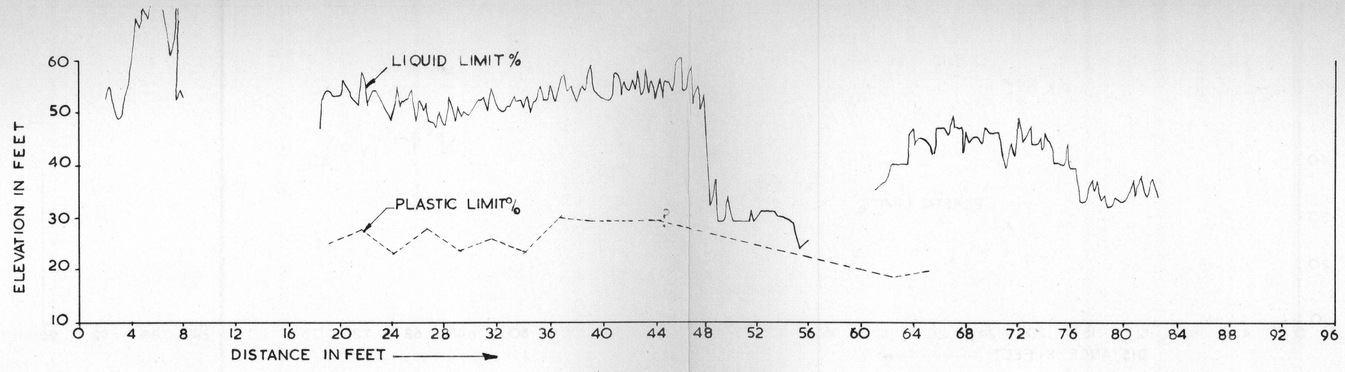
SUKIAN

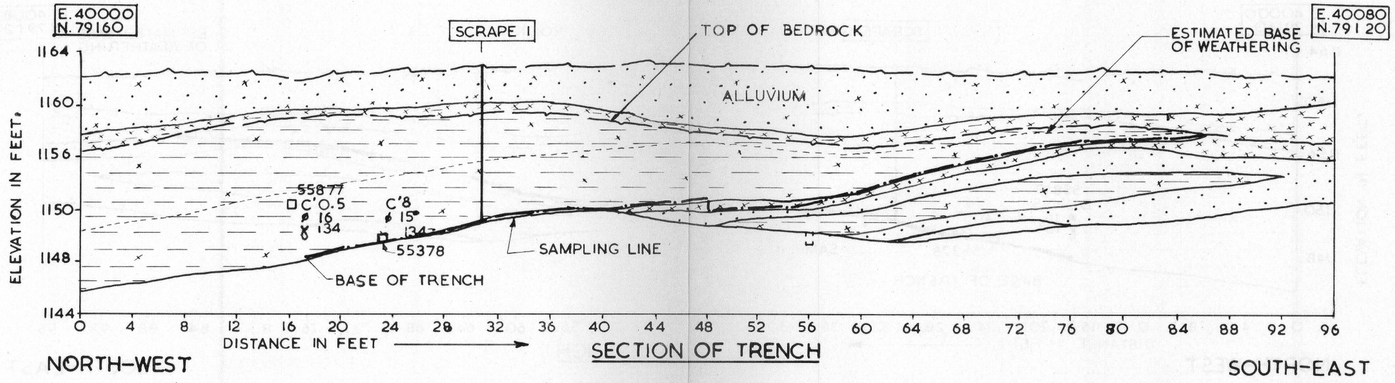
SITE INVESTIGATION 1963—64

TRENCH SK26

(SHEET 3 OF 3)

FIG. 44.

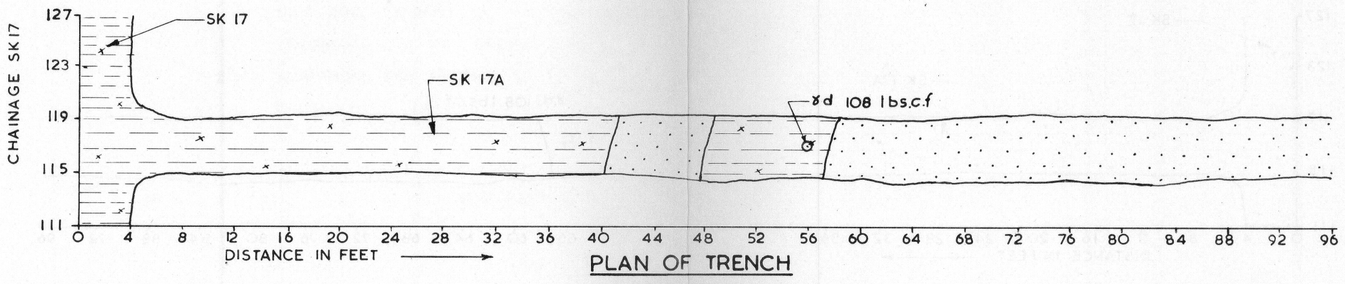




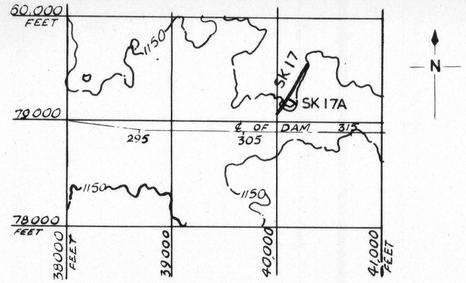
NORTH-WEST

SECTION OF TRENCH

SOUTH-EAST



PLAN OF TRENCH



PLAN

NOTES:

1. DIPS ARE APPARENT.
2. WORK THIS DRAWING WITH GEOLOGICAL MAP
3. LIQUID LIMITS TESTS WERE MADE ON SAMPLES FROM 0-25 FT. CENTRES.
4. PLASTIC LIMIT TESTS WERE MADE ON SELECTED SAMPLES INDIVDUAL RESULTS ARE SHOWN ON THE GRAPH.
5. ATTERBERG SAMPLES WERE TAKEN FROM HORZONTAL GROOVES FROM THE TRENCH WALL NEAR THE BASE OF TRENCH & FROM THE VERTICAL SCRAPES FROM THE WALL OF THE TRENCH.
6. FIELD DENSITY TESTS WERE MADE IN THE LOCATIONS SHOWN ON THE PLAN AND SECTION OF THE TRENCH.
7. BLOCK SAMPLES WERE TAKEN FROM LOCATION SHOWN ON THE SECTIONS.
8. LIQUID LIMIT RESULTS OF VERTICAL SCRAPES SHOWN ON THE GRAPH ARE PROJECTED DOWN DIP ON TO THE HORIZONTAL SAMPLING LINK.

LEGEND

- SILTY CLAY
- SILTY SAND
- SANDY SILT
- CLAYEY SILT
- SK17A — EXPLORATORY TRENCH.
- SANDSTONE
- DENSITY. PIT.
- 55377 — UNDISTURBED BLOCK SAMPLE

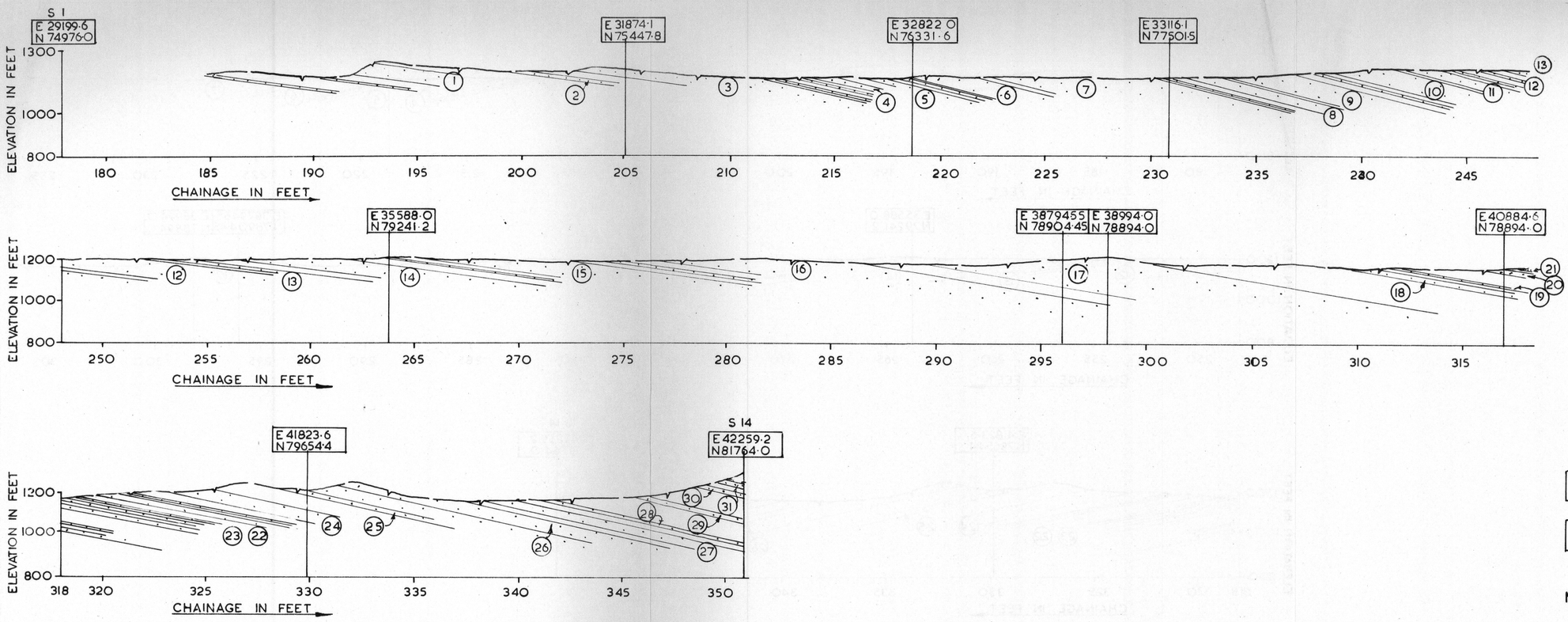
INCHES 1 2 0 5 10 15 20 FEET

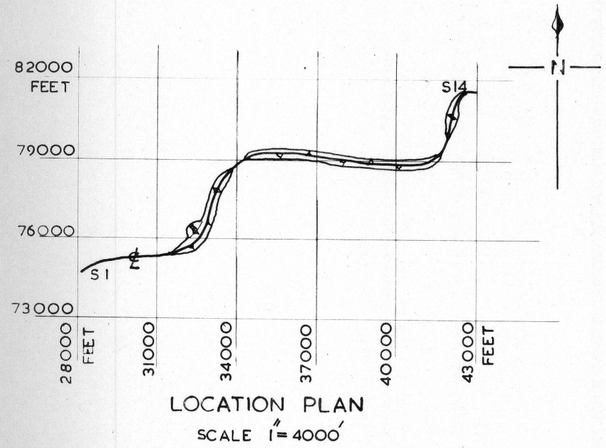
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SITE INVESTIGATION 1963-64

TRENCH SK17A

FIG. 45.





LOCATION PLAN
SCALE 1" = 4000'

LEGEND

SANDSTONE

NOTES:

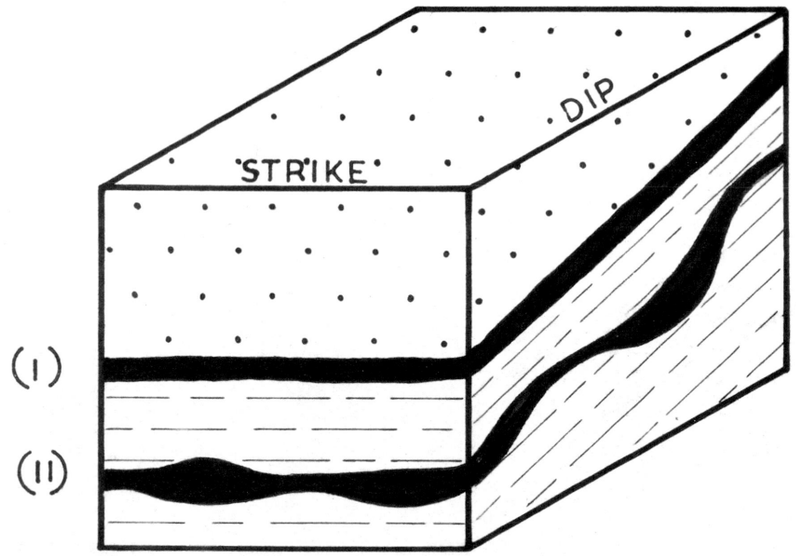
1. DIPS ARE APPARENT
2. OVERBURDEN IS NOT SHOWN
3. SANDSTONE BED NUMBER IS SHOWN THUS (18)

SCALE 0 400 800 FEET

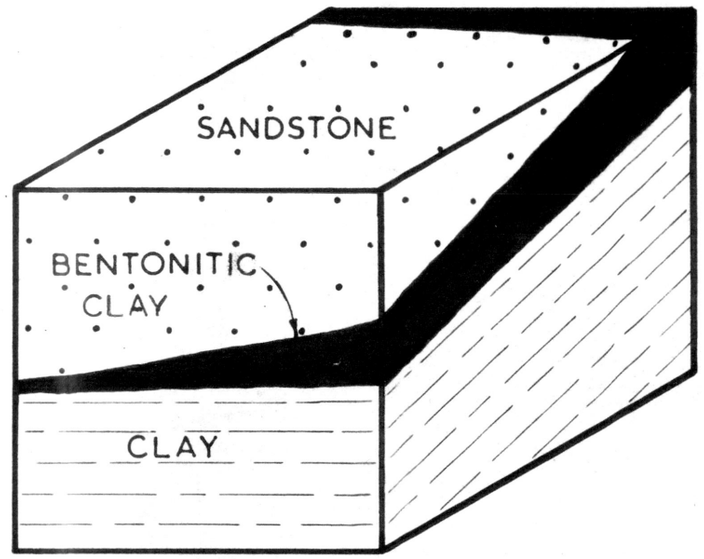
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SITE INVESTIGATION 1963–64
GEOLOGICAL SECTION ALONG ℄

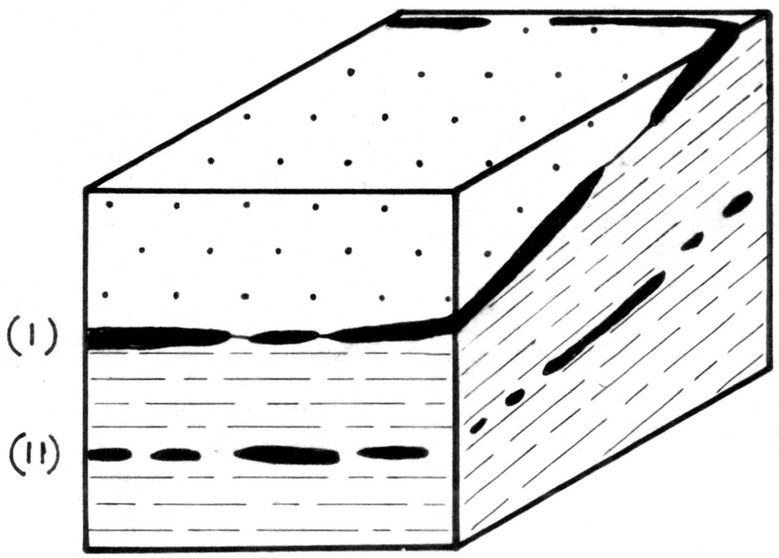
FIG. 46.



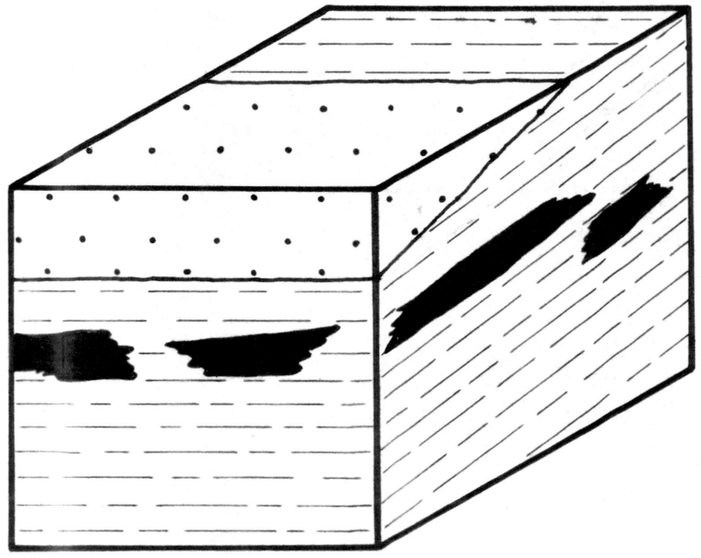
a) (I) NORMALLY BEDDED
(II) UNDULATING BEDDING



b) WEDGE BEDDED



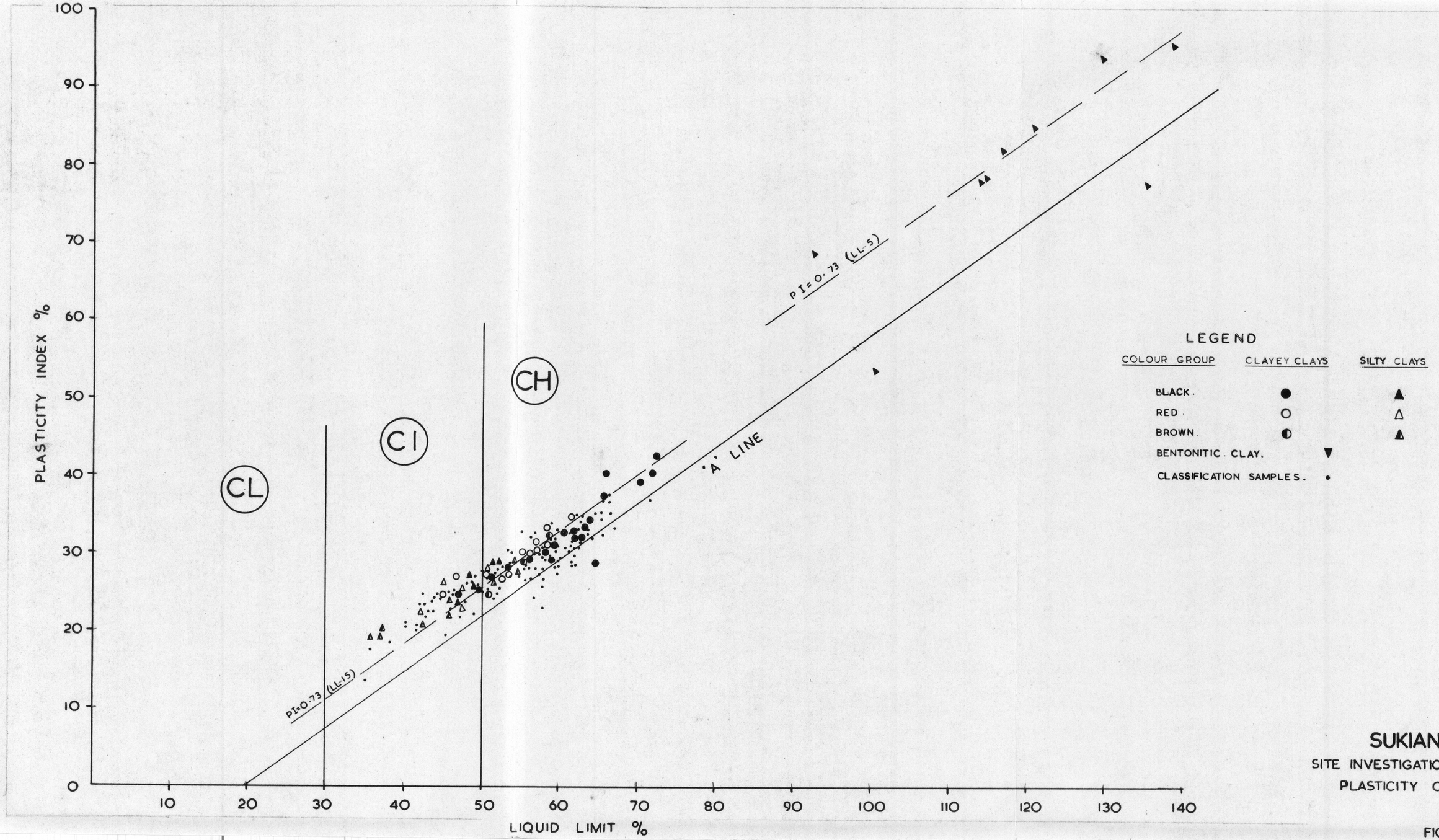
c) (I) LONG LENSES NORMALLY BEDDED
(II) INTERMITTENT LENSES



d) IRREGULAR BEDDING WITH SHARP OR GRADATIONAL BOUNDARIES

SUKIAN

SITE INVESTIGATION 1963-64
POSSIBLE FORMS OF
BENTONITIC CLAY BEDS
FIG. 47.

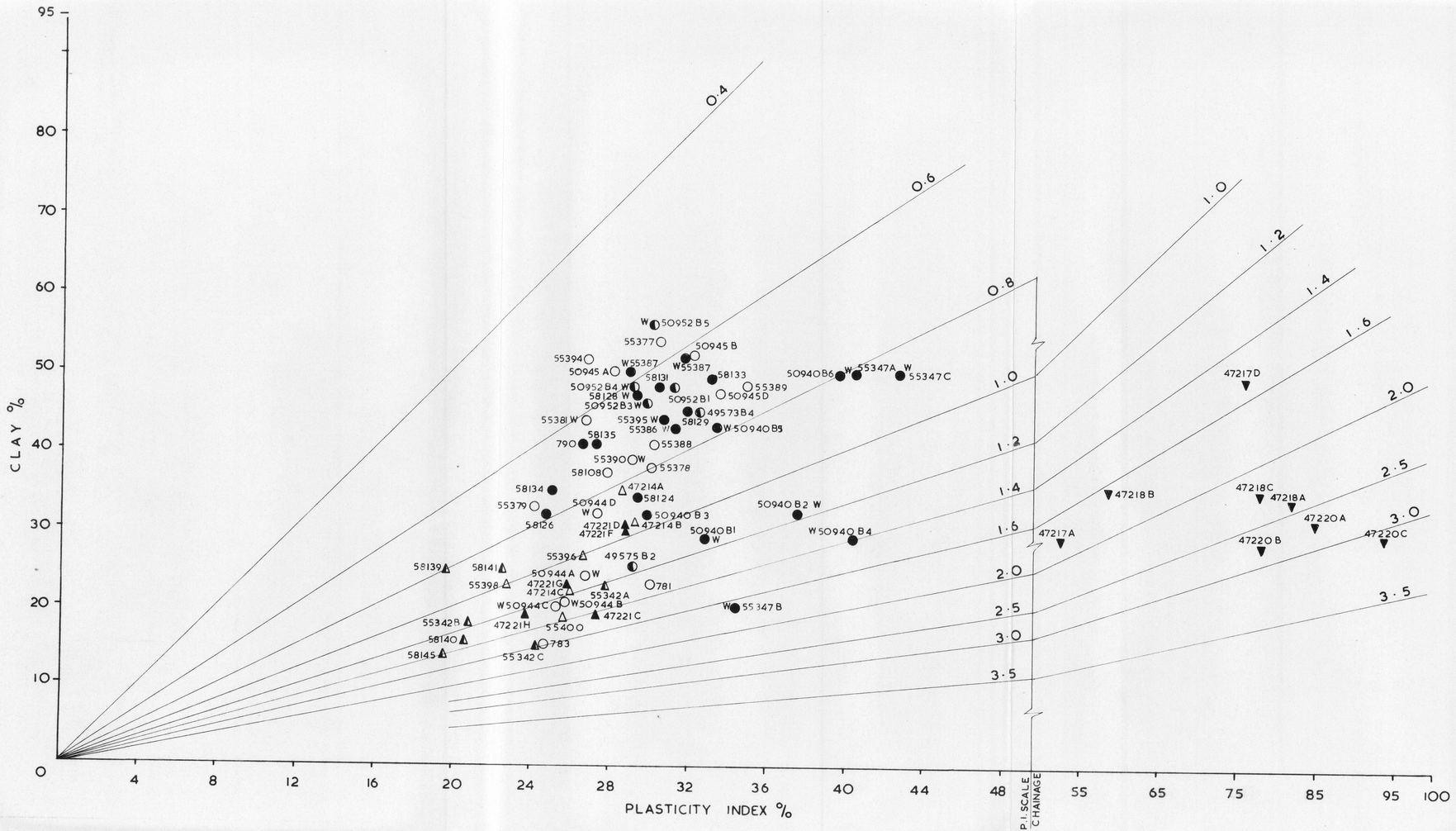


SUKIAN

SITE INVESTIGATION 1963-64

PLASTICITY CHART

FIG. 48.



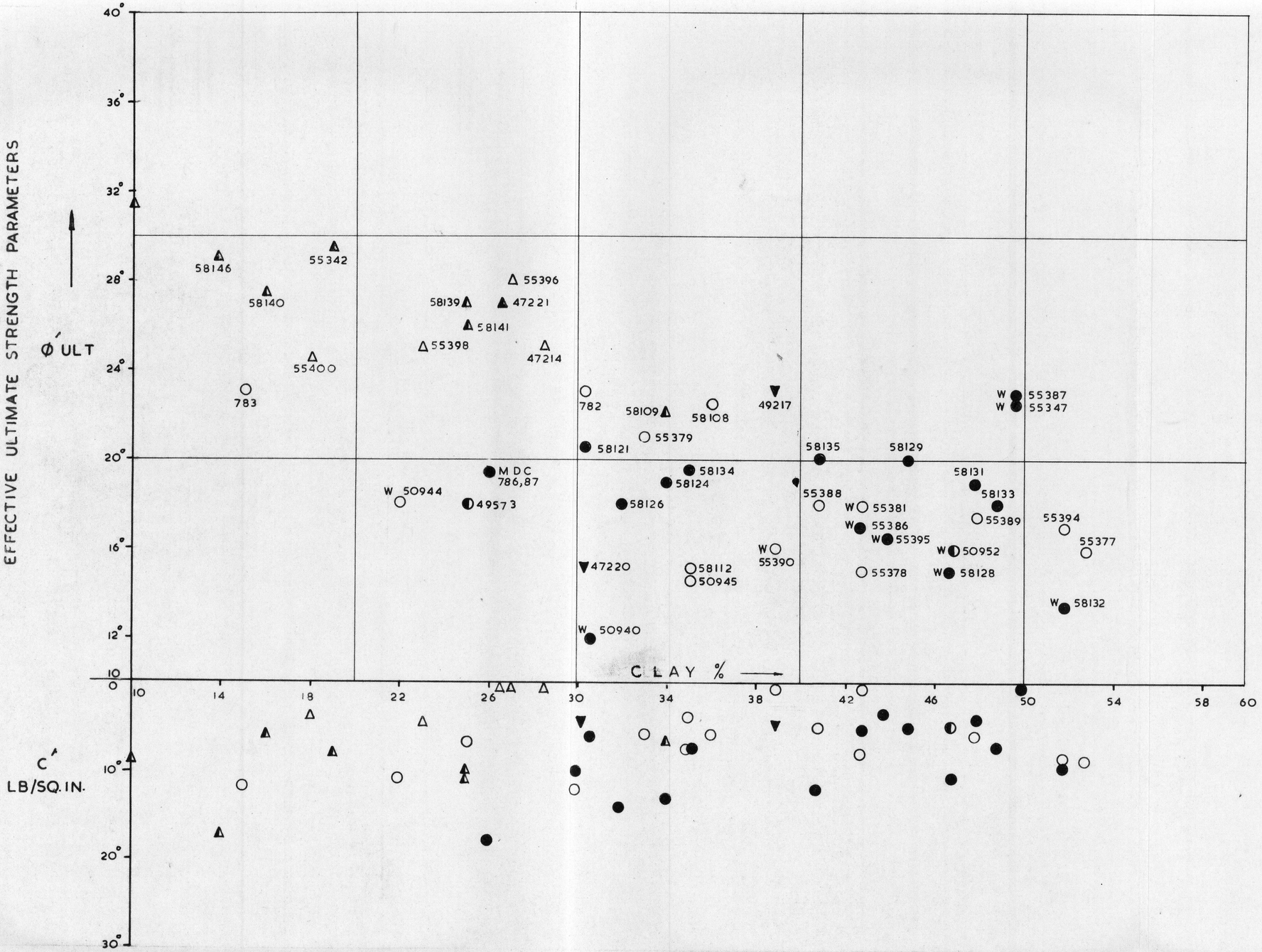
LEGEND

COLOUR GROUP	CLAYEY CLAYS	SILTY CLAYS
BLACK	●	▲
RED	○	△
BROWN	◐	◭
BENTONITIC CLAY	▼	

W = WEATHERED SAMPLE (FIELD OBSERVATION)

SUKIAN

SITE INVESTIGATION 1963–64
CLAY FRACTION VS
PLASTICITY INDEX
FIG. 49.



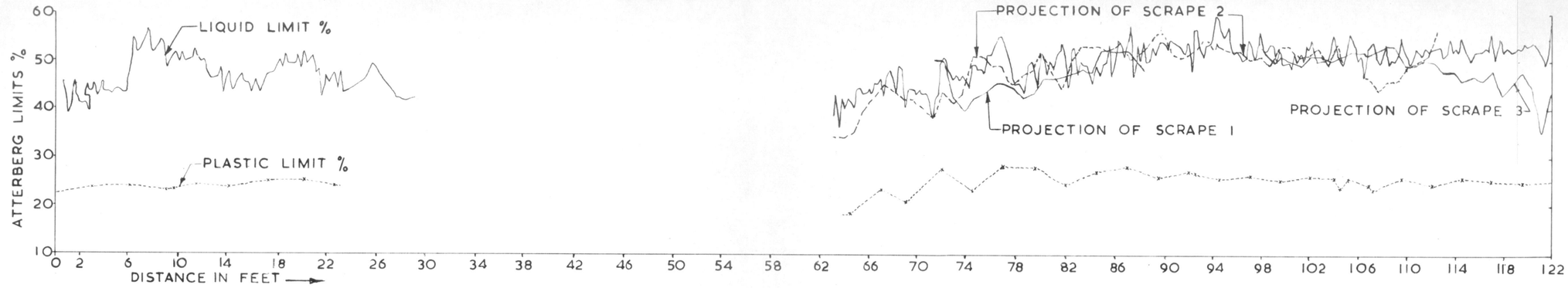
LEGEND

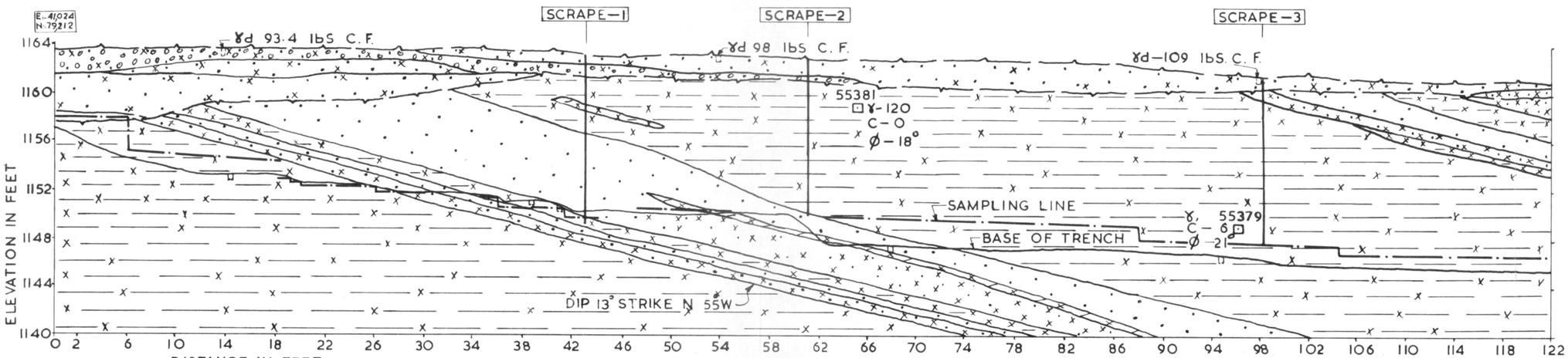
COLOUR GROUP	CLAYEY CLAY	SILTY CLAY
BLACK	●	▲
RED	○	△
BROWN	◐	◭

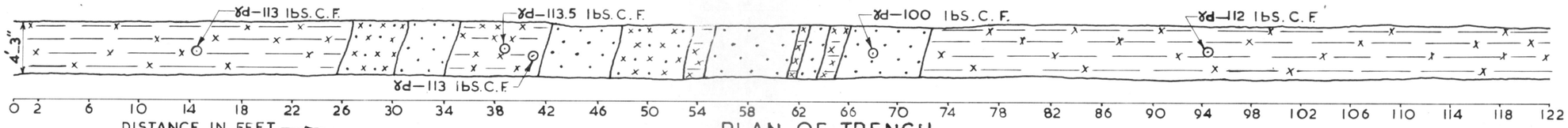
W – SAMPLE FROM WEATHERED ZONE (AS OBSERVED IN FIELD)

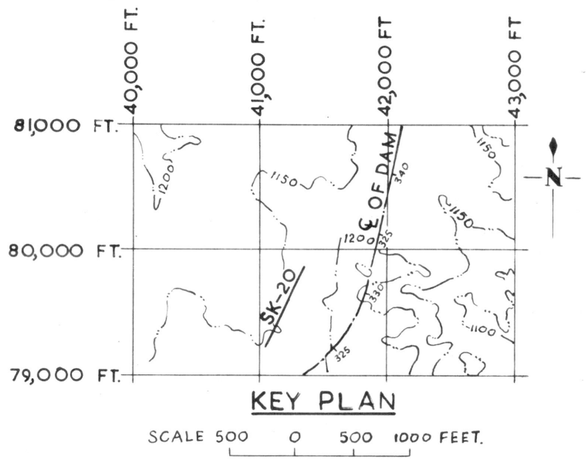
SUKIAN

SITE INVESTIGATION 1963–64
STRENGTH VS CLAY FRACTION
FIG. 50.









LEGEND

- OVER BURDEN
- SANDY SILT
- CLAYEY SILT
- SILTY SAND
- SILTY CLAY
- SANDSTONE
- GRAVEL
- 55381 UNDISTURBED BLOCK SAMPLE
- DENSITY PIT.
- TOP OF ALUVIUM
- TOP OF BEDROCK

NOTES

1. DIPS ARE APPARENT.
2. LIQUID LIMIT TESTS WERE MADE ON SAMPLES TAKEN FROM 0.25 FT. CENTRES.
3. PLASTIC LIMIT TESTS WERE MADE ON SELECTED SAMPLES. INDIVIDUAL RESULTS ARE SHOWN ON THE GRAPH.
4. ATTERBERG SAMPLES WERE TAKEN FROM HORIZONTAL GROOVES ON THE TRENCH WALL NEAR THE BASE OF THE TRENCH AND FROM THE VERTICAL SCRAPES ON THE WALL OF THE TRENCH.
5. FIELD DENSITY TESTS WERE MADE IN THE LOCATIONS SHOWN ON THE PLAN AND SECTION OF THE TRENCH.
6. BLOCK SAMPLES WERE TAKEN FROM LOCATION SHOWN ON THE SECTION
7. LIQUID LIMIT RESULTS OF VERTICAL SCRAPES SHOWN ON THE GRAPH ARE PROJECTED DOWN DIP ON TO THE HORIZONTAL SAMPLING LINE.

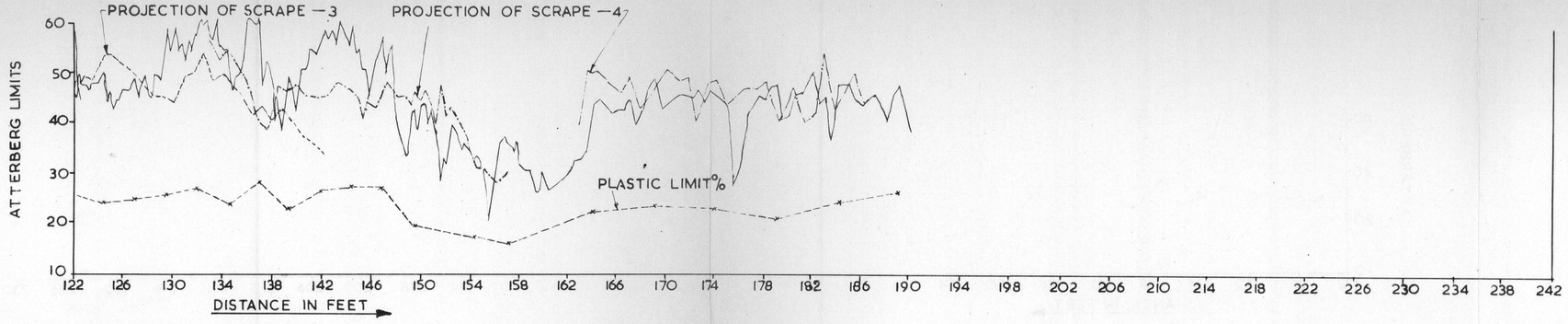
SCALE 120 5 10 15 20 FEET

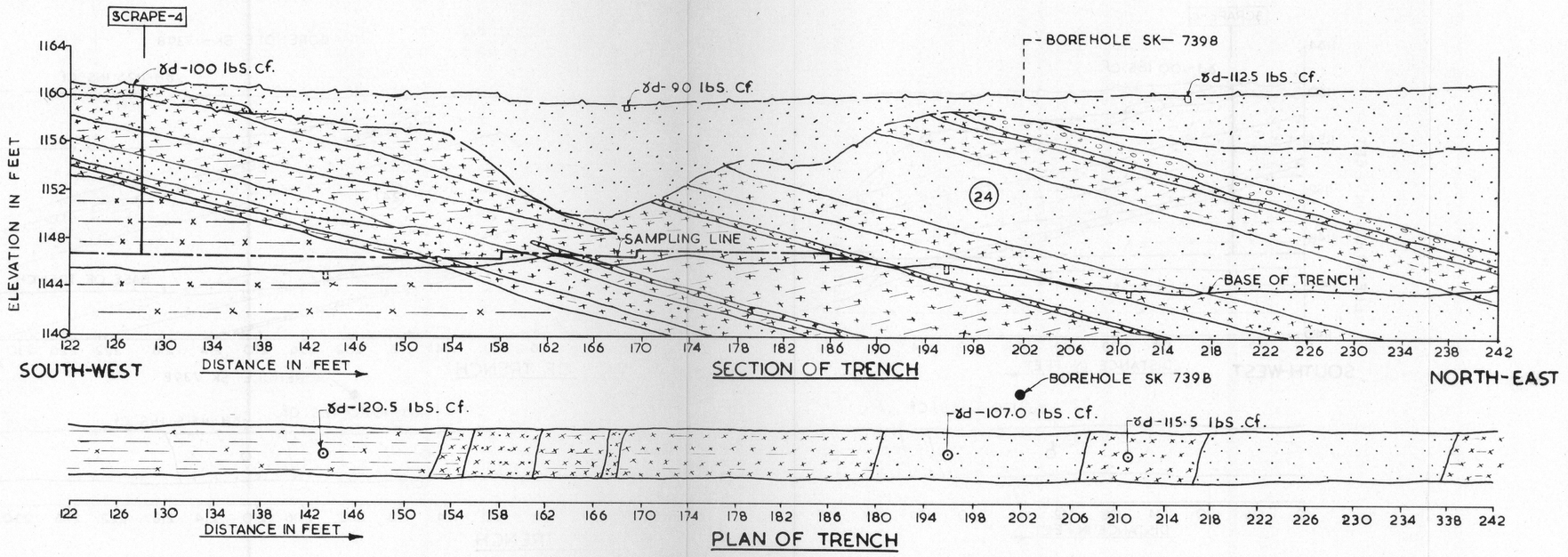
SUKIAN

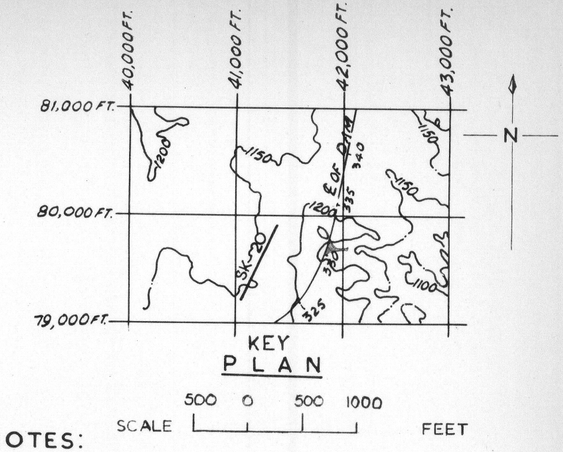
SITE INVESTIGATION 1963-64
TRENCH SK 20

SHEET 1 OF 2

FIG. 51.







NOTES:

1. DIPS ARE APPARENT
2. WORK THIS DRAWING WITH GEOLOGICAL MAP.
3. LIQUID LIMIT TESTS WERE MADE ON SAMPLES TAKEN FROM 0·25 FEET CENTRES.
4. PLASTIC LIMIT TESTS WERE MADE ON SLECTED SAMPLES, INDIVIDUAL RESULTS ARE SHOWN ON THE GRAPH.
5. ATTERBERG SAMPLES WERE TAKEN FROM HORIZONTAL GROOVES ON THE TRENCH WALL NEAR THE BASE OF THE TRENCH AND FROM THE VERTICAL SCRAPES ON THE WALL OF THE TRENCH.
6. FIELD DENSITY TESTS WERE MADE IN THE LOCATION SHOWN ON THE PLAN AND SECTION OF THE TRENCH.
7. LIQUID LIMIT RESULTS OF VERTICAL SCRAPES SHOWN ON THE GRAPH' ARE PROJECTED DOWN DIP ON TO THE HORIZONTAL SAMPLING LINE.
8. SANDSTONE BED NUMBER IS SHOWN THUS---- (24)

LEGEND

- TOP OF ALLUVIUM
- TOP OF BEDROCK
- SILTY CLAY
- SANDY SILT
- CLAYEY SILT
- GRAVEL
- SANDY SILT
- SILTY SAND
- SANDSTONE
- DENSITY PIT.
- BOREHOLE

INCHES 12 0 5 10 15 20 FEET

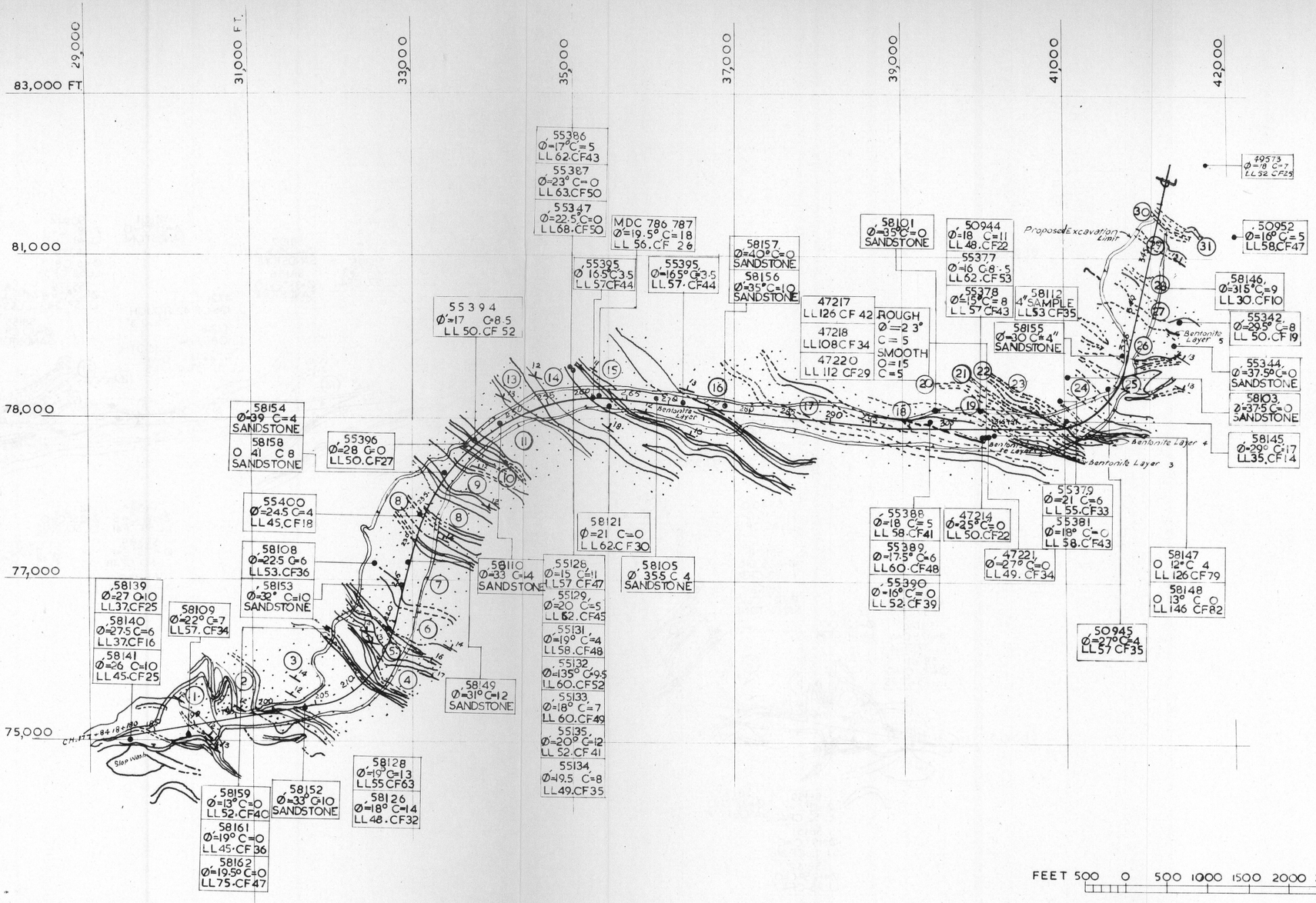
SUKIAN

SITE INVESTIGATION 1963-64

TRENCH SK 20

(SHEET 2 OF 2)

FIG. 52.



N

NOTES:

1) LABORATORY RESULTS OF TRIAXIAL TESTING OF BLOCK SAMPLES ARE SHOWN THUS

55386 SAMPLE NO.
Ø' ULTIMATE STRENGTH
C' COHESION.
LL LIQUID LIMIT
CF CLAY FRACTION

2) BLOCK SAMPLE LOCATIONS ARE SHOWN IN THEIR CORRECT GEOLOGICAL POSITION.

LEGEND

- (3) SANDSTONE BEDS
- SILT & CLAY BEDS
- 12° DIP STRIKE
- SHEAR ZONE
- BENTONITE.

SUKIAN

SITE INVESTIGATON 1963—64
GEOLOGY AND TRIAXIAL RESULTS
FIG. 53.

FOUNDATION INVESTIGATION AT MANGLA, JARI AND SUKIAN

Immediately following the Sukian site investigation came the foundation investigation of Mangla, together with associated subsidiary foundation investigations of Sukian and Jari. Results of the first* exploration available before the foundation investigation, were presented as geological plans and sections on a 1" to 500' scale, together with results from a few classification and loading tests plus eight triaxial tests for shear strength. The results of this work is summarised in the Tender Documents for the Project 1961. Because of the relatively poor amount of exposed bedrock available the geological sections were drawn and samples were taken, principally from boreholes. Several hundred holes were drilled and in addition one 600' long and several smaller, exploratory adits were constructed.

The foundation investigation at Mangla began in Spring 1964. Two approaches were made; firstly numerous classification tests on nearly every bed exposed, together with associated shear strength tests on 'intact' clay; and secondly an investigation on the 'planes of discontinuity' in the clays, which was limited to detailed studies at a few locations.

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* The initial work at Mangla was a site exploration‡ between 1958 and 1961. On this work the 'tender' design was based. Some work continued at Mangla itself after 1961, but only picked up impetus again in 1964.

The investigation of the 'intact' properties of the clay was developed along the lines of Jari and Sukian together with two major improvements. Firstly construction was in full swing and practically every clay bed on the site at one time or another was exposed, and although some trenches were dug to get at some of the clay beds, there was no planned geometrical trench work as there had been at Jari and Sukian. Access to beds was easy and convenient. Secondly, with the improvement by experience of the 'look and feel' of the clays and improved training of the field staff, 'type'* sampling was fully used. Several hundred scrapes were made (for example, fig. 54 showing scrape locations in the Lower Stilling Basin of the Main Spillway) from top to bottom of individual beds (for examples see figs. 13 and 14 from the Upper Stilling Basin). In some conditions scrapes were taken along beds from features of particular interest, to establish continuity of properties laterally (for example see fig. 55).

In the early stages of the investigation samples were generally tested for liquid limit, but as more results became available clay fraction replaced liquid limit as the principal index property tested.

Jari and Sukian were re-investigated during construction in the same way. Work at Sukian was mainly carried out during the winter, spring and summer of 1965 and of Jari during the spring and summer of 1965. As beds were exposed by excavation they were 'type' sampled for clay fraction tests and occasional block samples were taken for shear strength

* See p. 47.

tests. In addition to clay fraction, liquid limit tests were also performed on the Jari samples. At Sukian, in addition to a few trenches, logging and sampling generally followed the progress made by construction excavations. At Jari the complete range of beds found at the damsite from oldest to youngest was sampled and logged (see fig. 56) by careful selection of excavation cuts and cleanup of slopes by bulldozer. Owing to the relatively steep dip of the beds at Jari, it was not practicable to sample from top to bottom of each bed as at Mangla, so in general horizontal scrapes were resorted to, similar to the trenches of the 1962/63 investigation.

Block samples taken during the foundation investigation for strength tests, were sampled in the manner previously described in Part I. Special samples on shear zones, thrust shear joints, fissures and bedding planes were orientated with reference to the dip and strike of the bedrock in the manner also described in Part I (fig. 19).

It is convenient to discuss the study of planes of discontinuity separately as it formed a large part of the foundation investigations, before generally discussing the results of this foundation investigation.

PLANES OF DISCONTINUITY

Introduction

On the Project discontinuities in clay beds were classified according to their assumed origin and measured geometry. Discontinuities which originated by shear movement were important because it became clear that the shear strengths of the surfaces of these discontinuities were passed their peak and the surfaces were at or approaching their residual condition. It therefore became important to know the strengths of these planes in order to produce design parameters, and equally important to know the geometry and extent of them to analyse the form of potential foundation failures.

The spatial relation of the main structural features which form discontinuities are illustrated in the form of a block diagram, fig. 21. The Mangla features can be grouped into three groups, viz.:

(a) Fissures. Small sized (typically up to 3' in maximum dimension) and forming the planes of discontinuity in 'fissured clay' (plates 17 and 18). They are of diverse and composite origin. Some fissure surfaces were polished or slickensided and were assumed to have a tectonic shearing origin; others were not slickensided and were assumed to have a non-shearing or tension origin. These latter include drying and other recent cracks. Fissures formed by tension can show typical plume markings and fringe joints as described by Hodgeson (1961); slickensided fissures do not show these features.

(b) Thrust (shear) joints and shear zones* These are of large areal extent; they are formed as a direct result of beds adjusting to the folding movements which were caused by compressive earth stress.

The thrust (shear) joints form discreet planes cutting the bedding and often extending from top to bottom of the bed. The strike of the joint plane is approximately parallel to the strike of the bedrock and some joints have been traced in this direction for at least 300'. Plates 31, 32 and 33 show typical joints, from the Upper Stilling Basin of the Spillway. The clay beds containing the joints have dried out and are showing typical crazed patterns.

The shear zones are the special case of a thrust where shearing is approximately parallel to the bedding and the dislocation keeps in one layer within the bedding. Shear zones can be several inches in vertical thickness. They have been traced with certainty for up to 1,500'. Plates, 34, 35 and 36 show typical examples; details are discussed later.

(c) Faults (except the Changhar faulted fold). This group can either be a discreet plane of dislocation (like the thrust (shear) joints)or a zone of dislocation (like the shear zones). They cut the bedding at a low angle generally between 15° or 45° to the horizontal and have been found with displacements of up to 25'. Unlike groups (a) or (b) they cut across

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* Full geological name is bedding plane slip or flexural slip shears.

many beds. Faults found at Manglaappear to have been formed later than the folding. Plates 20 and 21 show typical examples ; details are discussed later.

The attitude of the shear features in general varies slightly in accordance with their position in the fold limb and for easy reference both in the field and in setting up of samples for shear testing in the laboratory structural features were related to the macroscopic fabric axis for the site. Figs. 19 and 20 illustrate this relationship diagrammatically.

The thrust (shear) joints, shear zones and faults are tectonic shear planes that form fairly regular patterns. The arrangement of these patterns can be synthetised on stereograms, block diagrams and structural maps. Fig. 9 shows the fabric axes for the Mangla site on the lower half of an equal area projection*, the 'c' axis has been assumed to be vertical. The direction of the 'b' axis (the strike direction) is $42^{\circ}W$ and is the mean of some 330 readings from the Mangla area, the range of readings is $\mp 12^{\circ}$. West of the Spillway and east of Sukian the strike changes and is not represented on this diagram (see fig. 4). Also shown on fig. 9 are the two principal movement directions of local faults and thrust (shear) joints; the black circles indicate the area in which poles to planes usually plot out. It is clear that two directions occur, mutually at right angles; the north-west

---

* All stereographic projections given here are plotted on this system.

direction locally is called the 'Baluchistan' direction which is approximately at right angles to the Baluchistan mountain range to the north-west of Mangla and the other the 'Himalayan' as it is approximately at right angles to the north-west trending Himalayan range north-east of Mangla. These names are for convenience and are not intended to indicate anything more than a superficial relationship to the compressive tectonic forces at right angles to the mountain ranges.

Table XVII summarises some of the facts and assumptions of the local structures. Some simplification has been necessary to construct the table:

T A B L E XVII

Discontinuity	Assumed Origin	Geometry	Approx. size	Approx. age	Stress/ Strain Characteristics
'Fissures'	a) Chemical (a secondary fissure)	No clear pattern	Up to 3' long	Penecontemperaneous with deposition or any age	Peak or residual (?)
	b) Shrinkage (tension fissure)	-do-	-do-	-do- or any age	Peak(?)
	c) Rebound	Approx. horizontal	-do-	Late age	Peak(?)
	d) Tectonic (shear fissure)	As joint & fault pattern	-do-	Folding & post folding	Virtually no peak
Faults	Compressive stress	Low angle thrusts	Crosses many beds	Post folding	Virtually no peak
Shear zones	-do-	Parallel to folding & bedding	Extensive Generally over 1500'	Same age as folding	-do-
Thrust (shear) joints	-do-	Conjugate (diamond) pattern	Same as a bed or less	Similar age to folding	-do-
Tension joints	'Tectonic' (tension)	Parallel to axis of fold ('b' axis)	Up to 10s of feet	Same age as folding and post folding	Peak(?)
Drying cracks	Shrinkage (tension)	Crazed or columnar	Up to few feet	Recent	Peak(?)
Artificial	a) saw	-	Small	Recent	Virtually no peak
	b) knife	-			
Crack	Stress relief (tension)	Approx. parallel to cliff face	Large	Recent	Peak (?)

Fissures

The paper 'Orientation of fissures in stiff overconsolidated Siwalik Clay' discusses aspects of Mangla and Jari fissures; a reprint from Geotechnique is enclosed in the end pocket.

The fissures in the Siwalik clays unlike the tectonic shear planes discussed following are undoubtedly formed and perhaps later modified by one of the several possible methods. They were originally measured at Jari in 1961 to see if they had any preferred orientation and when it became clear that pronounced trends were present they were then studied at Mangla (in the Spring of 1964). Again fairly clear trends emerged, but although a fairly large amount of fieldwork was carried out it was only enough to make an introductory approach to the subject and considerable amount of work remains before a proper measure of understanding is achieved.

Studies were all made in the field from excavation cuts, pits or adits. The majority of exposures were in locations which could not be enlarged to permit measurement of more fissures, therefore, the studies made suffer from the real disadvantage of a limit on the number of readings. Locations were only chosen when three or more exposed faces were available for study, in order to get no preferential selection of fissures in one attitude.

Fissures can conveniently be considered 'minor geological structures' and in the same context the Mangla faults, joints and shear zones are 'intermediate' and the folds and features

like the Changhar monocline which is a faulted fold are 'major geological structures'. The terminology of fissures is certainly not clear. Engineers following Terzaghi (1936) usually restrict the term to the small cracks in stiff clays. British Code of Practice 2001 (1957) is inconsistent as 'fissured' clay (C.242) is defined in accordance with Terzaghi but 'fissure'(C.129) is defined as 'a crack, break or fracture in strata or rock masses caused by faulting, jointing or other causes'. This latter definition follows geological practice which does not restrict the size of the fissure. Some authorities, for example Rice (1941) and the American Geological Institute (1962) go further and reserve the term for large features, viz. 'An extensive crack, break or fracture in the rocks. A mere joint or crack persisting only for a few inches or a few feet is not usually termed a fissure by geologists or miners, although in a strict physical sense it is one'. It appears most authorities agree on the form of the feature, but confusion arises in size and sometimes in the origin; as an example of the latter, Hodgson (1961) refers to fissures as 'the superficial expression of a joint is commonly a fissure resulting either from mechanical separation of the faces of the joint or weathering along the surfaces'.

Geological usage urges the term to indicatelarge cracks, but definitions are not rigorous. Engineering usage is clear on 'fissured' but not so clear on 'fissures'. Therefore, the definition used for Mangla fissures is restricted

to minor geological structures that are planes of discontinuity, that do not cross geological boundaries (i.e. between beds) that occur in cohesive material, and which are up to 3' in maximum dimension. No planes longer than this which could not definitely be ascribed to jointing (by Billings' definition, see enclosure) or faulting were found at Mangla*. Average smallest dimension was about 1", but down to a mm. or so (by eye) were not uncommon. Dried clay surfaces commonly produce fissure bounded blocks about the size of a pea, while unweathered fresh clays commonly produce blocks the size of a fist; a rough classification on the degree of fissuring of clays was used in the field. It was based on the number of surface fissures visible on a block of 1' cube.

0	-	intact
1 - 10	-	lightly fissured
10 - 50	-	fissured
above 50	-	heavily or highly fissured.

(Plate 18 shows 'fissured' clay). No other classification for degree of fissuring has been found in the literature, but until more work is done on clays outside the Mangla area any universal classification is premature. The maximum number of fissures counted from one block, by breaking it open piece by piece, using finger pressure only, was 232**. Small shear surfaces associated with faults and shear zones are not called

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* Shear zones with extensive discontinuities, i.e. principal planes, were defined on site as the special case of a fault, viz., a fault parallel to the bedding.

** Preliminary work now in progress, in the Civil Engineering Department, Imperial College, on blocks of London clay, have found up to 500 fissures per 1' cube.

fissures as their genesis although not clear in detail is obviously related to the shearing and, therefore, they can be classified in some shear nomenclature.

It is concluded from the preliminary work at Mangla and that by previous workers (outlined in the enclosure) that 'Terzaghi type' fissures are capable of being formed in several ways. Not enough work has been done yet to attempt classification of the Mangla fissures by mode of formation, though some methods of formation suggest themselves (see enclosure).

Tectonic Shear Planes

Shear fractures* in the bedrock were produced by an overall compressive stress and the shear deformation across a particular bed must have been approximately constant over any given area of several hundred feet (such an area is small compared to the scale of the geological fold structure) yet the response of the bedding to this deformation is not constant. It is dependent on the lithology and strength of the beds, the relative position in the fold structure and on locally induced stress fields. This concept is well known in geology, for example, see discussions by de Sitter, p. 122 (1956). At Mangla the clay beds have reacted to the deformation by folding, thrust (shear) joints, thrust faults, shear fissures and bedding plane shears. Over short distances the following shear patterns and features were recognised and are now discussed in more detail.

---

* viz., shear joints, faults, shear zones and shear fissures.

(i) Thrust (shear) joints

These occur commonly in the clay and sandstone beds. Only the first order joints are easily distinguished; the extent of individual joints is quite variable and can extend from a few feet to tens of feet when the joint extends from top to bottom of the bed in which it is contained. Some clay joints pass into the overlying and underlying sandstone beds; where this occurs the joint generally flattens its angle and disappears within a few feet (plate 31). The joint pattern varies in detail as it is dependent on the geological properties and position of the beds together with localised stress patterns. Nevertheless from the engineering standpoint within reason, the patterns and frequency of spacing are reliably regular. The strike of the joint plane is approximately parallel to the strike of the bedrock and dipping from approximately 5° to 45° steeper than the dip of the bedrock. Fig. 57 shows contour diagrams of thrust (shear) joints from the Mangla area at locations of about 500' square feet in area and of about 75 readings each diagram. The complementary dipping sets with a north-west strike are clearly shown.

Fig. 58 shows a frequency histogram of two hundred shear joints for the Mangla area. All joints measured at Mangla were used to construct the diagram; they were plotted in their dip direction. The order of accuracy of measurement in the field was say $\mp 5^{\circ}$. The diagram

again clearly shows (about 70%) the predominance of joints striking in the same direction as the bedrock strike. A small proportion of the joints are striking north-east and dipping north-west; south-east dipping joints are extremely rare.

Figs. 59, 60 and 61 show typical joint patterns and frequency of spacing; the joints are associated with concentrated shear zones and only the larger joints are shown. Fig. 62 shows a detailed scale drawing of a typical joint pattern and frequency. The clay/sandstone interface shows localised polishing and slickensiding. Thrust (shear) joints, tension joints and fissures are labelled. In addition, figs. 59, 60 and 62 show detail of classification sample locations connected with the studies on the properties of tectonic shear surfaces. Samples were taken parallel to and normal to joints and shear zones and from razor blade scraping of the surface of the discontinuity.

The surfaces of joint walls are tight when fresh and when examined carefully they are always polished and sometimes slickensided. Some of the joints have measurable relative displacements (up to $\frac{1}{2}$"; greater displacement than this, by site definition were called faults) of the opposite walls of the joint. Fig. 63 is of a small study made on joint surfaces at Jari where the beds are dipping almost due north at approximately 45^{o}. The complementary sets of joints are slightly

steeper or shallower than this, but both sets are dipping north. The study, although only on 40 joints and from one locality, clearly indicates from the measurements of the lineation directions on the joint surfaces that movement was in a similar direction to the dip direction of the joint, i.e. in the same horizontal direction as the fold compression.

(ii) Shear Zones

Shear zones like the shear joints are the product of the brittle deformation associated with the elastic strains produced by folding stresses. Many of the fracture features described following can also be seen in fault zones.

Apart from very minor undulations shear zones are parallel to the bedding. They generally occur in the 'weakest' portion or layer within a clay bed and there is some tendency for them to occur near the top of a bed (where often by 'graded bedding' the highest clay fractions occur). When looked for carefully at Mangla approximately two clay beds in three were found to be sheared, at Jari where the beds are steeper approximately three shear zones per bed were found. For example, fig. 56 shows a continuous geological columnar section of Jari. The section contains 32 clay beds with a total thickness of about 540', in all the section is 960' thick. The clay beds contain 111 shear zones of which 6 were classified in the field as 'intense', 40 as 'moderate' and 65 as 'slight'. These terms are discussed following.

Two principal types have been recognised:

1) A zone of concentrated shear, a few cms. in thickness and continuous over long distances;
2) One or two shear planes in association and continuous over long distances.

Within the zones of concentrated shear various intensities of shearing can be discerned, for example:

(a) The most intense shearing produces very closely spaced shear surfaces sub parallel to each other and the bedding. These surfaces are called 'mille feuilles' structures and individual leaves bounded by surfaces may be up to 5 mms. thick and 20 cms. long, but typically are cardboard thick (for example fig. 61 and plate 37).

(b) Less intensive shearing produces shear surfaces of short length generally inclined to bedding and defining a series of lenses when seen in section ('ac' plane). The long axes of the lenses are sub parallel to the bedding and individual lenses may be up to 10 cms. thick and 30 cms. long (see plate 38). Shear zones may consist of from one to five or six layers of lenses (for example fig. 59 and plate 34).

The surfaces of lenses are always polished and often striated (plates 38 and 39). Striations usually follow the dip direction of the bedding but with the complicated en echelon packing in more advanced and complex stages of shear zones immediately before the 'mille feuilles' state has been reached, slip striae are often inclined

to this direction. Faces of fairly thick lenses (early formed(?) where the 'c' axis is approximately ½ the length of the 'a' axis) are bounded by what may be 'Riedel' and thrust shears (see fig. 64), but in a more advanced condition the individual shears have apparently undergone some rotation and many of the thrust shears have coalesced to form principal shear planes which are parallel to the bedding. It is clear that the principal amount of bed over bed slip has taken place along these planes (Fookes 1965[2]). In all the slope failures examined in which the failure had taken place on a shear zone, the failure surface followed a principal plane (Fookes 1965[3]). The greatest continuous length that a principal plane was traced was for 43' and then this was only limited by the amount of exposure and not because the plane ended. In the thicker zones more than one principal plane was noted. Sketches of these planes in section are given in fig. 64.

Fig. 68 shows in detail measured profiles from the failure surfaces of natural slides which slid on the principal lower plane of a shear zone. Measurements were made in the field within an hour or two of failure (in hot weather the slide surfaces dry and craze within a few hours) to $\mp \frac{1}{4}$"*. The drawing is typical of several

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* A 6' straight edge was laid on the surface and measurements at right angles to the surface were made from the surface up to the base of the straight edge with a 6" rule. Where the straight edge rested directly on the surface a zero reading was recorded.

made on failure surfaces and clearly shows the planar nature of the surface and the occasional undulating 'steps' in the surface produced by the removal, by the slide action, of shear lenses existing immediately below the principal plane down which the failure occurred. Plate 40 is of a slide and shows the lower principal plane.

The response to deformation in unsheared or even in sheared beds (apart from the shear zone itself) is apparently taken by movement distributed more or less uniformly throughout the bed as a series of very small shears on a large number of shear fissures and thrust (shear) joints. Both on shear fissures and joints the movement is small (say in the order of one or two millimetres, but this is enough to cause slickensiding and on studies of all types of fissures up to 25% of them have been found slickensided (Fookes 1965[1])). Careful observation on sandstone/clay interfaces has shown that sometimes the interface is polished and geological bottom structures* are sheared (see fig. 62). These interfaces are classified as 'slightly' sheared.

The differing response of a clay bed to essentially the same overall deformation is chiefly an expression of the variation in lithology and strength of the bed, the weakest portions of the geological sequence show the most marked deformations, these are the shear zones themselves. The

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* Examples of bottom structures, flute marks, scour casts, flame structures, clay balls in sandstone.

strength variations can be conveniently expressed by the clay fraction. Clay fraction at Mangla has been related to shear strength and the highest clay fractions usually have the lowest shear strength (for example see fig. 65, which is discussed later). Figs. 66 and 67 show vertical sections through clay beds with shear zones; these occur at the highest clay fraction layers in the bed. By similar reasoning some of the stronger beds, the silts, siltstones and sandstones may not be sheared parallel to the bedding at all. But even within a bed known to be sheared and in which the overall deformations must be constant over a considerable area, there is not necessarily always a continuous shear surface for in addition to the lithology and the strength of the bed controlling the type and intensity of deformation, local influences may also affect the deformation. For example, where a shear zone occurs near a sandstone/clay interface that is irregular sometimes the shear zone may take the form of a succession of small thrusts constituting a condition superficially resembling an imbricate structure. Such a condition is illustrated in fig. 64. Owing to the temporary existance of the three foundation exposures showing this feature the exact nature of the pattern was not established, i.e. whether the thrust shears were moved into position or whether they were created insitu (if this were the case then they could better be called fracture cleavage(?)). Similarly the position of the shear zone in the fold structure may offset the degree of deformation. There is from theoretical considerations likelihood that the

shear intensity will die away on approaching the crest of a fold as the bed over bed displacement necessary to get concentric folding will be nil at the crest. Fig. 55 shows a shear zone traced from a point some 500 yds. from the assumed position of the crest for some 500 yds. further away from the crest. The intensity of the shearing increases away from the crest but the clay fraction which is dependent on the original conditions of deposition, is fairly uniform. See also discussion p.167.

(iii) Faults

All the faults found on the Project (this excludes the Changhar faulted fold south of the Reservoir) are thrust (or reverse) faults. Displacements along the fault plane of up to 25' were recorded from Mangla, but only three very small faults from Jari and two from Sukian were found. Fig. 70 gives stereographic projections of all known faults from Mangla (up to December 1965). Like the first order thrust (shear) joints at Mangla the faults occur in one of two main sets, one striking approximately parallel to the strike bedrock and the other approximately at right angles to this. The faults from the Fabri Dam shown on the first diagram were complicated, appeared slightly curved, and were undoubtedly influenced by the Changhar folding though the nature of this relationship was not investigated. These and the faults from the Intake were dipping south, but further away from the Changhar feature on the right bank of the Jhelum in the Main Dam and Spillway areas the majority of faults dip northwards. The diagrams clearly illustrate this.

Plates 20 and 21 show typical Z configuration of the faults. When passing through clay the faults were either single polished planes (like the 'slight' shear zones) or with two or three thicknesses of lenses (like thin 'moderate/intense' shear zones. Stress/strain curves from triaxial and shear box tests on faults from location IV *(discussed following) were similar to shear zone curves, i.e. no or only a small peak. The fault planes were commonly striated in the dip direction, although variations for these were quite common over even small (4 sq.ft) areas.

When passing through sandstones faults could be traced either as fractured sandstone with gouged material on either side of the fault or a thin line of black clay up to $\frac{1}{4}$" thick (for example plates 41 and 42). Small 'thrust' or 'Riedel' shears were usually found in sandstones on either side of the fault plane (plate 21) and occasionally these would enclose a shear lens in the same manner as shear zones. The black clay was once subject to an in situ shear test‡. An adit was dug 30' in from a cliff face to meet a fault plane and a block containing the plane was left proud. The block was then loaded to the original overburden condition and sheared in a specially constructed box by jacking. It gave results in the order of $30^{\circ}\emptyset$' res.; clay fraction of the sheared black clay was ca. 30%.

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* Locations I - IV are described in Appendix IV.

Fieldwork on Shear Zones

The first exposures of what may have been two shear zones were noted from Mangla in August 1961 by J. Rollins (internal correspondence Binnie & Partners) during the course of plane table mapping of the Fort Hill. They were of very limited exposure only and at that time were considered flat lying or low angle thrust faults by the author and labelled T_a and T_b. They were photographed and traced for a limited distance on the map but no further work was done until a major shear zone was exposed and recognised in adit JA 5 at Jari in January 1962. This was what was later called 'moderate' in the field classification scale of shearing intensity, about 3" thick and parallel to bedding. A small laboratory index test programme was carried out on this shear zone in the spring of 1962 and an adjacent zone found near the mouth of the adit, by sampling across the zone and in the clays bounding the zone. It was thought that on average liquid limits were about 10% higher in the zone, though the results were somewhat scattered. Fig. 69 gives the result of this work. On a block of material adjacent to the shear zone cut so that one face of the block was of sheared and polished material, samples for clay fraction tests were taken at $\frac{1}{2}$ mm. distances serially in from the block face. Material† for the tests was obtained by careful razor blade scraping starting at the polished surface and working inwards and very carefully collecting the scraped material for layers of $\frac{1}{2}$ mm. thickness. Results indicated that the 'skin' of the polished surface was about 5% higher liquid

limit than the 'intact' material a few mm. beneath. The experiment was only performed once as the work was tedious but the technique is worth further study.

By the summer of 1962 the JA.5 shear zone had been traced intermittently, as exposures permitted, from the adit (near what is now Kakra Dam) to trench ABC, a distance of some 2,000' (see fig. 33). By this time trench ABC had been excavated (July 1962) and it was realised shear zones were fairly numerous and a normal Jari feature. Locations of shear zones found in the other trenches and results of laboratory tests on shear zones are given in the foregoing discussion on the Jari Site Investigation, p.69.

It was not until the Foundation mapping of Summer 1963 in the Mangla Main Dam Core Trench and Intake areas that any further serious fieldwork was done on shear zones and their extent at Mangla appreciated. Shear zones were then studied, sampled and tested in some detail at several locations at Mangla and Jari during the Foundation Investigation of 1964/65 and Sukian 1965.

In the field, by summer of 1964, three classes of shear were named, 'intense', 'moderate' and 'slight'. It is emphasized that these were only field terms but they had great use during the investigation both in the field and in the laboratory, and the laboratory work concerned with shear zones was based on this nomenclature. The intense shear zone could be the end product of the shearing sequence as the name suggests, but more fieldwork is required, especially tracing shear zones across country preferably where the dip is increasing (where

this was attempted, e.g. fig. 55, the increase in dip was only 1 or 2°).

(a) The Intense shear zones (for example see following results from location I* and fig. 61 and plate 37) consist of a tight mass of slickensided or polished leaves of clay. The clay gives the appearance of having been sheared and streaked in thin (up to 5 mm. thick) leaves or slivers, and looks somewhat like 'mille feuilles' pastry (a thousand leaves);

(b) The moderate shear zones (for example, location II*, or figs. 59 and 60 and plates 34 or 35) consist of a tight mass of slickensided or polished flattened lenses of clay. The typical size of an individual lens is $2\frac{1}{2}$ cm. thick and 20 cm. long though these figures are variable, and the ratio of the 'c' axis to the 'a' axis is generally between 1:6 and 1:10, typically 1:8. The diagnostic feature of the moderate shears is the lens shape when seen in the 'ac' plane.

(c) The slight shear zone (for example location III*, fig. 62 and plate 32) consists of either a single line of lenses or a polished and slickensided contact between bedding planes, together with increased development of fissures near the contact. The polished plane constitutes the principal plane in this case.

The following Table XVIII and drawing fig. 64 from the Mangla foundation investigation 1964 summarises the above field classifications:

* Locations I - IV are described in Appendix IV and Fookes & Head (1964).

T A B L E XVIII

Type	Characteristics	Thickness of zone normal to bedding	Extent	Example
Intense	Thin leaves of polished clay 'mille feuilles'	3 cm - 30 cms.	Have been traced in field for over $\frac{1}{4}$ mile	Location I - Intake Slopes
Moderate	Lenses of polished clay	3 cm - 30 cms.	Have been traced in field for over $\frac{1}{3}$ mile	Location II Intake Core Trench
Slight	Polished contact between beds or single line of lenses	0-3 cms.	Either local (upto 50') or en echelon zones or polished contacts up to $\frac{1}{4}$ mile	Location III - Lower Stilling Basin

All the shear zones on site (by definition) are parallel to the bedding; zones deformed in a similar manner (e.g. Location IVB, plates 43; 44 or 45) but cutting across the bedding were called 'fault zones'. When traced over long distances, intense and moderate shear zones can vary from a few cm. to ca. 30 cms. in thickness (measured normal to the bedding) within one zone. Intense and moderate shear zones have been traced over several hundred feet whenever suitable exposures were available, but slight shear zoneswere generally less extensive and often found to die out or exist in en echelon groups; polished contacts between beds (classified as 'slight') were traced for over $\frac{1}{4}$ mile.

Slickensides on the leaves or lenses of clay within the shear zone indicate relative movement in the bedding dip direction and the orientation of thrust (shear) joints and imbricate structures(?) are in agreement with this.

The sense of movement and attitude suggests the shear zones were formed at the same time as the folding, as they are generally striated in the dip direction and the position of Riedel and thrust shears is consistent with movement in the bedding direction. Because of the still unconfirmed nature of the Changhar folded fault the total fold angle of the Mangla and Jari beds due to the Mirpur syncline alone is likely to be in the order of 80^{o} so that considering the thickness of the beds folding displacement of several feet would not be unreasonable. At one exposure in the Jari left abutment, a silt filled clastic dyke appeared to have been displaced by 4' across a moderate shear zone though from the nature of the temporary exposure this evidence was debatable.

Slope Failures

No specific work was done on natural slope failures during the exploratory or investigation stages.

Only one circular(?) slip was noted (plate 13), but rock and soil falls were common in the Siwaliks and numerous in the Mirpur silt. Some translatory slides on the steep dip slopes of both abutments at Jari were also noted. Failure occurred by sandstone beds slipping over clay beds when their toe support was undercut by erosion. At Mangla a few giant scars of what may have been ancient translatory slides (for example on the north-east face of Fort Hill) were noted.

In general the landform was too young for residual clay slopes (Skempton & deLory 1957) to have developed, in addition the local geological structure which had a dip of similar order

to the residual angle of the clay would have caused additional complications if this aspect had been studied. However, studies elsewhere on the Siwaliks (e.g. East Pakistan) in different structural and climatic settings would be of interest.

During construction up to the time of writing (September 1965) some 50 failures were noted on construction slopes; there may have been more but were not seen by the author. Only failures in excess of ca. 10 cu.yds. of material are included in the following tables. All the failures were directly or indirectly related to the geometry of the geological and structural situation. Therefore, the following classification based on the construction failures is defined in terms of geometry and not mechanics and will be of limited application outside areas which do not have similar geometry to the Mangla situation.

Three principal types were recognised:

(1) Slides. Translational failures with a flat or approximately flat surface. The failure planes follow a weak layer within the soil mass and are capable of approximate mathematical analysis, for example Terzaghi (1962). Three subdivisions of this type occur:

(a). The classical slide failure along a bedding plane consisting either of a bedded layer of weak material or a structural deformity such as a shear zone or bedding plane joint (for example plates 40 & 46);

(b) Failure along a plane inclined to the bedding. This type of failure was confined to thrust (shear)

joints and generally involved only the bed which contained the joint (for example Fookes &Wilson 1966);

(c) Failure along a fault plane. This generally involved more than one bed (for example Fookes & Wilson 1966).

(2) Slips. This term was reserved for those failures with a curved surface ('rotational' slips), existing structural discontinuities were not followed for a major portion of the total length of the slip surface. Only one such was observed during construction (at Sukian), although there was an element of doubt about the precise path the failure followed.

(3) Falls. This term was reserved specifically for high angle failures where individual blocks of fall debris had free fall after being detached from their parent material. The failure surfaces were bounded by random fissures and joints and the overall form of the fall was not clearly controlled by attitude of the bedding or predominant joints like the slides. The fissures and joints were opened up after excavation by shrinkage or drying and stress release on removal of lateral support.

Types (1)(a) and (b) were dominated by the strike direction of the bedrock. Table XIX(i)lists 48 failures, their type and the alignment of the excavated slopes on which the failure occurred. It is clear from the table that the slides occurred approximately parallel to the dip of the bedrock, whereas falls could occur on steep slopes facing any direction. Jari dam is aligned with its centreline approximately parallel to the strike direction. This results in the majority of

steep construction cuts sloping approximately north or south. However, at Mangla and Sukian Dams are not aligned to follow the strike and are curved in plan giving steep construction cuts where directions vary in different places.

Table XIX (ii) lists numbers of failures, their type and approximate size. It is clear that 'falls' are numerous, similar and small in size; their smallness is partly due to the number of steep cuts being kept to a minimum during construction.

T A B L E XIX (i)

Number of Failures of Excavation Slopes in Relation to their Alignment

Failure Type	Alignment of cut slope							
	N	NE	E	SE	S	SW	W	NW
Slides	14*+5	1	5	-	-	-	-	-
Slips	?1	-	-	-	?1**	-	-	-
Falls	6	2	-	1	1	8	1	2

T A B L E XIX (ii)

Number and Approximate Size of Slope Failures

Failure Type	Approximate size in cu. yards		
	10 - 1,000	1,000 - 10,000	above 10,000
Slides	16	8	1*
Slips	?1	-	?1**
Falls	21	-	-

* Jari
** At Jari pre-construction

PLATE No. 31 February 1965

Two typical thrust (shear) joints (arrowed), clay bed 214, Upper Stilling Basin, Mangla. The dip angle of the joints steepens slightly from left to right as they enter siltier material below the overlying clay bed (shown by the cubical drying pattern). Length of the photograph about 5'.



PLATE No. 32 February 1965

Surface drying pattern in clay bed 211 Upper Stilling Basin, Mangla, partly obscuring tectonic planes, viz. the plane dipping towards the right at 2' 10" is a 'slight' shear zone, i.e. a single principal plane parallel to the bedding. Minor slight shear zones are shown at 4'4" and the flat lying plane at 1'3½" is a small thrust (shear) joint.

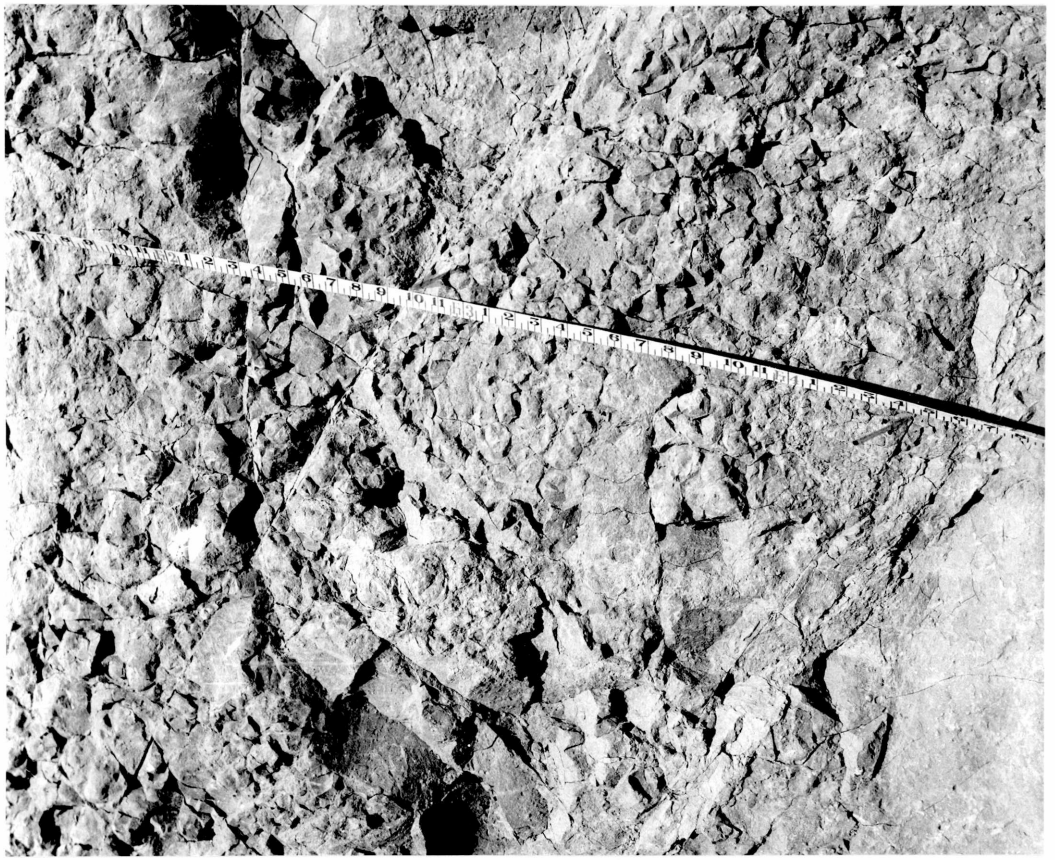


PLATE No. 33 January 1965

Two thrust (shear) joints, clay bed 214 Upper Stilling Basin, Mangla; they steepen and then die out as they pass from the clay bed (with the drying cracks) into the overlying sandstone bed. The black and white scale on the lower joint is 3' long.

PLATE No. 34 July 1965

A moderate shear zone from the left abutment, Jari, the dip of the bedrock is shallow from left to right. The form of individual lenses, seen here as sections in their ac plane, is clearly shown. Height of the photograph about 3'.

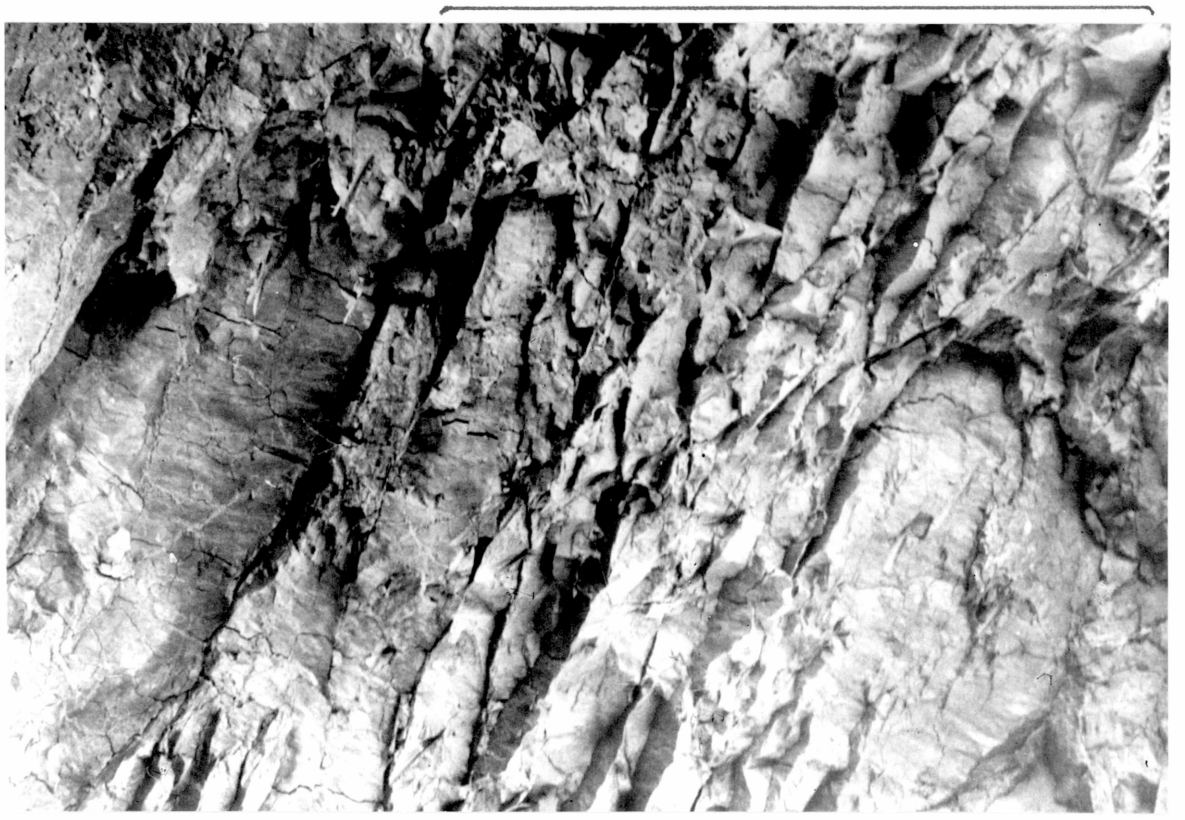


PLATE No. 35 June 1965

An excellent example of a thin (ca. 3") moderate shear zone bounded top and bottom by two principal planes. Dip of the bedrock about 45° right to left. The shear zone is exposed in its ac plane and below it are clearly seen thrust (shear) joint in Riedel and complementary shear patterns apparently passing into but not crossing the shear zone. Right abutment, Jari.

PLATE No. 36 June 1965

Another example of a moderate shear zone from Jari showing identical features to plate 35.



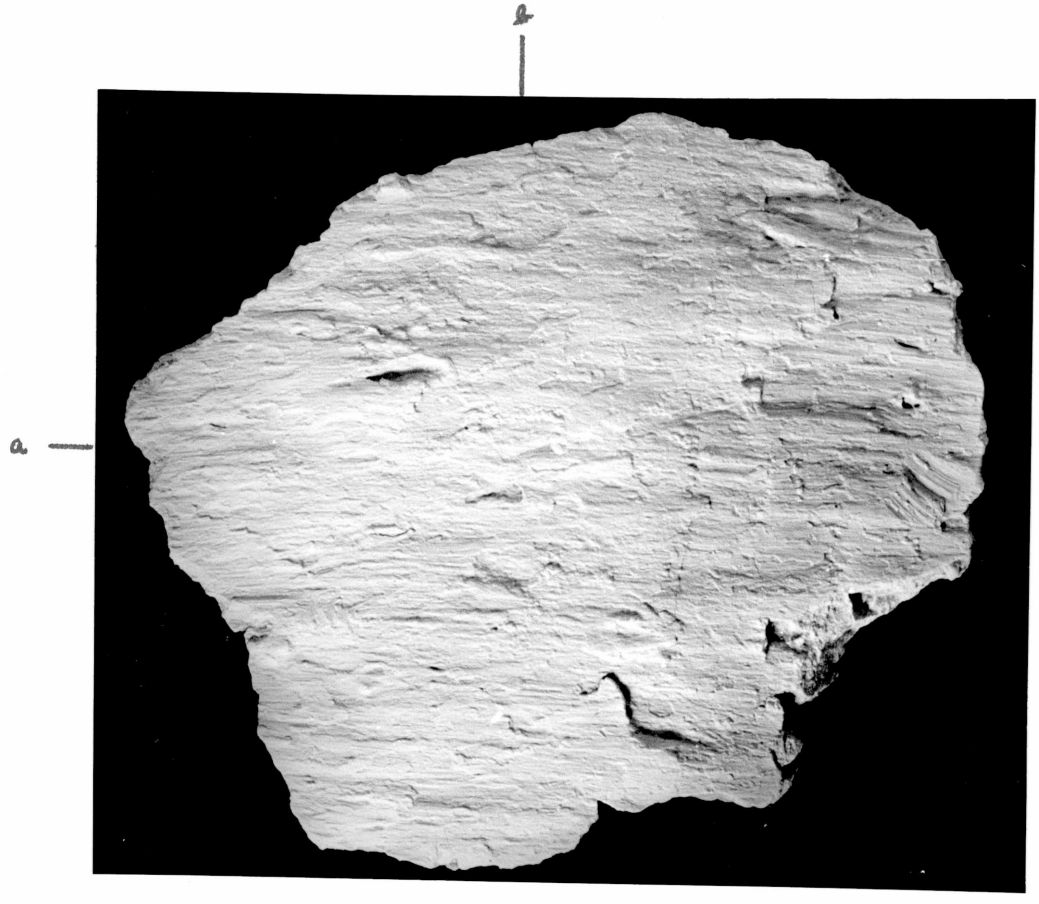
PLATE No. 37 July 1964

The type example of an 'intense' shear zone, Location I Intake slopes, Mangla. The 6" slide rule crosses from top to bottom of the 'mille feuille' zone (indicated in red). A small development of imbricate structures immediately below the 'mille feuille' zone is indicated by the black arrows.



PLATE No. 38 July 1962

A typical single clay lens from a moderate shear zone; the surface of the lens is striated in the a direction (i.e. parallel to the supposed movement direction) and the left hand end of the lower photograph shows the characteristic curling associated with some of the lenses. Length of the a axis 5".


b
a

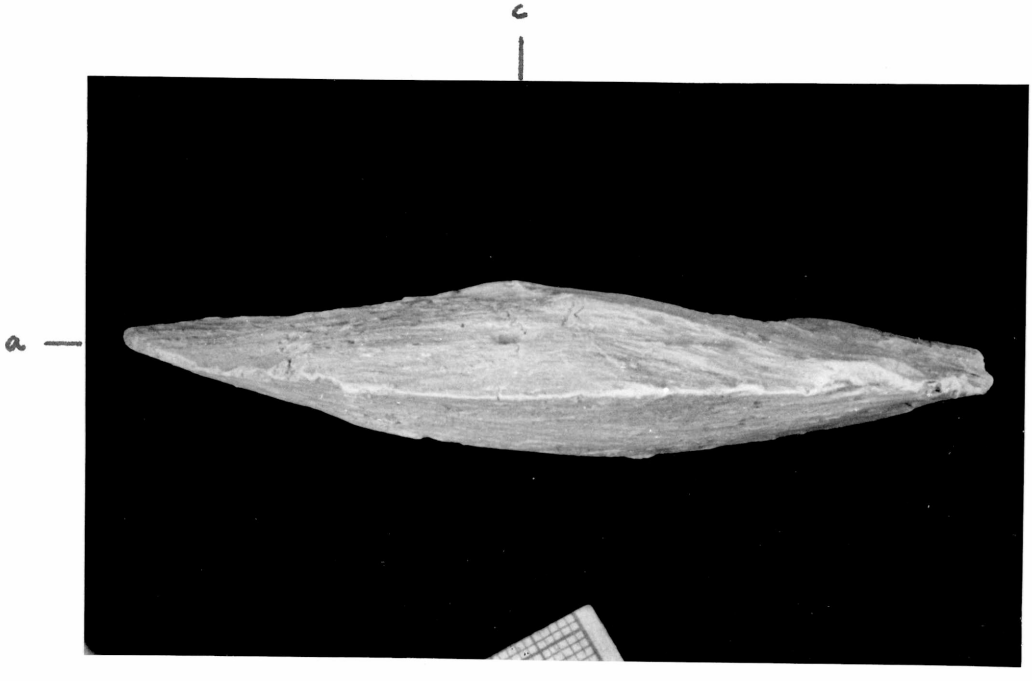
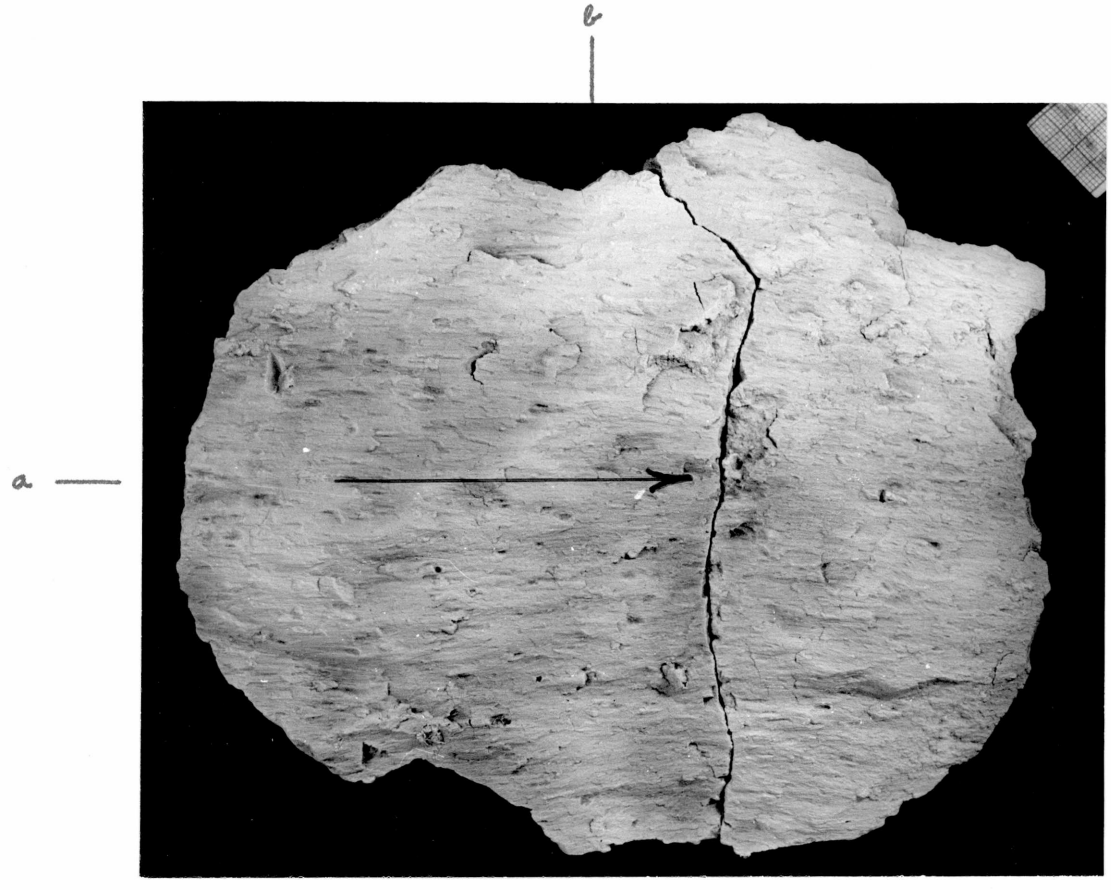

c
a

PLATE No. 39 July 1962

A typical single clay lens from moderate shear zone (partly damaged in transit to the photographers). The ab surface indicates movement from left to right in the same way as ice striated surfaces. The lens has been coated with magnesium oxide to show up surface detail. Length of the a axis 9".


b
a

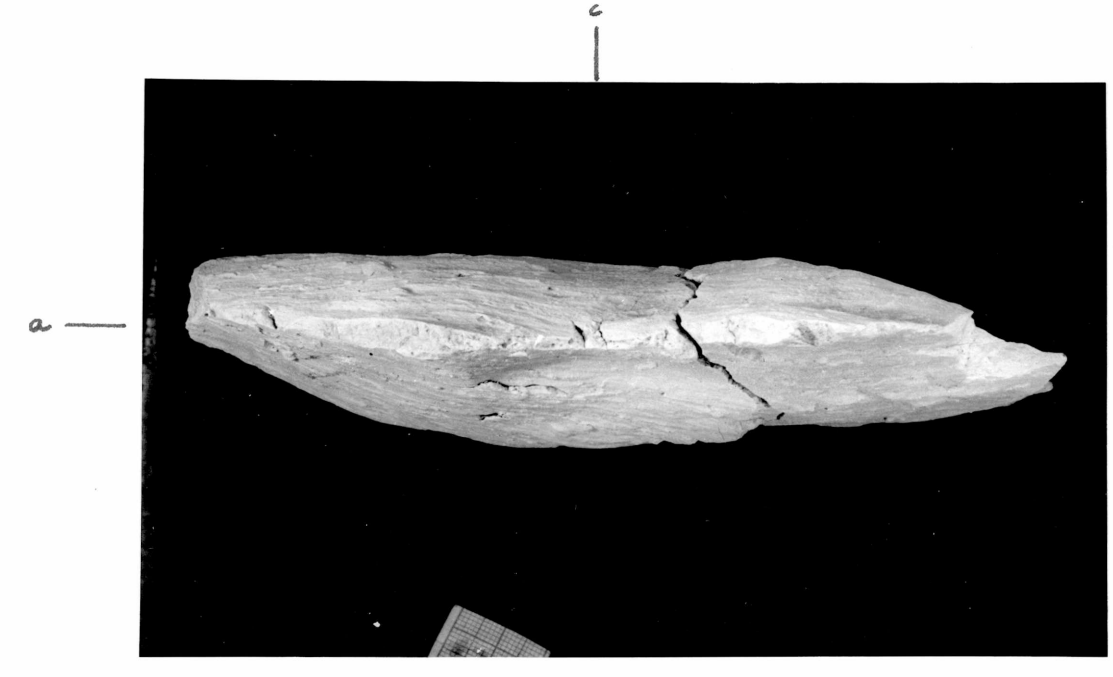

c
a

PLATE No. 40 May 1965

Failure surface of a slab slide which failed during construction, Jari left abutment. The failure surface of the slide was the lower principal plane of a moderate shear zone, the back and side walls of the slide were bounded by fissure and joint surfaces. Debris from the slide was immediately brushed away and measurements of the planarity of the surface made and presented as fig. 68. The photograph was taken an hour or two later than when the measurements were made and some surface drying and cracking, shown clearly on the photograph by the hammer handle, had commenced.



PLATE No. 41 November 1961

Reverse fault, RF_c, from the west face of Fort Hill, the trace of the fault was freshly exposed in an adit dug to follow it in from a cliff face. The fault occurs as two 1/8" - ¼" thick planes of black silty clay (indicated by the two fingers) contained in a medium to coarse sandstone bed. A clay ball within the sandstone, is seen truncated by the upper clay plane. Displacement along the fault was about 5', this fault was one of the RF series of minor reverse faults found at Mangla.



PLATE No. 42 November 1961

A second photograph of the fault shown in plate 41. A plane of sheared(?) and comminuted sandstone parallel to and about 1' above the upper clay is clearly visible. This zone of shearing appears to have shifted the lines of bedded clay balls about $\frac{1}{2}$" (by the arrow) but it does not contain black clay like the fault plane proper.

PLATE No. 43 July 1964

A moderate/intense fault zone crossing a shear zone, Location IV B Lower Stilling Basin, Mangla - only the fault zone is clearly shown. The rule is 1' long and is placed on the fault zone.

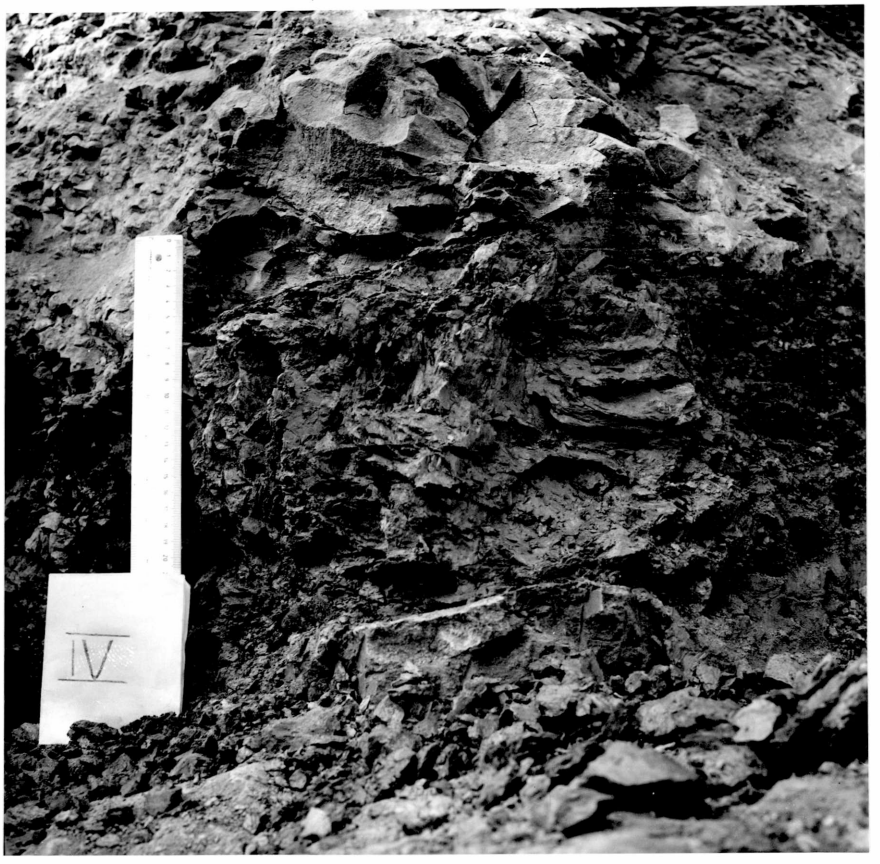

IV

PLATE No. 44 November 1964

A clayey silt bed (211) in the Upper Stilling Basin Mangla, containing a slight shear zone parallel to the bedding and on which the base of the 1' rule is standing. It is cut by a small low angle reverse fault which has displaced the shear zone some 2'6". The minor reverse faults are always found cutting shear zones; shear zones were not found cutting the reverse faults.

PLATE No. 45 July 1964

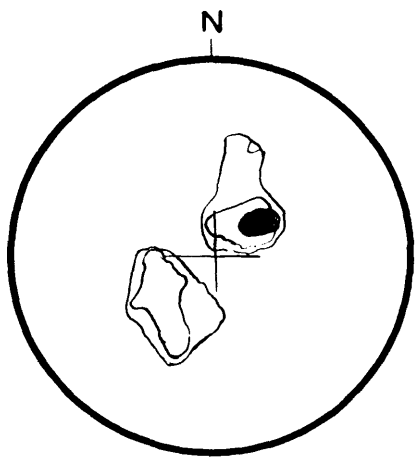
Two minor reverse faults (arrowed) showing 'moderate' intensity of shearing in the alpha sandstone bed, Lower Stilling Basin, Mangla. Total displacement along this fault (which generally occurred as a single plane) was approximately 26'. The fault is also shown on plate 43 where it is cutting across a clay bed and a shear zone.



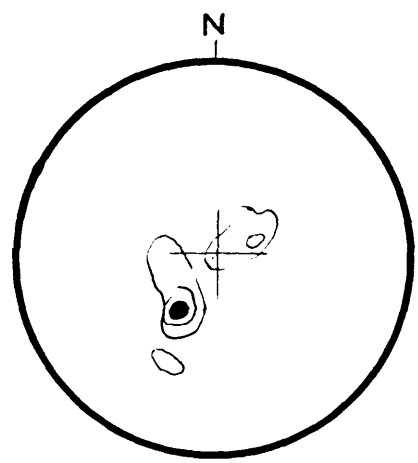
PLATE No. 46 September 1962

The failure surface of a slab slide which fell into trench PQ, during the site investigation of the right abutment at Jari. The slide failed on a moderate shear zone and although 'principal planes' of shear zones were not recognised at the time of the slide, it is now clear that the failure surface was the lower principal plane of the shear zone. Continuity of principal planes were not appreciated until the foundation investigation 1964/5 when several slides occurred during construction in the same area as trench PQ.

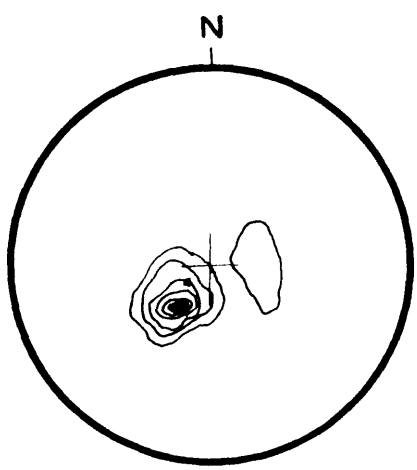
There is nobody under the hat - it is resting on the surface of the slide.



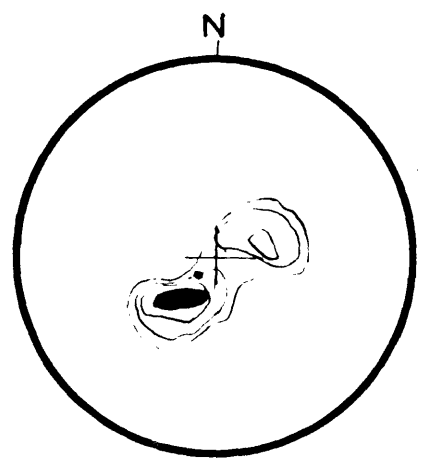
INTAKE



INTAKE



MAIN SPILLWAY



MAIN SPILLWAY

NOTES

LOWER HEMISPHERE

EQUAL AREA PROJECTION

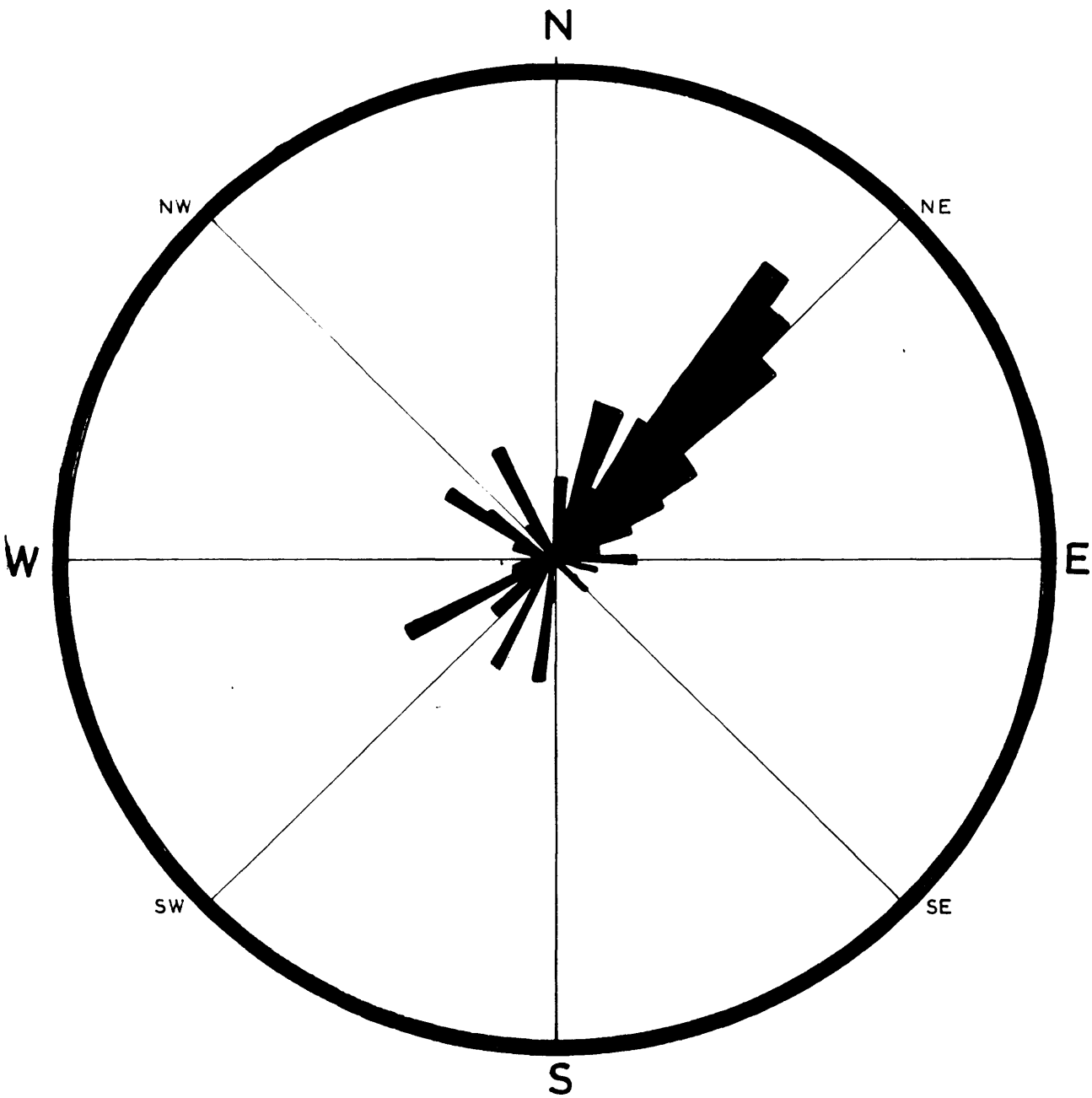
MANGLA

FOUNDATION INVESTIGATION 1964-65

CONTOUR DIAGRAMS OF

THRUST SHEAR JOINTS

FIG. 57



NOTES

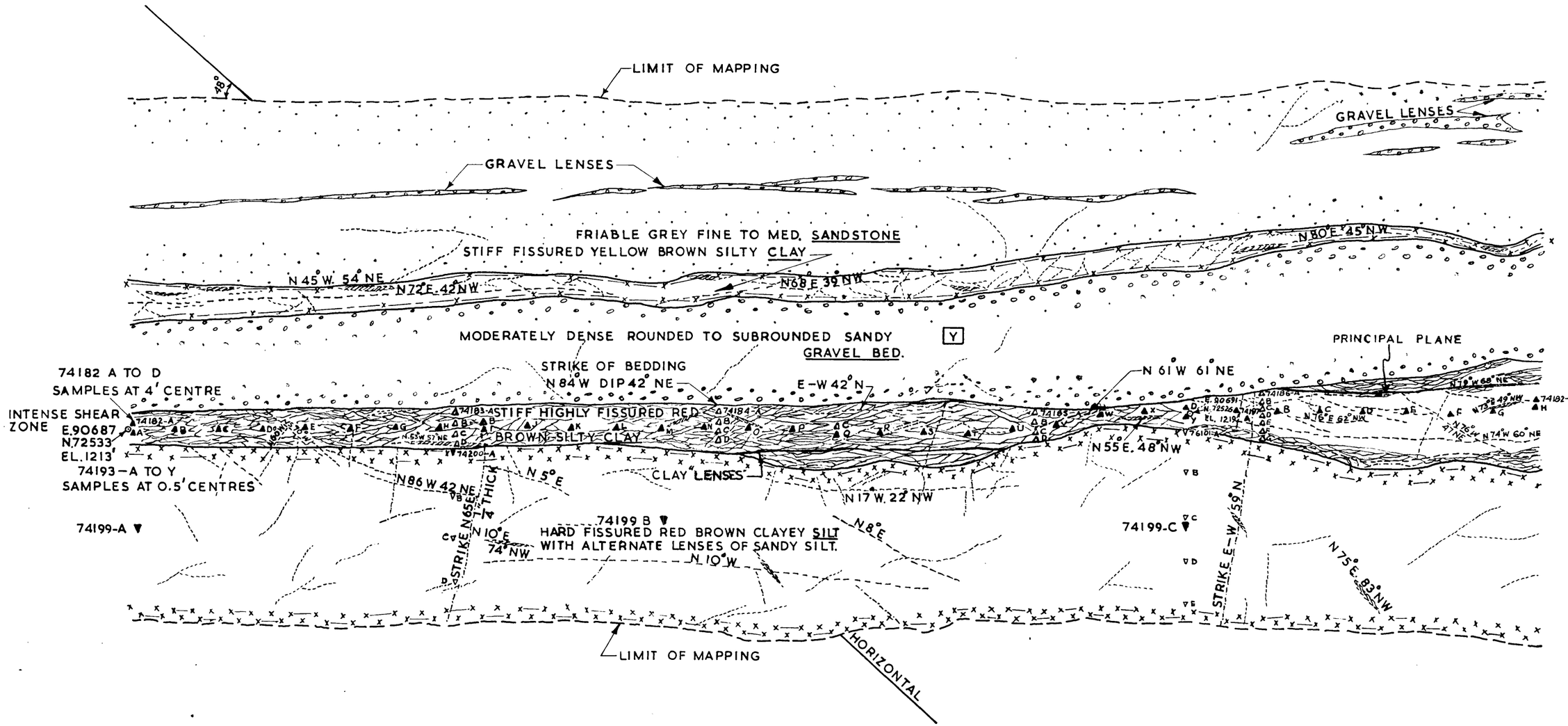
1. THRUST SHEAR JOINTS PLOTTED BY THEIR DIP DIRECTION.
2. ALL THRUST SHEAR JOINTS MEASURED AT MANGLA ARE PLOTTED.

MANGLA

FOUNDATION INVESTIGATION 1964-65

FREQUENCY DIAGRAM OF THRUST SHEAR JOINTS

FIG. 58.



CONTINUED ON SHEET 2

LEGEND

- THRUST SHEAR JOINT
- TENSION JOINT
- FISSURE
- SLICKEN SIDED FISSURE FACE.
- CLASSIFICATION SAMPLES AT 0.5' CENTRES ALONG THE SHEAR ZONE.
- CLASSIFICATION SAMPLES AT 4' CENTRES ALONG THE SHEAR ZONE
- CLASSIFICATION SAMPLES AT 0.1' CENTRES ACROSS THE SHEAR ZONE.
- CLASSIFICATION SAMPLES AT 0.5' CENTRES. ACROSS THE BED ADJACENT TO THE SHEAR ZONE.

NOTE

1. ALL MEASUREMENTS WERE MADE ON FRESH UNWEATHERED SURFACES.
2. 'CLAY LENSES' ARE LARGELY DIAGRAMATIC

SCALE 0 1 FOOT

JARI

FOUNDATION INVESTIGATION 1965

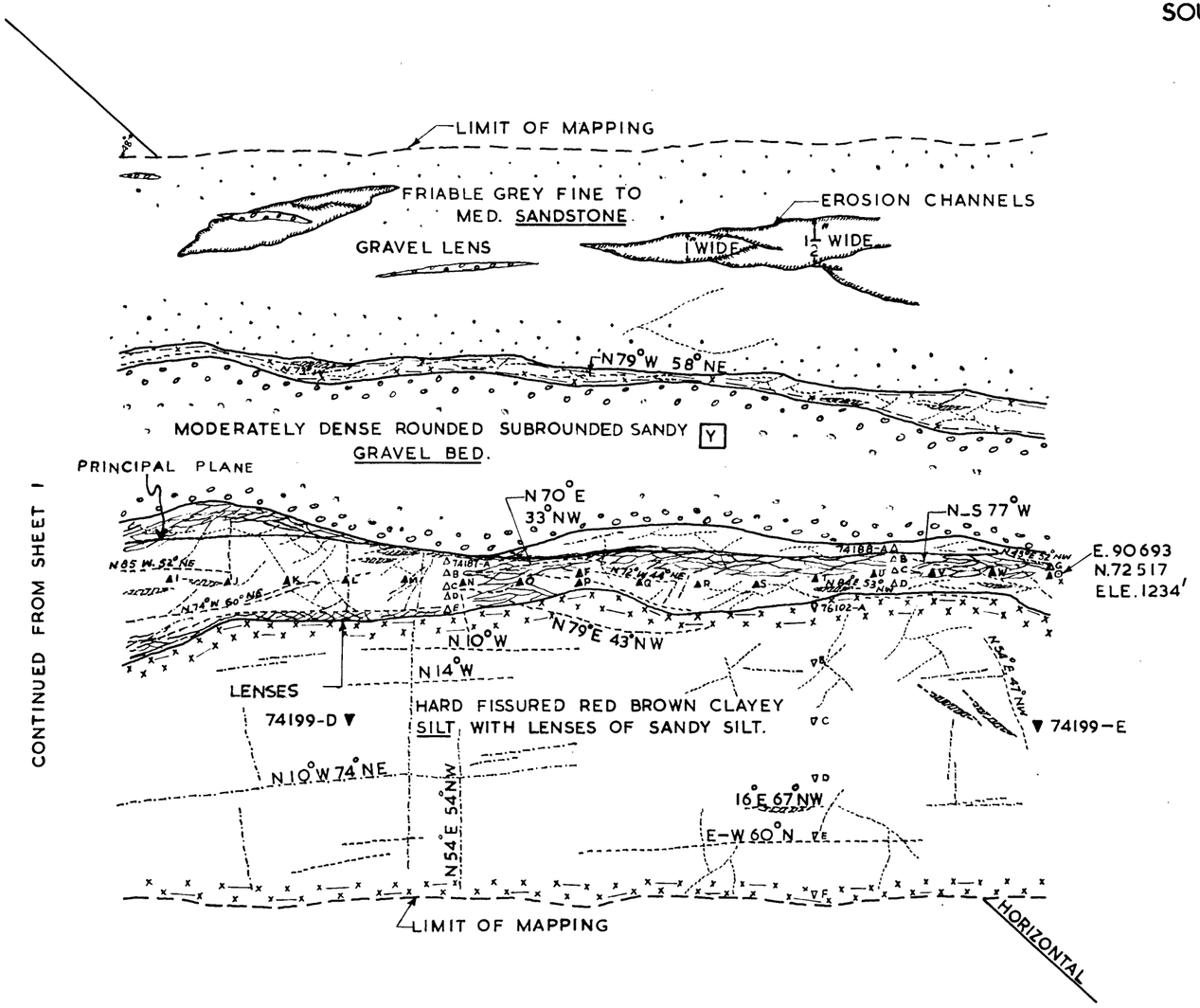
SHEAR ZONE 'A'

(SHEET 1 OF 2)

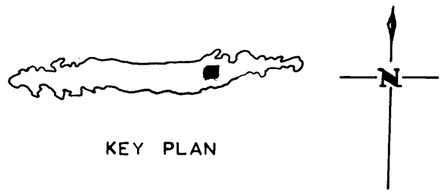
(AFTER F.O.K. & Z.U.H.) FIG. 59.

NORTH

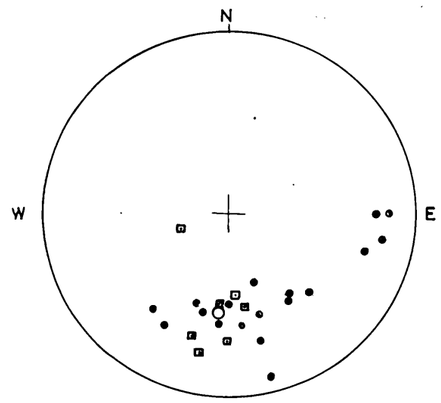
SOUTH



CONTINUED FROM SHEET 1



KEY PLAN



POINT DIAGRAM OF THRUST SHEAR JOINTS AND FISSURES

- ⊡ THRUST SHEAR JOINT
- • FISSURES
- O BEDDING

LEGEND

- THRUST SHEAR JOINT.
- TENSION JOINT.
- FISSURE
- SLICKEN SIDED FISSURE FACE
- ▲ CLASSIFICATION SAMPLES AT 0.5' CENTRES ALONG THE SHEAR ZONE.
- ▲ CLASSIFICATION SAMPLES AT 4' CENTRES ALONG THE SHEAR ZONE.
- △ CLASSIFICATION SAMPLES AT 0.1' CENTRES ACROSS THE SHEAR ZONE.
- ▽ CLASSIFICATION SAMPLES AT 0.5' CENTRES ACROSS THE BED ADJACENT TO THE SHEAR ZONE.

SCALE 0 ____ 1 FOOT

JARI

FOUNDATION INVESTIGATION 1965

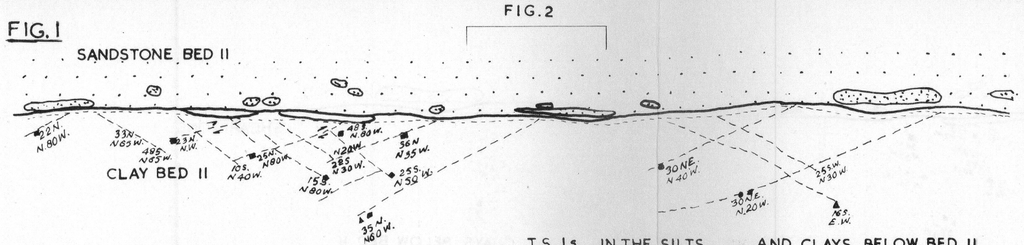
SHEAR ZONE 'A'
(SHEET 2 OF 2)

(AFTER F.O.K. & Z.U.H.) FIG. 60.

NORTH

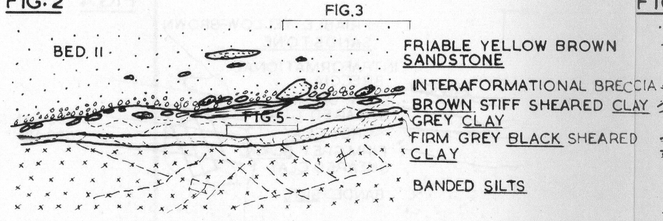
SOUTH

FIG. 1



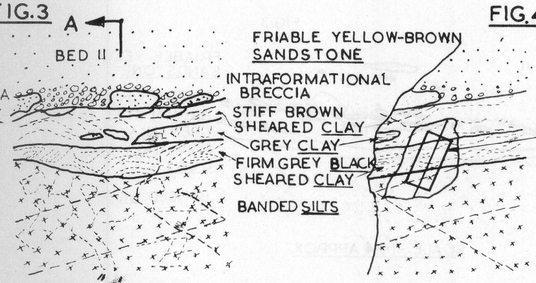
DIAGRAMMATIC

FIG. 2



SCALE:- 1" = 4' APPROX.

FIG. 3

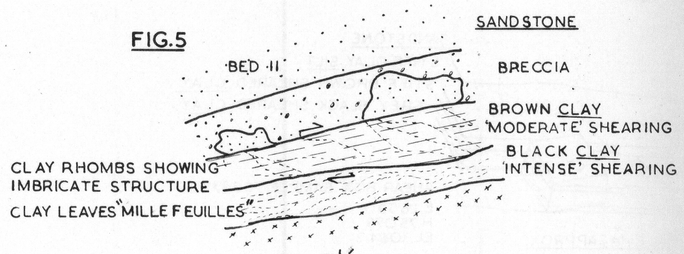


SCALE:- 1" = 2' APPROX.

FIG. 4

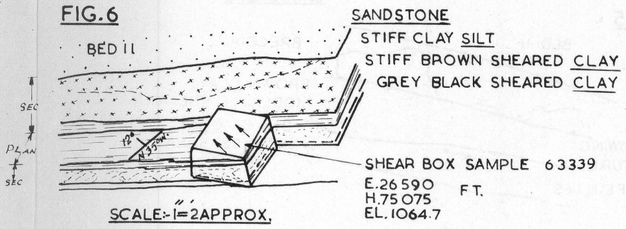
SECTION A-A'

FIG. 5



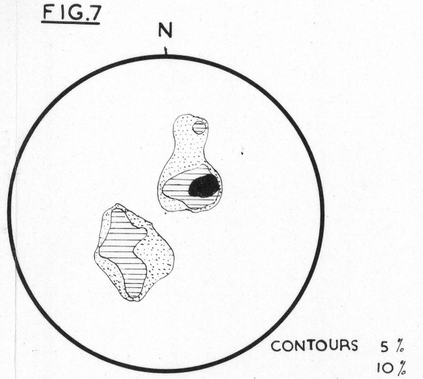
SCALE:- 1" = 1' 1/2 APPROX.

FIG. 6

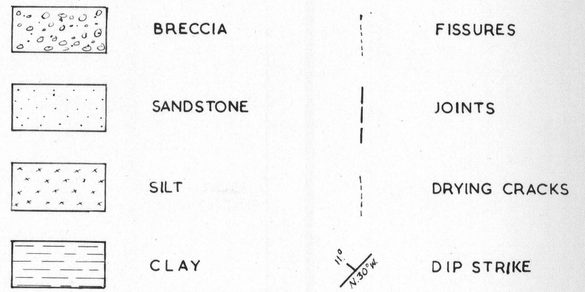


SCALE:- 1" = 2' APPROX.

FIG. 7



LEGEND

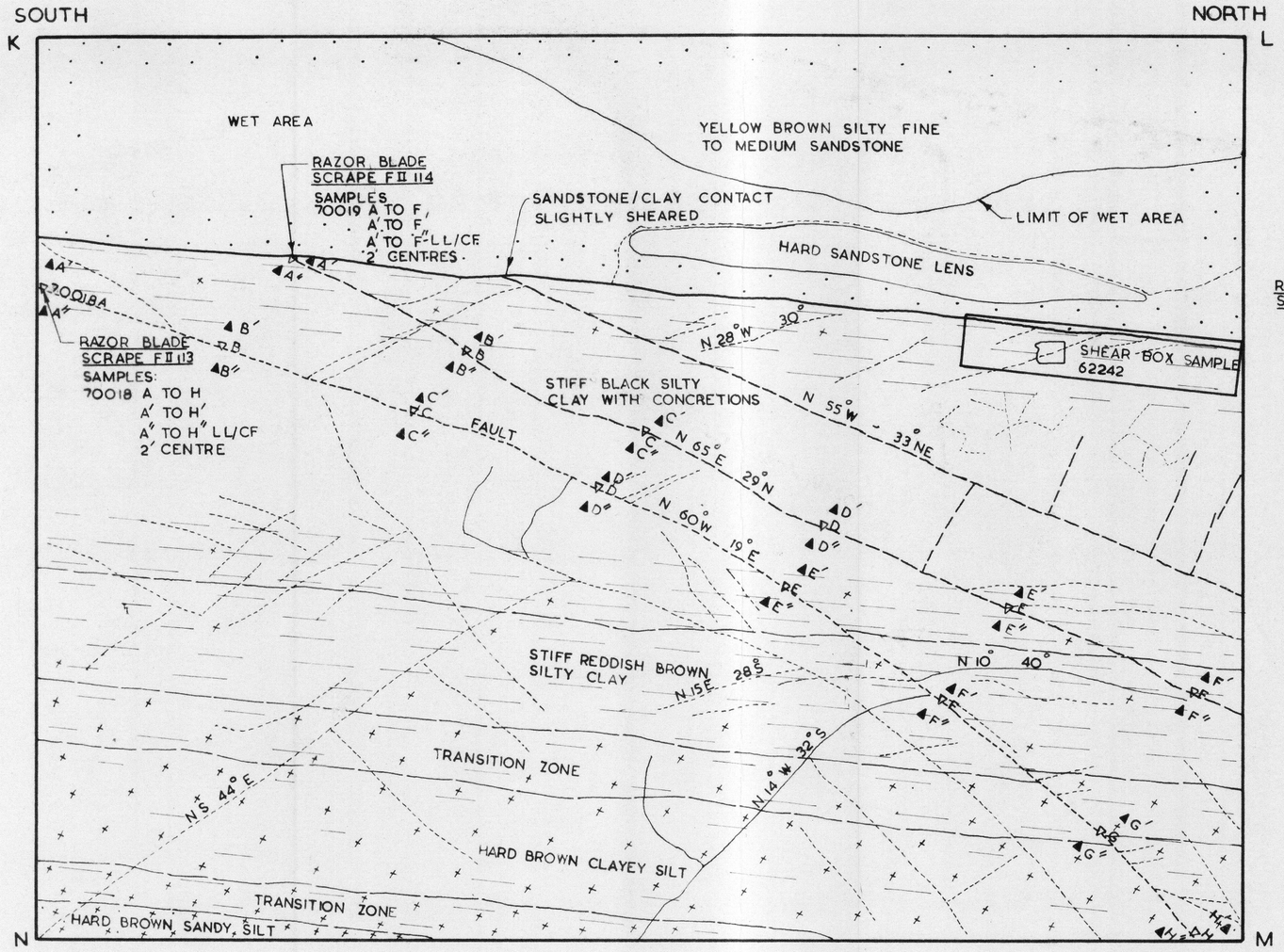


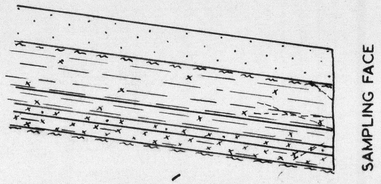
MANGLA

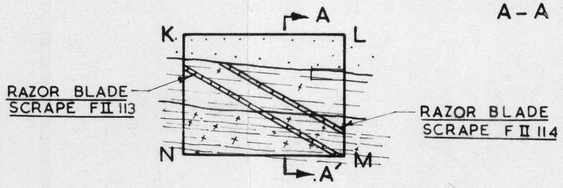
FOUNDATION INVESTIGATION 1964

SHEAR ZONE LOCATION 1

FIG. 61.







LEGEND

- SANDSTONE
- SANDY SILT
- CLAYEY SILT
- SILTY CLAY
- FAULT
- JOINT
- FISSURE
- CLOSED CRACK
- SHEAR ZONE SLIGHT
- CLASSIFICATION SAMPLE
- RAZOR BLADE SCRAPE

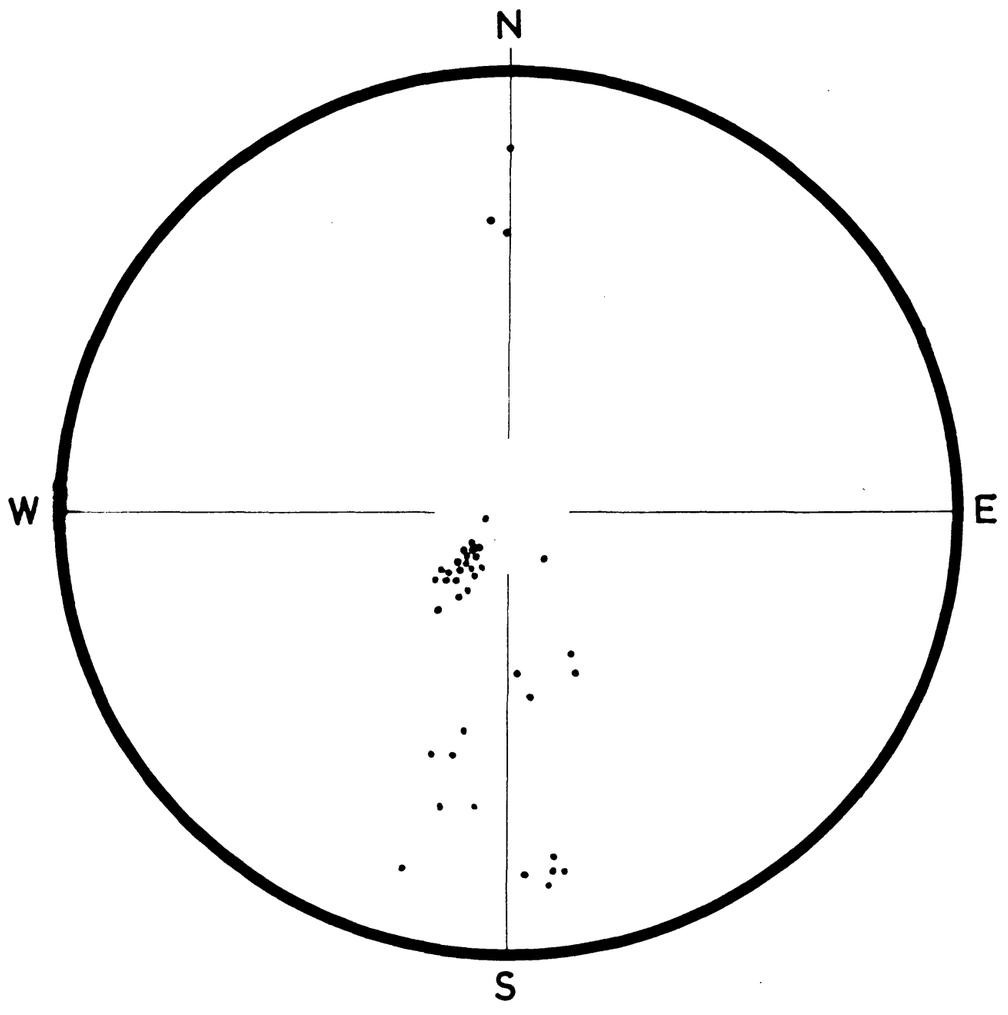
SCALE : INCHES 6 0 6 12 18 24 30 INCHES.

MANGLA

FOUNDATION INVESTIGATION 1964

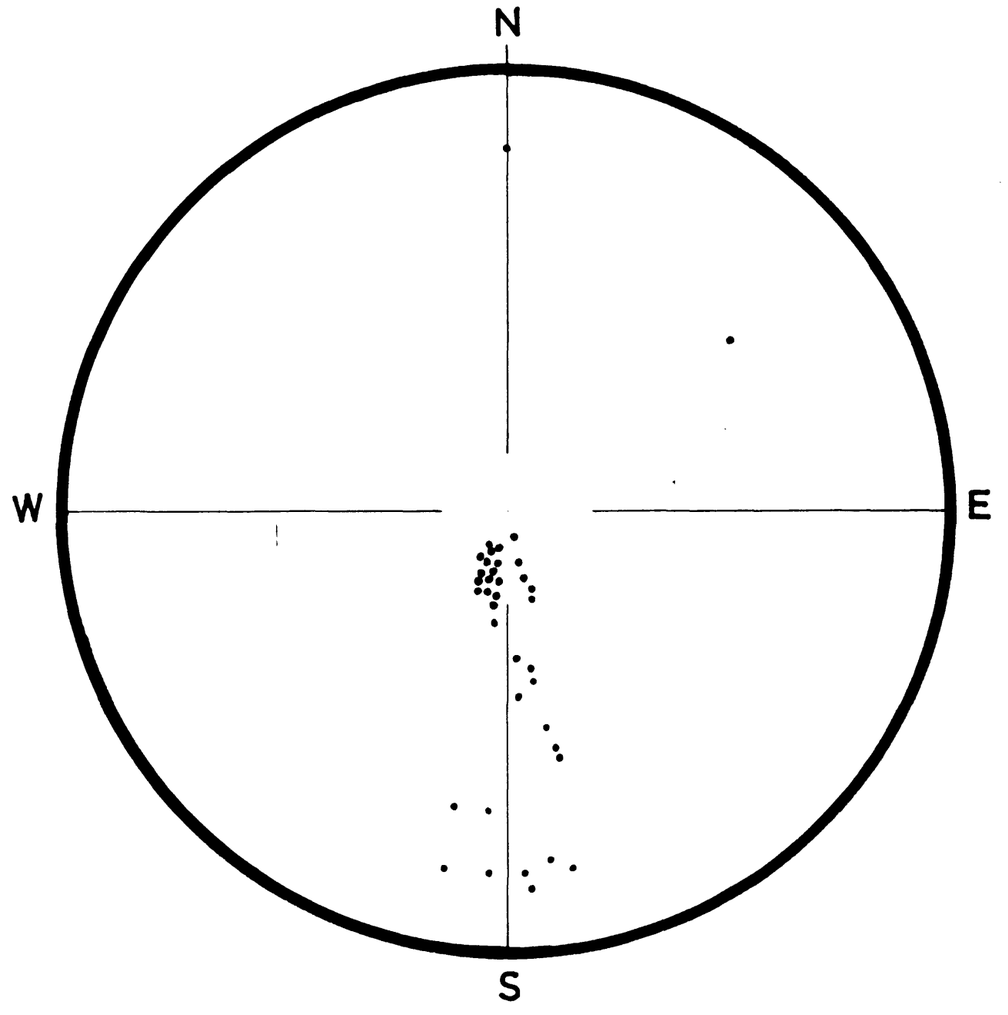
SHEAR ZONE LOCATION III

FIG. 62.



THRUST SHEAR JOINTS
JARI D/S NULLA 3 EAST

40 READINGS
EQUAL AREA PLOT
LOWER HEMISPHERE



LINEATIONS ON
THRUST SHEAR JOINTS

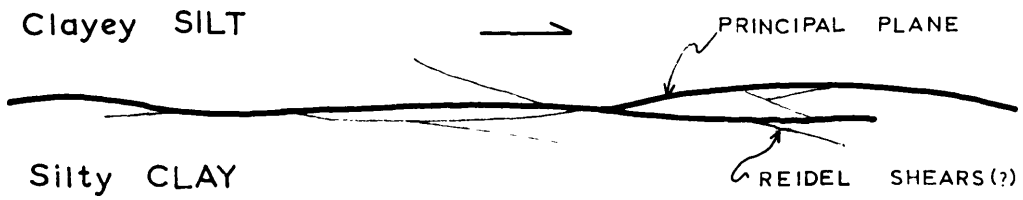
JARI

FOUNDATION INVESTIGATION 1965

POINT DIAGRAM

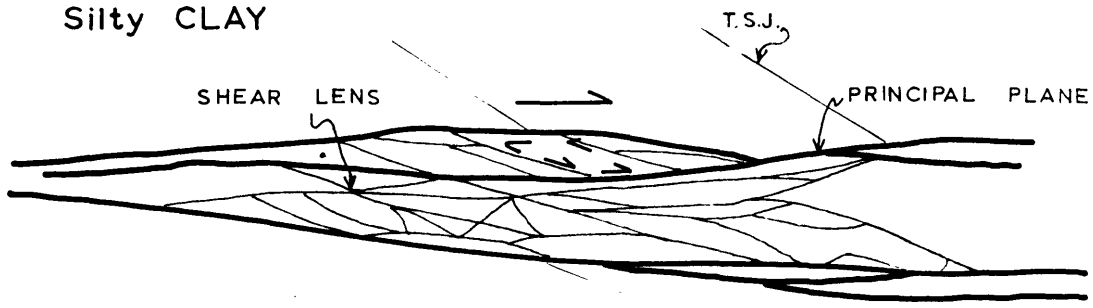
THRUST SHEAR JOINTS
FIG. 63.

'SLIGHT'



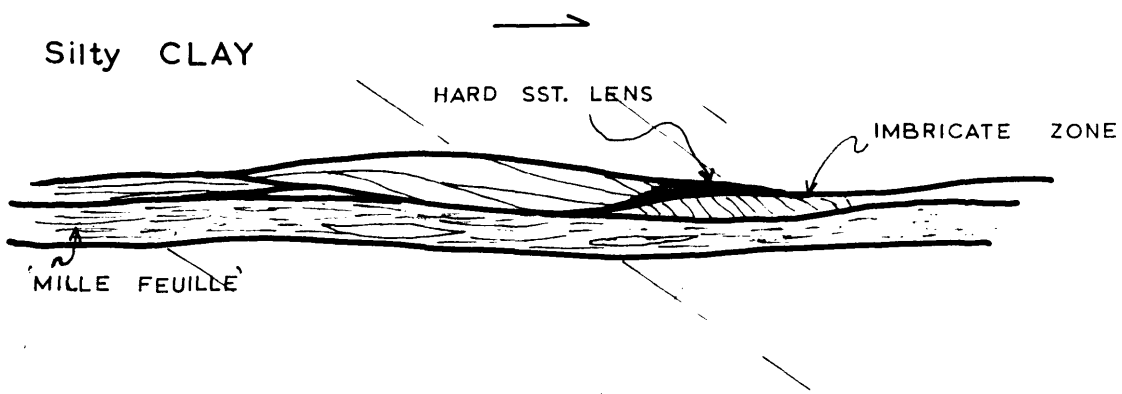
(UPPER STILLING BASIN BED 214)

'MODERATE'



(JARI D/S NULLA 3 EAST)

'INTENSE'



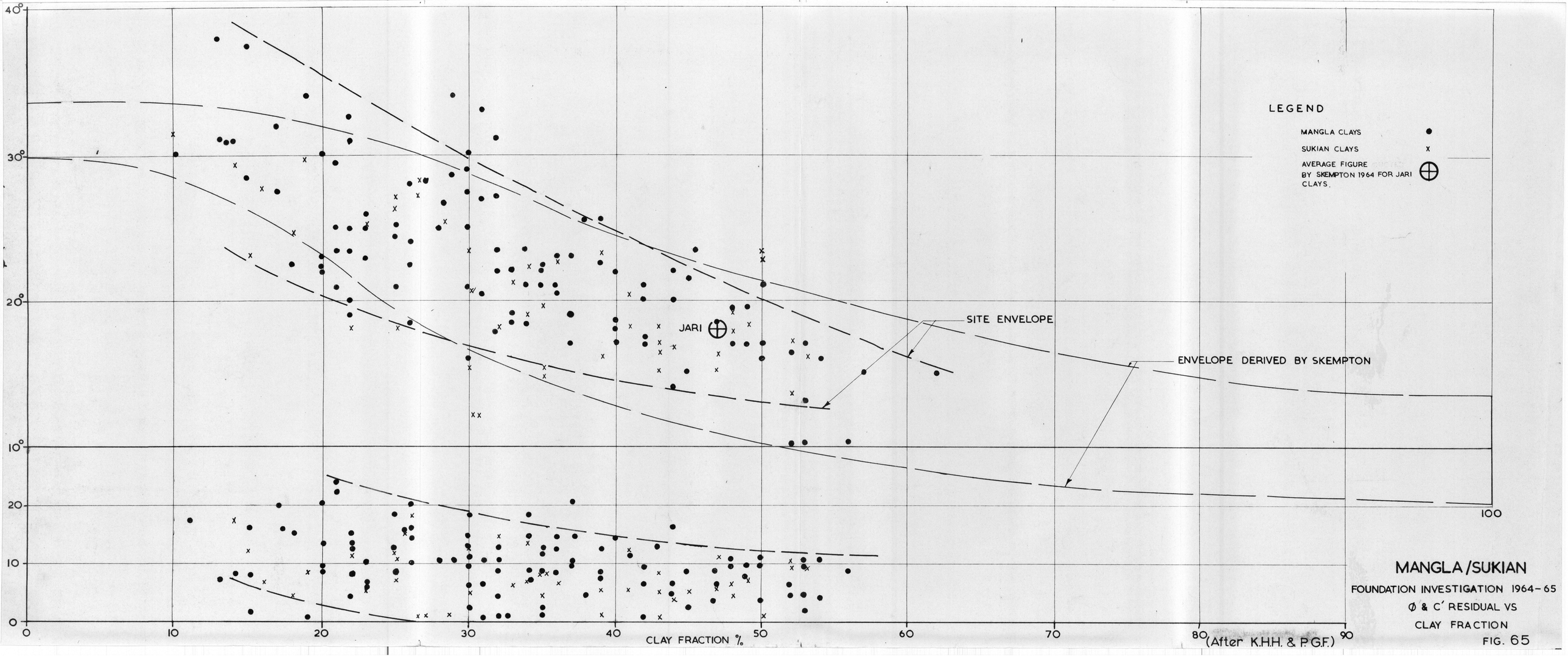
(LOWER STILLING BASIN BED 201)

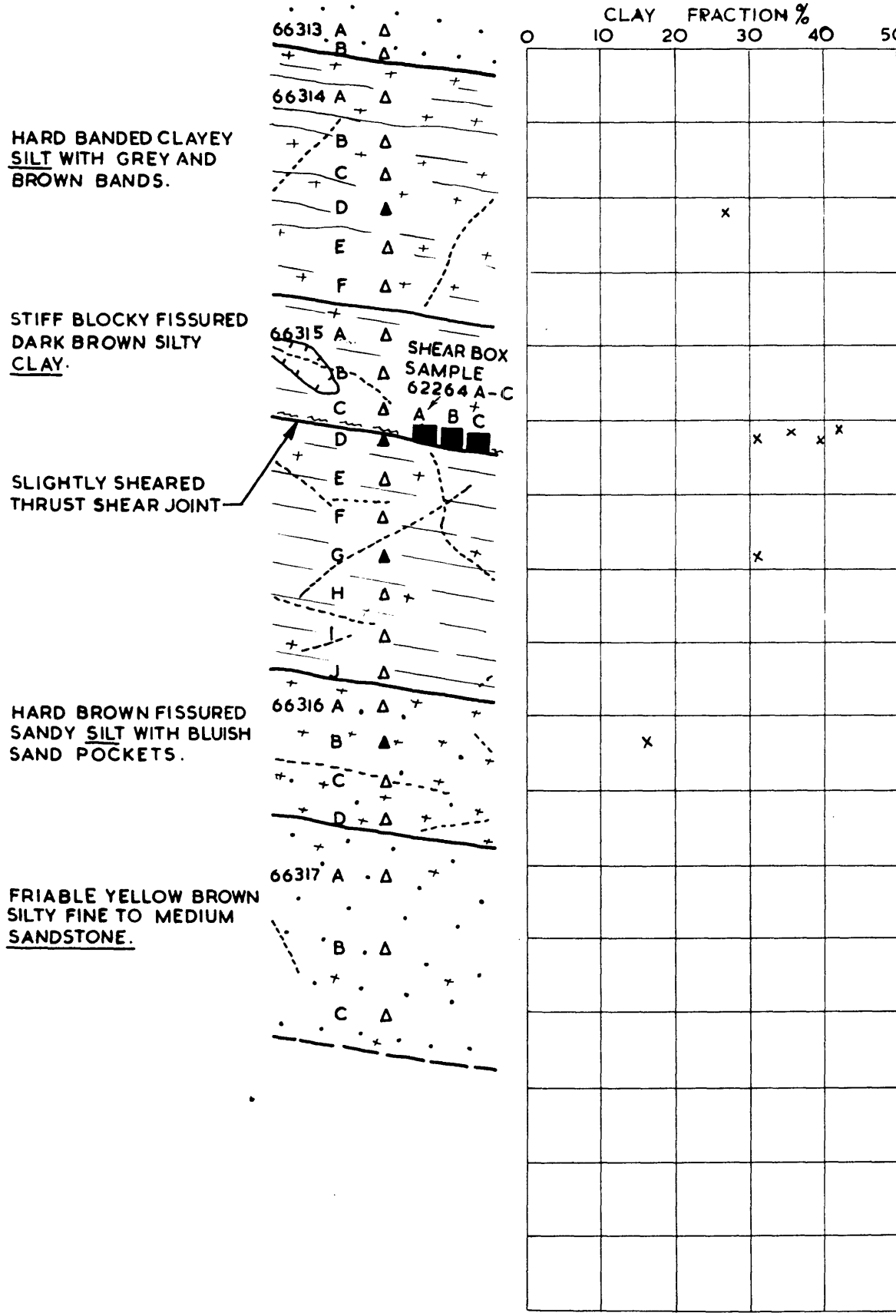


MANGLA / JARI

FOUNDATION INVESTIGATION 1964

FIG. 64. FIELD CLASSIFICATION OF SHEAR ZONES


40°
30°
20°
10°
0
10
20
30
40
50
60
70
80
90
100
CLAY FRACTION %
LEGEND
MANGLA CLAYS
SUKIAN CLAYS
AVERAGE FIGURE BY SKEMPTON 1964 FOR JARI CLAYS.
JARI
SITE ENVELOPE
ENVELOPE DERIVED BY SKEMPTON
MANGLA/SUKIAN
FOUNDATION INVESTIGATION 1964-65
Ø & C' RESIDUAL VS
CLAY FRACTION
(After K.H.H. & P.G.F.)
FIG. 65

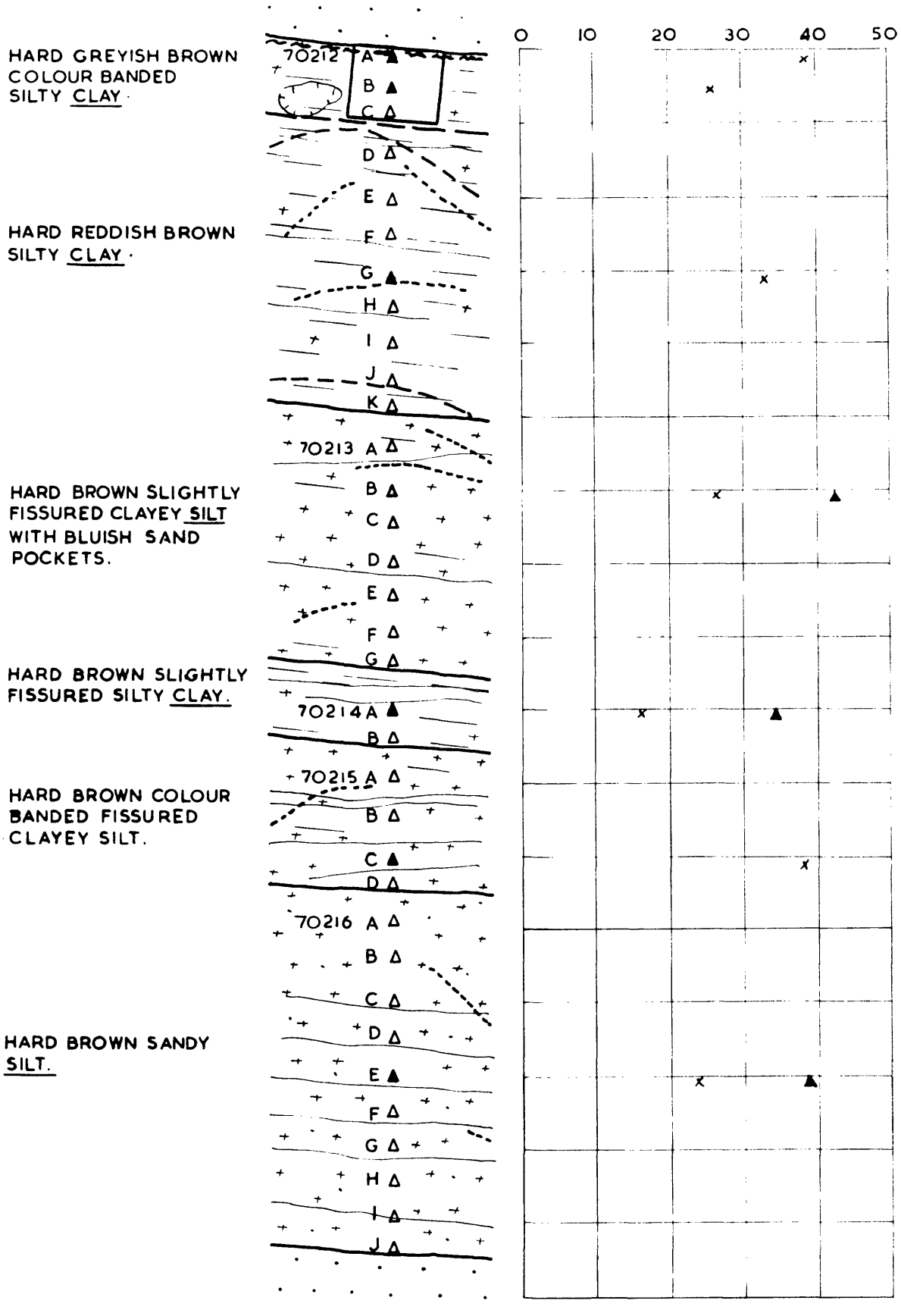


MANGLA

FOUNDATION INVESTIGATION 1964-65

TYPICAL 'SCRAPE'

FIG. 66.

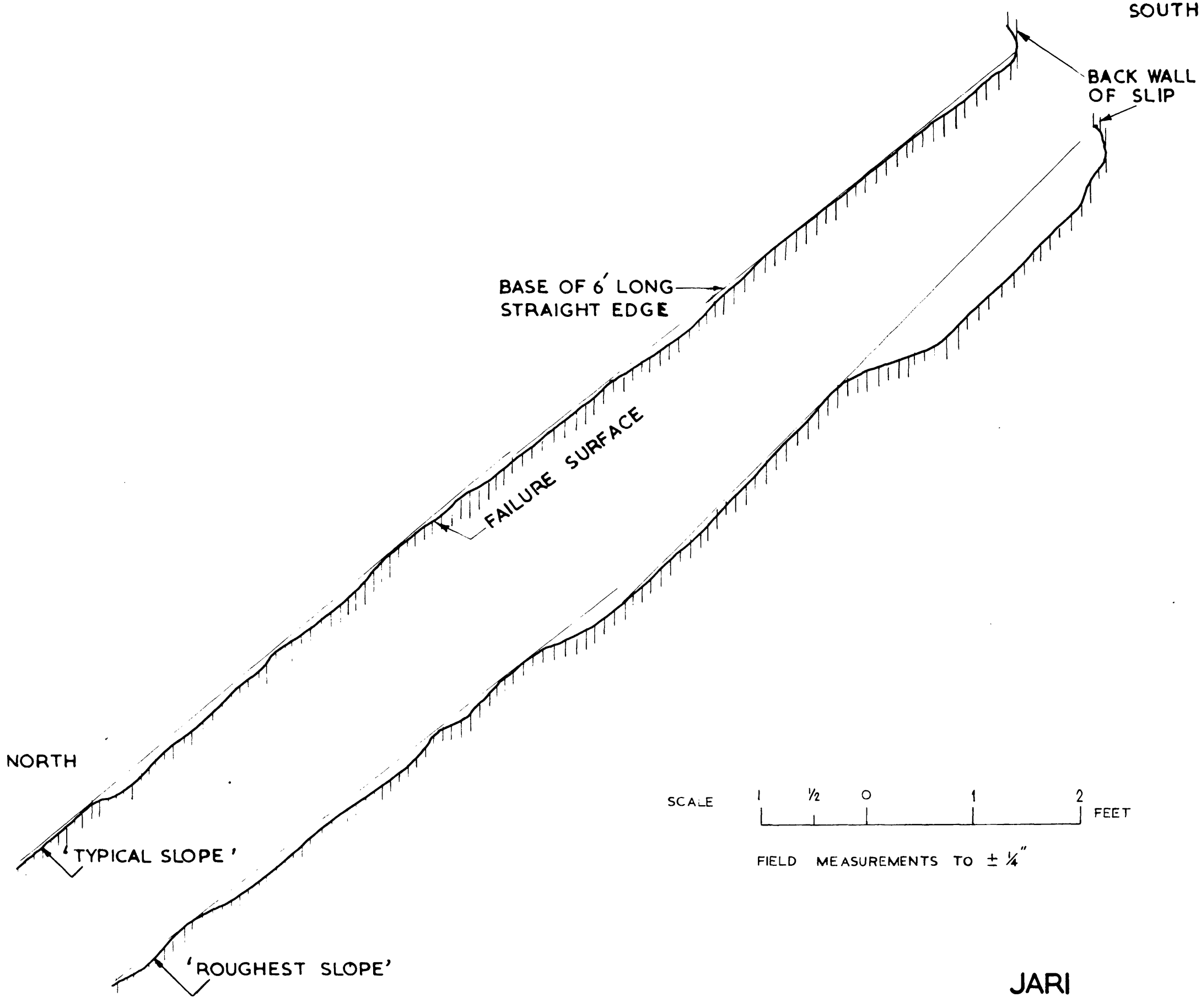


MANGLA

FOUNDATION INVESTIGATION 1964-65

TYPICAL SCRAPE

FIG. 67.



SCALE 1 ½ 0 1 2 FEET

FIELD MEASUREMENTS TO ± ¼"

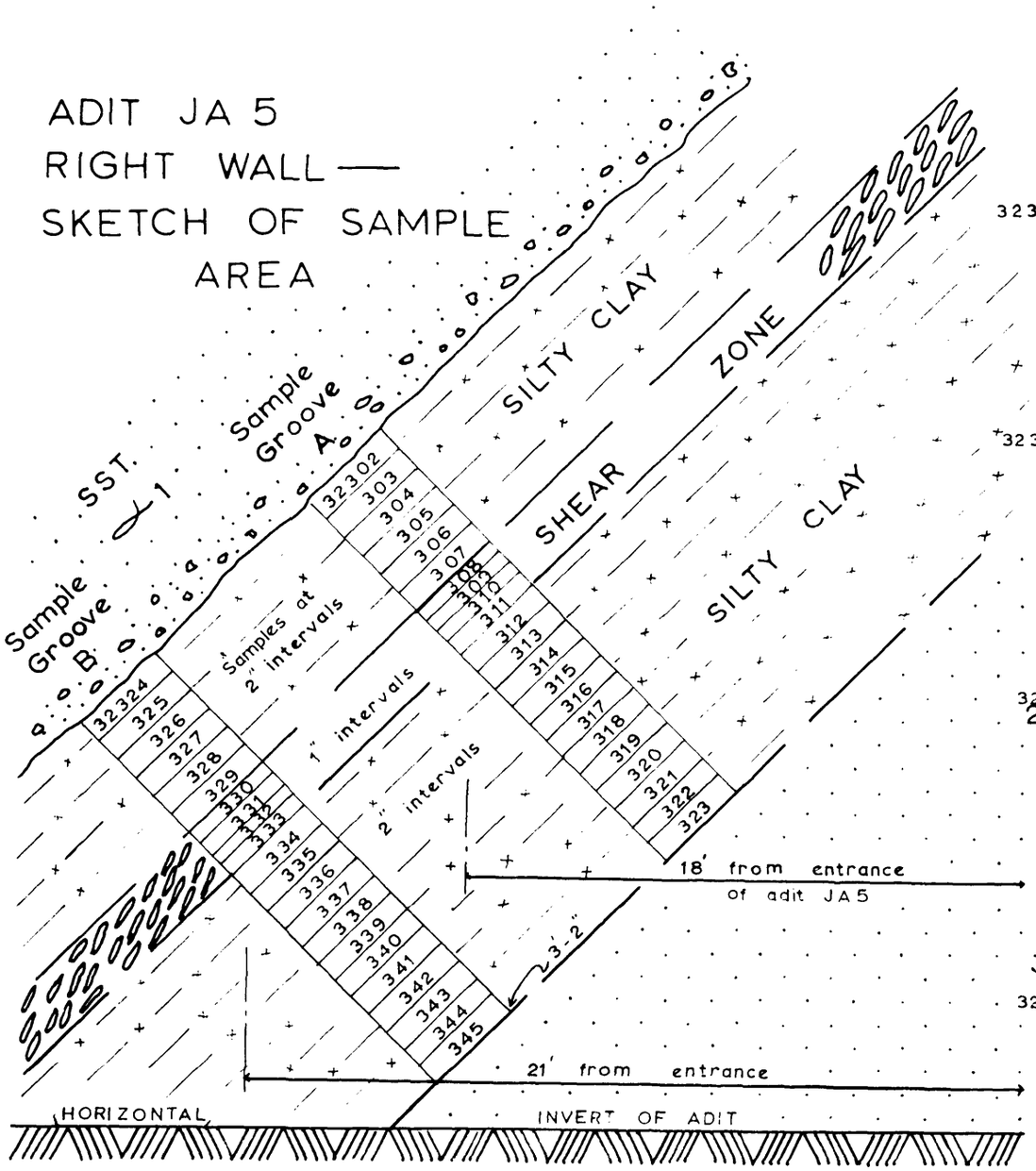
JARI

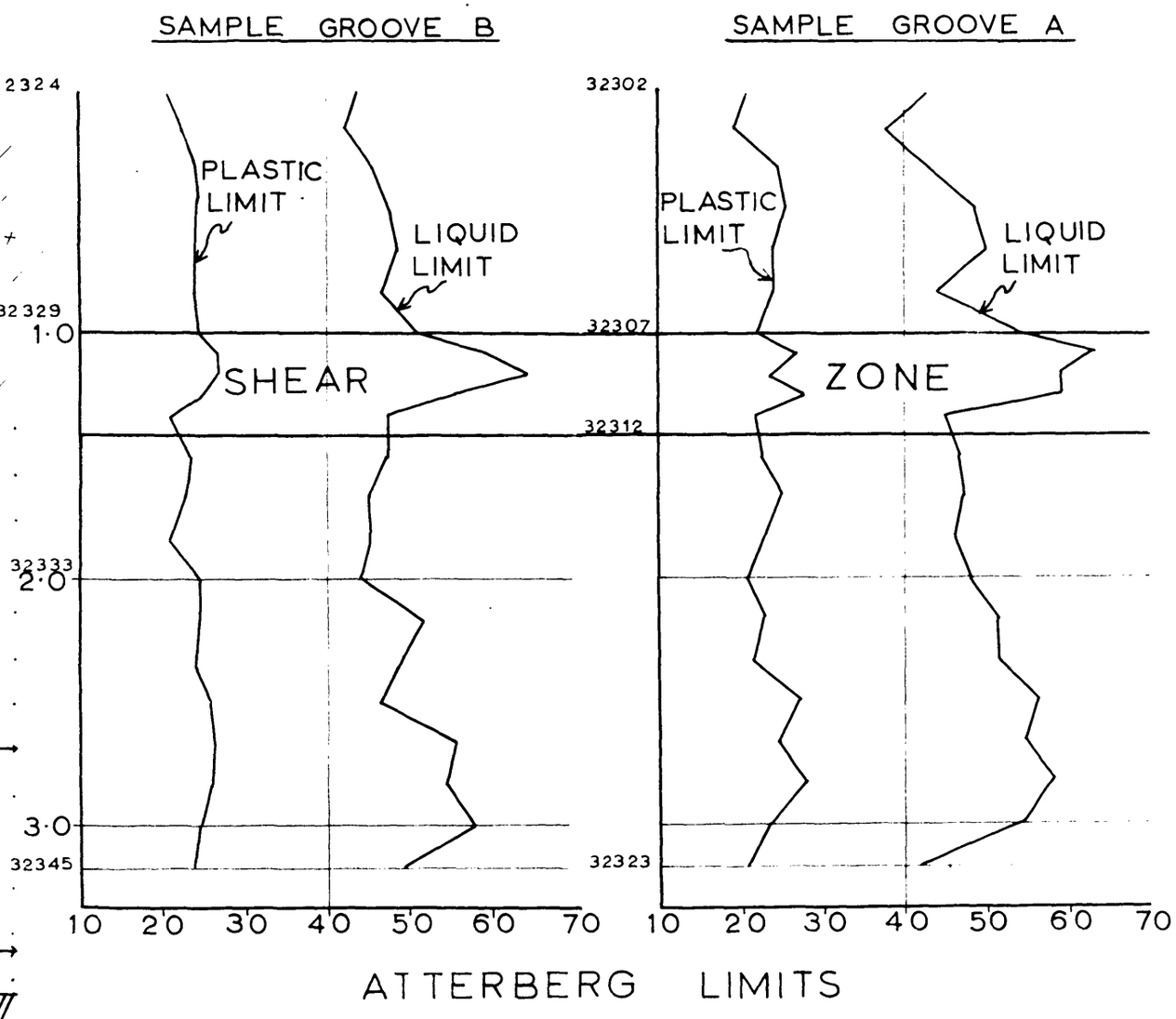
FOUNDATION INVESTGATION 1965

FAILURE SURFACE PROFILE

FIG. 68.

ADIT JA 5
RIGHT WALL —
SKETCH OF SAMPLE
AREA



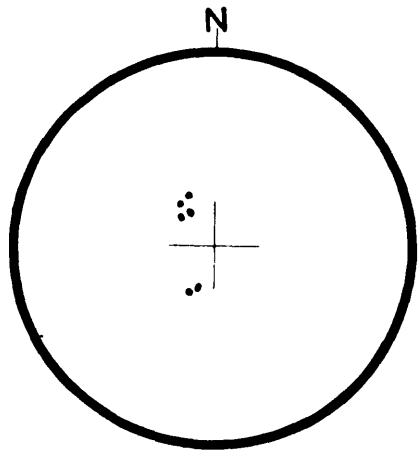


JARI

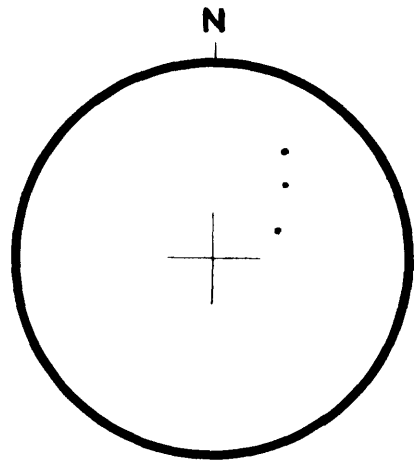
SITE INVESTIGATION 1962/3

THE ORIGINAL FIELD INVESTIGATION ON SHEARED CLAY

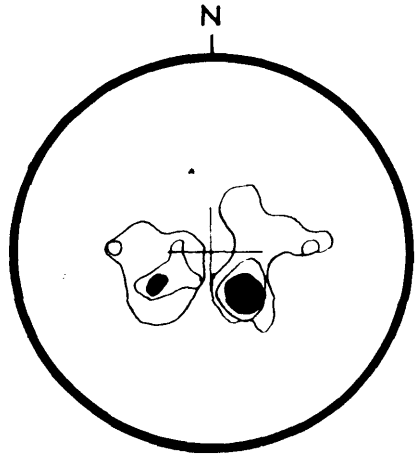
FIG. 69.



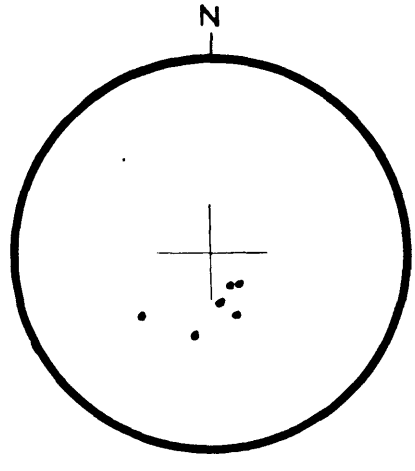
INTAKE



FABRI DAM



MAIN DAM



MAIN SPILLWAY

NOTES

LOWER HEMISPHERE

EQUAL AREA PROJECTION

MANGLA

FOUNDATION INVESTIGATION
1964 · 65
POINT DIAGRAM OF FAULTS

FIG. 70.

LABORATORY TESTS ON SHEARED MATERIAL

Sampling Procedure

In order to test effective shear strengths of shear zones, block samples were cut in the field for laboratory testing both by shear box and triaxial equipment. Block samples for shear box tests were cut so that the plane of the shear zone was parallel to the top and bottom of the block. Sets of three shear box specimens were then trimmed in the laboratory so that the plane of the shear zone (i.e. the polished surfaces of the leaves or long axes of lenses of the shear zone) was parallel to the failure plane in the shear box. This ensured that shearing in the laboratory took place in the same direction as the supposed tectonic shear movement in situ (i.e. in the same direction as the 'a' fabric axis but dipping parallel to bedding). A similar test was carried out on samples cut from the same blocks but sheared at right angles to this direction, i.e. parallel to the strike ('b' fabric axis) direction. Results from these were of a similar order to those tested in the 'a' direction but the test procedure may have been faulty so no conclusions were drawn.‡ No repeat test was made.

When difficulty was experienced in removing a block sample from its field location, a 6 cm.sq. shear box sample cutter was pushed into the shear zone normal to the plane of the zone (i.e. normal to the dip plane of the bedrock).

Block samples for 4" dia. triaxial tests were cut in the field so that when the specimen was erected in the triaxial cell the shear plane was inclined at approximately 30° to 35° to the vertical.

The orientation of triaxial samples was not always exactly as was intended due to vagaries of the materials. In most cases several unsuccessful attempts were made before a reasonably satisfactory sample could be obtained.

Laboratory Test Procedure

(i) Shear Box Tests‡

Consolidated-drained shear box tests formed the basis of the strength testing for this investigation. Tests were carried out on standard 6 cm.sq. by $\frac{3}{4}$" thick samples, orientated as described above to measure the shear strength along the plane of tectonic shear. The standard procedure which was employed is briefly outlined below.

In order to be reasonably certain that the samples were saturated before shearing commenced, they were loaded up to the normal stress used for the test, unloaded to a small load, and reloaded, after first surrounding with water (in the shear box apparatus). From the square-root-time consolidation curve for the final load increment the value of c_v was calculated from which a rate of strain was computed (Bishop & Henkel's method) which would ensure virtually complete dissipation of pore pressures during shear. Typical rate of strain was 0.24% per hour*.

In some instances where the residual value was not fully achieved at the full travel of the shear box, the machines

---

* In later tests the rate of strain was reduced (0.12% per hour) and the tests ran much slower with up to 5 reversals. This work is at present in progress and is, therefore, not presented here (autumn 1965).

were reversed, using a somewhat greater rate of strain (usually 0.48% per hour), back to the zero position. Shearing was then resumed at the original speed.

(ii) Triaxial Tests‡

Triaxial tests were carried out on orientated 4" diameter samples to supplement the shear box tests, and to compare results. It was also considered that a 4" diameter sample might be large enough to allow the material to 'select' its own surface of failure, which would be the weakest of the possible surfaces. In addition the 4" diameter sample would have a failure surface 4 to 5 times larger than a shear box sample and would, therefore, be more representative of shear zone material.

Each 4" diameter sample was saturated and consolidated as described in Part I using filter paper side drains. An effective cell pressure of 60 lb/sq.in with a back pressure of not less than 20 lb/sq.in. was used for each sample.

The main difficulty with samples was in the trimming. The nature of the material, and the necessarily awkward orientation of shear planes, resulted in several samples breaking up when almost ready for the cell. Material from location II was the most difficult and the attempts to trim a 4" diameter sample from here had to be abandoned. Instead a set of three $1\frac{1}{4}$" diameter samples were trimmed from three pieces of a disintegrated block but their orientation in space could not be determined. Standard triaxial tests were carried out on these samples, at effective cell pressures of 20, 60 and 120 lb/sq.in.

Triaxial and shear box test results are directly comparable with the exception of Mangla location III, where the relatively high strength of the triaxial sample is probably due to the presence of the sandstone/clay contact; in the shear box tests failure surfaces were restricted within the thin slightly sheared layers of the sample.

Descriptions written on the laboratory test sheets (Fookes & Head 1964) are laboratory descriptions of each individual sample or block and sometimes differ in detail from geological descriptions of strata made in the field. The field estimates of intensity of shearing were made at the time of selection of the locations studied, before any test data was available.

Discussion of Results

In fig. 24 the three types of stress/strain characteristics (types 'A', 'B', 'C') for Mangla and Jari clays are shown. Early tests from the Jari site investigations (1962/3) on different categories of clay bedrock indicated that clays from shear zones exhibited Type 'B' and 'C' characteristics, in contrast with 'intact' clays from elsewhere which were generally of Type 'A'. The foundation investigation 1964/5 confirmed these findings.

The ratios of peak to residual strength were generally less for triaxial tests than for shear box tests and residual strengths seemed somewhat higher. This was possibly due to the triaxial test being curtailed at a strain of 18 - 20% owing to distortion of the sample, since extension of the test by a process corresponding to the reversal in the shear box was not possible.

(i) Mangla Foundation Investigation 1964 (table XX)

Effective shear strength parameters Ø' (peak) and Ø' (ultimate) are plotted graphically against mean clay fraction for the block sample from each location in fig. 71. For comparison, Ø' (ultimate) values obtained from foundation investigations at Mangla on unsheared material are also plotted against clay fraction. No correction is made for c'.

Three factors appear from the graphical plot:

(1) Considering all results in general, there is a very rough correlation between Ø' (ultimate) and clay fraction; high clay fraction is associated with low effective strength.

(2) Ultimate (residual) strengths of all samples from the shear zone locations are close to the lower limit of the correlation.

(3) Intensity of shearing of shear zone samples appears to be related to clay fraction, the most intensely sheared material (for example location I described in Appendix IV) has the highest clay fraction.

Results from the shear zones, however, are based on shear box tests, with a single 4" diameter triaxial test for comparison, in four out of the five examples. Since a cohesion intercept could not be derived from a single Mohr circle, it was assumed by the laboratory that the c' value derived from the set of shear box samples was applicable. The tangent to the Mohr Circle was drawn

from the c' intercept point, and the gradient of this line was taken to be the Ø' value for the triaxial test. In all instances except location IVB from a fault zone, shear box tests give lower Ø' values than triaxial tests.

The foundation investigation 1964 test results confirmed previous experience that strengths of shear zone material, when plotted as shown fall in the lower half of the grouping. It is also considered by the site laboratory that shear box tests give somewhat lower results than triaxial tests, and that this accounts for a further reduction of Ø' values for a given clay fraction, bringing the plots of shear zone samples down to the lower limit of the correlation curve (see Fookes & Head 1964).

(ii) Jari Foundation Investigation 1965 (tables XXI(i) and (ii)

Further work during the foundation investigation of Jari 1965 (Fookes & Head 1965) is summarised in tables XXI and plotted against average clay fraction, for the set of three specimens, and shown in figs. 72, 73 and 74 for unsheared clays; slightly sheared clays and samples from thrust (shear) joints; and moderate and intensely sheared clays respectively. For comparison, results from previous work at Mangla and Sukian are shown and the Jari figures are ringed. No correction is made for c'.

Results for the unsheared and slightly sheared clays are too scattered to allow any clear relation to be drawn. But the results from the moderate and intensely sheared

clays again show increasing clay fraction is associated with decreasing residual strength.

In addition residual strengths of individual specimens from the Jari foundation investigation have also been plotted against clay fraction. Fig. 75 gives triaxial test results in the form of deviator stress for each of the three studied effective confining pressures. Fig. 76 gives direct shear strengths for each of three studied usual pressures from shear box tests. The correlation of the graphs is poor but shows some tendency for residual strengths to decrease with increasing clay fraction. The poor correlation is undoubtedly due in part to the site technique of plotting the results without compensating for a c' = 0 condition.

Ratios of peak to residual strength for Jari, Mangla and Sukian tests can be summarised as follows:

Unsheared clay	1.65 : 3.5
Slightly sheared or thrust (shear) joints	1.0 : 3.1
Moderately and intensely sheared	1.0 : 1.6
	(with 2 exceptions)

These values are in keeping with the field classification of intensity of shearing.

There is little doubt that the more intensely sheared clays have a higher clay fraction than moderately or slightly sheared clays. The question again arises whether shearing in situ followed beds of relatively high clay fraction, which are also 'weak' beds, or whether the relative movement of the

shearing process caused a breakdown or rearrangement of particles resulting in a higher clay fraction. It is considered that the former is the more likely alternative, though it is possible that some rearrangement of particles may have occurred in addition. Field evidence indicates shear zones tend to occur in the highest clay fraction clays. For example fig. 55 shows clay fraction results from a moderate/intense shear zone on Fort Hill tested from several locations spread out over 1,500'. It is clear, within limits of sampling and testing error that the shear zones clay fraction is a few % higher than adjacent clay. The bed was probably diachronous and the shear zone maintained a single facies horizon with the clay bed (see inset diagram on fig. 55) though in the absence of any confirmatory evidence, it could not be shown conclusively that the shear zone itself cut time planes and, therefore, it could not be shown conclusively from field evidence whether or not the shear zone followed a high clay fraction layer or created it itself.

Fig. 77 is a triangular plot of tested clay fractions with the field descriptions for each sample tested, indicated on the figure. The field description was made at the time of sampling and the preponderance of sheared material with a high clay fraction is clearly indicated by the symbols. A check on the accuracy of the field description is given by the histograms as the test results are plotted in accordance to their field description. Test results and field descriptions were taken from the Jari foundation investigation 1965 trench

logs, examples of which are shown as figs. 78 and 79. They show the improvement in the detail of logging from the original site investigation 1962 (for example figs. 27 or 28). A field description of each recognisable bed over 18" thick (from top to bottom of the bed) is given and a field classification for each shear zone is made. Logs of this type were drawn of every bed upstream to downstream at Jari on a 1" to 2' scale and from these the columnar section (fig. 56) and distribution of shear zones, were made. Plate 47 of the left abutment portion of the core trench shows cleaned up logging and sampling strips during the foundation investigation programme.

MANGLA
FOUNDATION INVESTIGATION 1964
SUMMARY OF TRIAXIAL TEST RESULTS FROM SHEAR ZONES.

Location Ref.	Sample No.	Type of Test	Clay Fraction %	Liquid Limit %	Effective Shear Strength Peak C' p.s.i.	Peak ∅'	Ultimate C' p.s.i.	Ultimate ∅'	Stress/Strain curve type	Mean Peak/Ult Ratio	Degree of Shearing (Field Description)
I	63343	4" TXL	33 *	55	-	-	4	16°	C	1	Intense
	63339	S.B.	53	58	4	13½°	4	10°	B - C	1.17	
II	63342	1½" TXL	35	49	-	-	2	22°	C	1	Moderate
	63340	S.B.	33	45	0	26°	0	19°	C - B	1.12	
III	62252	4" TXL	32	48	6	38°	5	29°	A - B	1.4	Slight (Slightly sheared contact)
	62248	S.B.	22	44	6	28½°	5	20°	B	1.34	
IV A	62251	4" TXL	38 *	48	5	25°	4	21°	B	1.2	Moderate to Intense
	62247	S.B.	44	58	5	15½°	4	13°	B - C	1.05	
IV B	62244	4" TXL	29 *	46	-	-	2	15°	C	1	Intense to Moderate (Reverse fault Zone)
	62243	S.B.	45	51	2	19½°			B - C	1.13	

* Average for whole 4" dia. samples; not representative of shear zone alone.

TABLE XX

JARI
FOUNDATION INVESTIGATION 1965
SUMMARY OF TRIAXIAL RESULTS ON CLAY BEDROCK

Location	Sample No.	Type	Sample axis to bedding	Clay %	Peak Resid. (average)	Shear strength c' lb/sq.in.	Shear strength Ø'
G 45	64125*	Mod. S.	30°	50	1.2	P. 3 R. 3	11° 9°
G 47	64127*	Mod. S.	Perpendicular	44	1.03	P. - R. 0	- 12°
G 49	64129*	U	Vertical	43	2.2	P. 20 R. 10	22° 13°
G 410	64130*	U	Vertical	43	2.1	P. 9 R. 4	19½° 11°
G 411	64131*	U	Perpendicular	29	2.0	P. 6 R. 2	27° 21°
G 417	64137*	Sl. S. Split	30° Split	42	1.02	P. - R. 4	- 15°
G 414	64134*	Mod. S.	30°	37	1.3	P. 0 R. 0	27° 22°
G 413	64133*	U	Vertical	39	1.65	P. 12 R. 7	25° 18°
G 415	64135*	Mod. S.	Horizontal	55	1	P. - R. 0	- 15°

Legend for Tables XXI (i) and XXI (ii)

* Rotating bush cells used.
U. = Unsheared
Sl.S. = Slight Shear Zone
Mod.S. = Moderate Shear Zone
Int.S. = Intense Shear Zone
P. = Peak
R. = Residual

TABLE XXI (i)

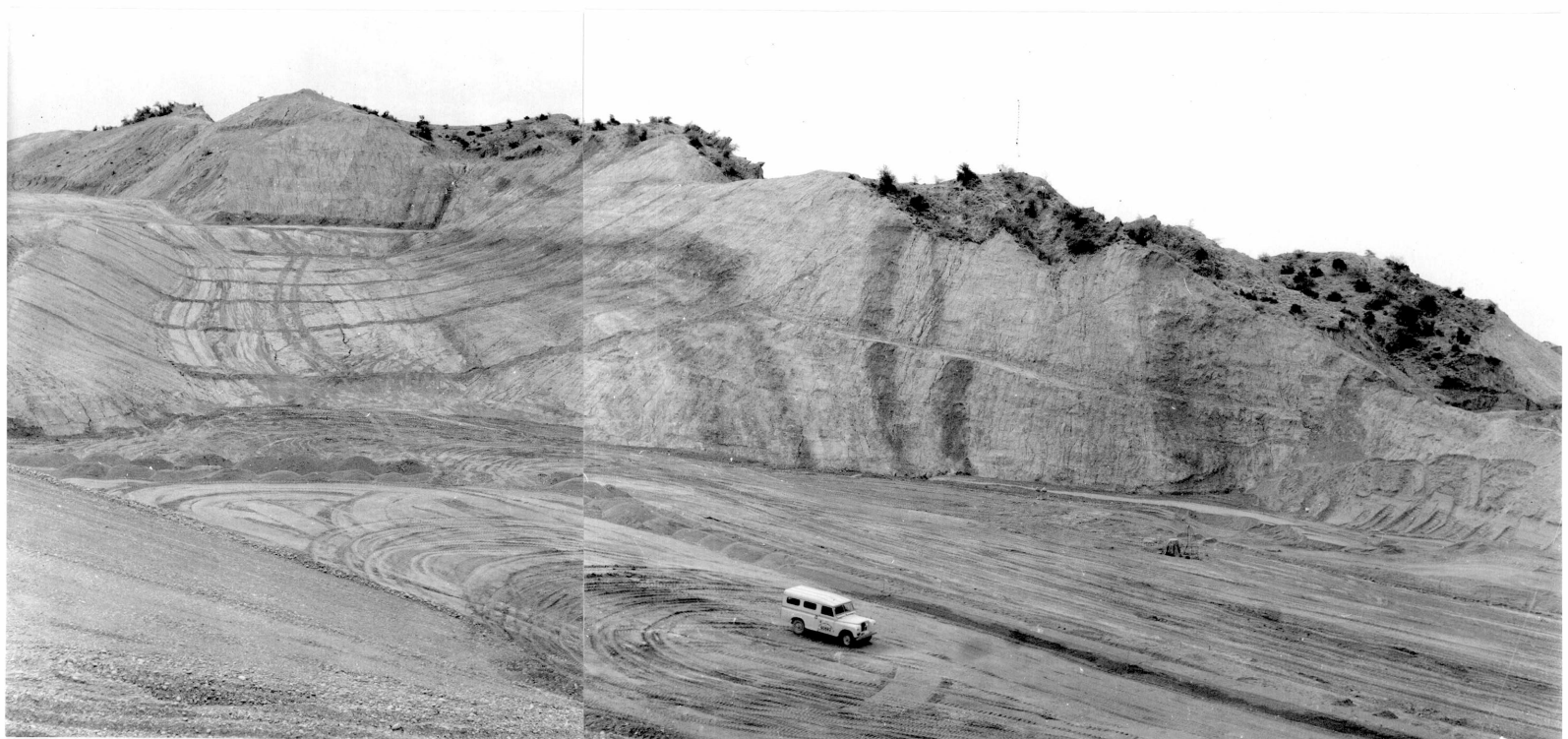
JARI
FOUNDATION INVESTIGATION 1965.
SUMMARY OF SHEAR BOX RESULTS ON CLAY BEDROCK

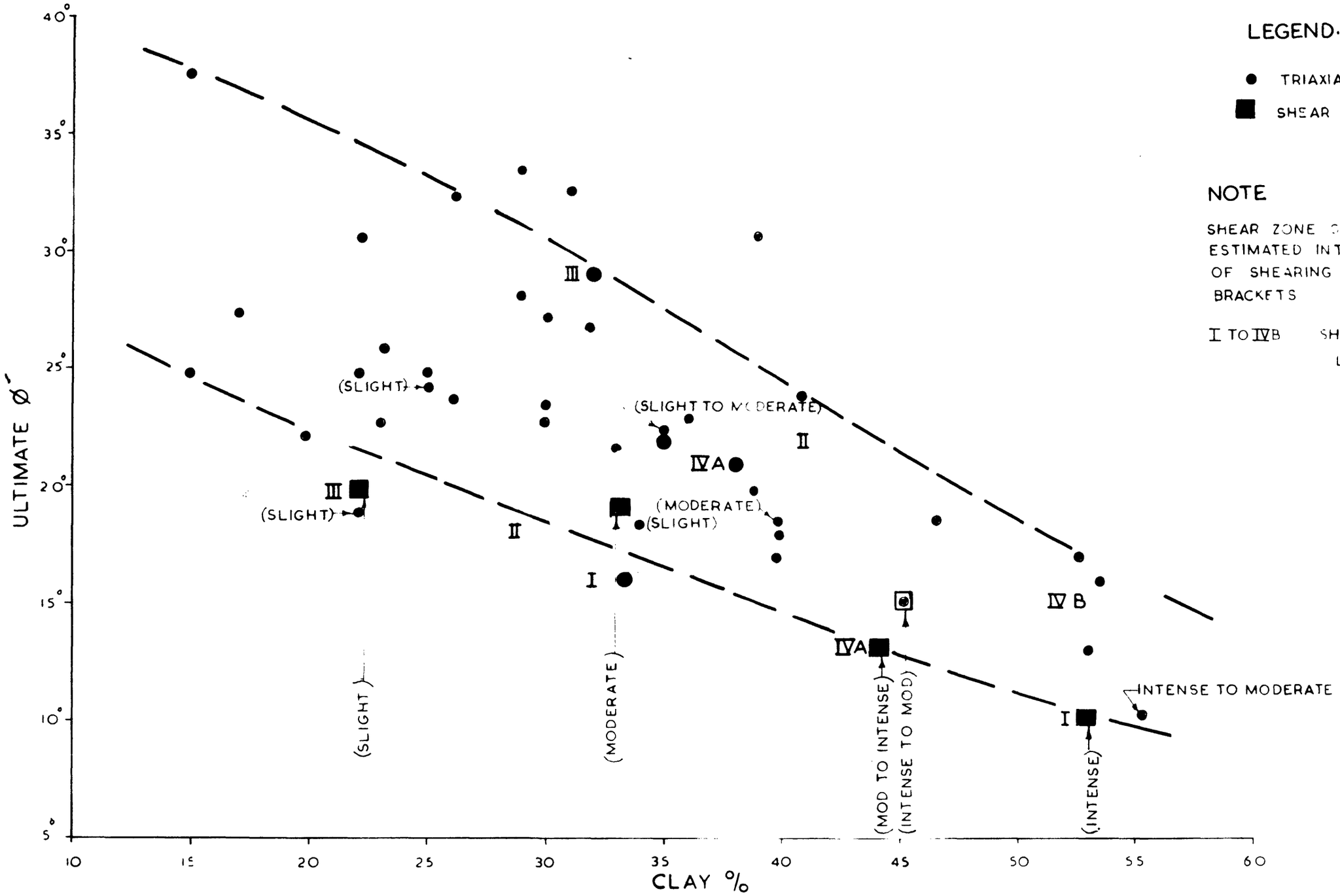
Location	Sample No.	Type	Shear direction to bedding	Clay %	Peak Resid.	Shear Strength c' lb/sq.in.	Shear Strength ∅'
G 41	64121	Contact Mod.S.	Parallel	36/42	1.4	P. 0 R. 0	18° 15°
G 44	64124	Mod. S.	Parallel (below Gravel)	52	1.5	P. 2 R. 0	15° 12°
G 42	64122	Int. S.	Parallel	60	1.9	P. 4 R. 0	12½° 10°
G 46	64126	U	Parallel (Adjacent to shear)	48	3.2	P. 8 R. 0	22° 11°
G 46	64126	Int. S.	Parallel ("Sandwich")	63	2.1	P. 5 R. 0	12° 8°
G 43	64123	Mod. S.	Parallel (one test only)	54	1.15	P. - R. -	12° 10½°
G 49	64129	U	Parallel	41	2.6	P. 5 R. 0	25° 11°
G 48	64128	U	Parallel	23	2.3	P. 7 R. 0	28° 14°
G 413	64133	U	Parallel	39	3.2	P.10 R. 2	29° 11°
G 411	64131	U	Parallel	22	2.1	P. 7 R. 0	24° 15°
G 412	64132	U	Horizontal	18	2.1	P.14 R. 5	18° 10°
G 414	64134	Mod. S.	Parallel	40	1.5	P. 7 R. 4	7° 5°
G 416	64137 (a)	Sl. S.	Parallel	58	1.9	P. 5 R. 0	16° 11°
G 417	64137 (b)	U	Parallel	15	1.9	P. 7 R. 0	25° 22½°

TABLE XXI (ii)

PLATE No. 47 June 1965

Left abutment Jari looking southeast and showing part of the core trench. Cleaned-up logging and sampling strips are seen on the higher portion of the trench; the same area before construction is shown in the background of plate 3.





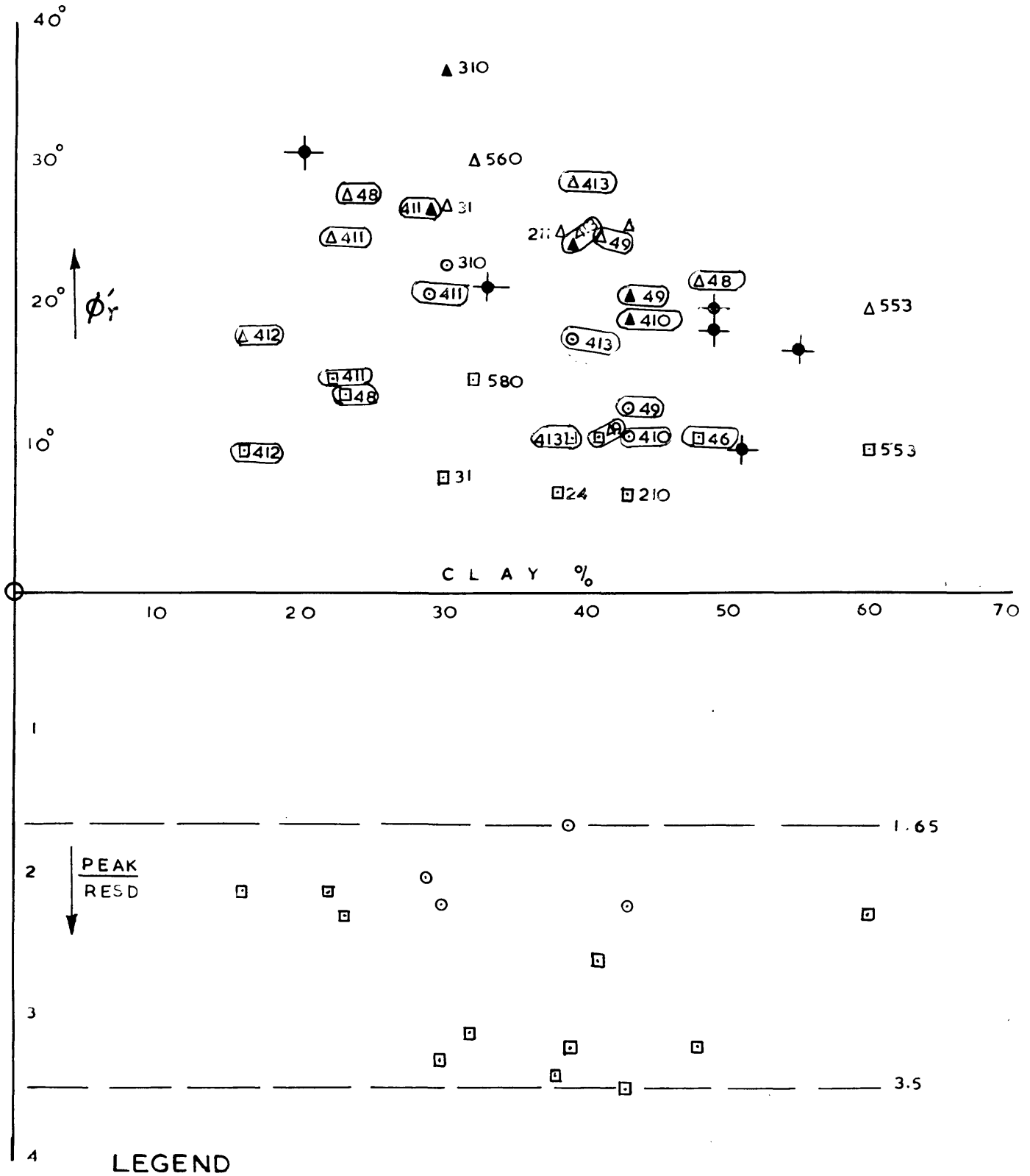
MANGLA

FOUNDATION INVESTIGATION 1964-65

ϕ'(ULT) VS CLAY FRACTION

(After K.H.H.)

FIG. 71.

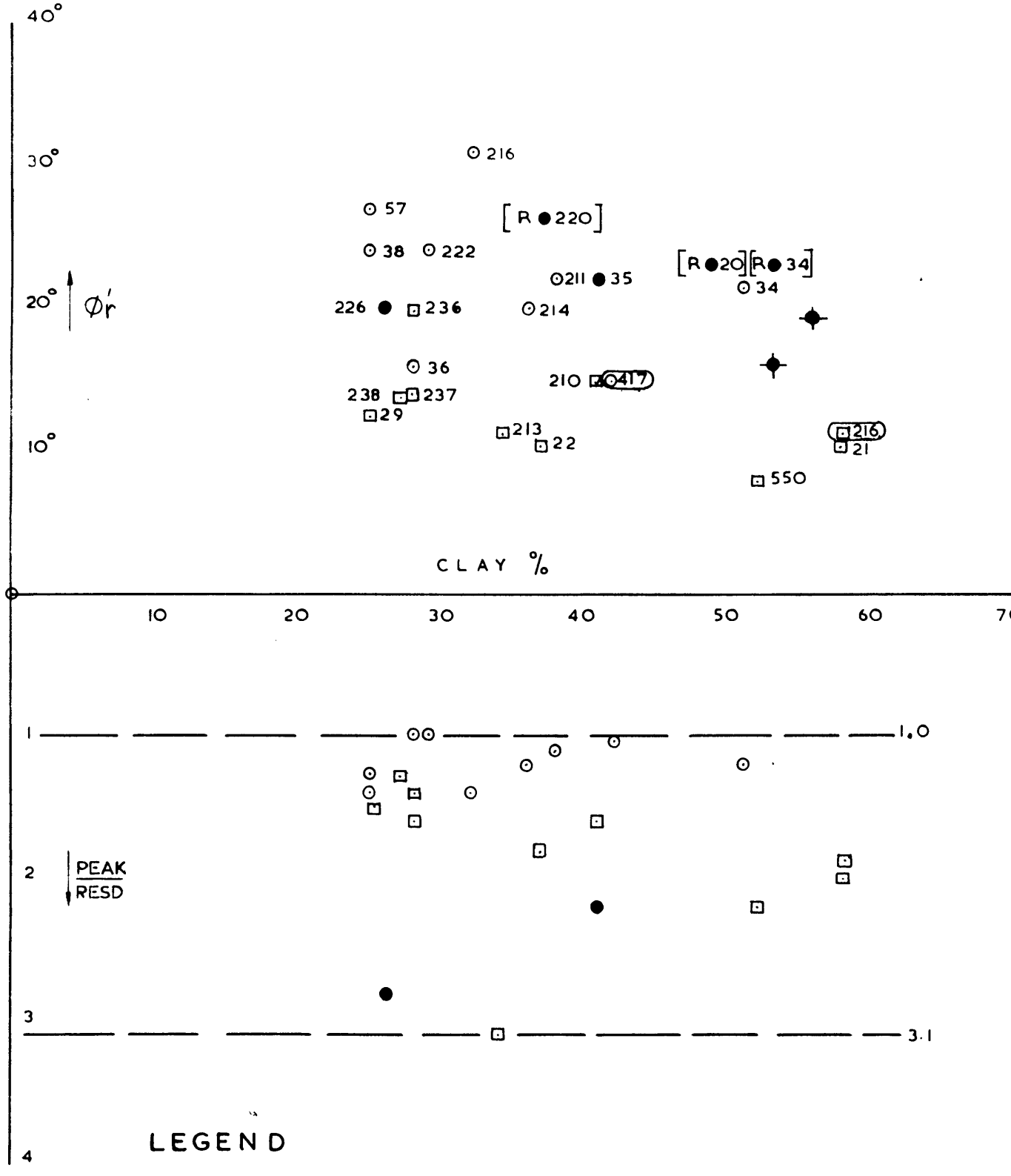


LEGEND

- PEAK TXL
- PEAK SHEAR BOX
- RESIDUAL (TXL WITH ROTATING BUSHES)
- RESIDUAL (SHEAR BOX)
- 1962/63 TXL TESTS RESIDUAL ONLY

JARI

FOUNDATION INVESTIGATION 1965
SHEAR STRENGTH VS CLAY FRACTION
(UNSHEARED CLAY)
(After K.H.H.) FIG. 72.



LEGEND

- RESIDUAL TXL ●
- RESIDUAL (TXL WITH ROTATING BUSHES) ⊙
- RESIDUAL (SHEAR BOX) ⊡
- REMOULDED [R]
- 1962-63 TXL TESTS (TRENCH H-1) 1962. ✦

JARI

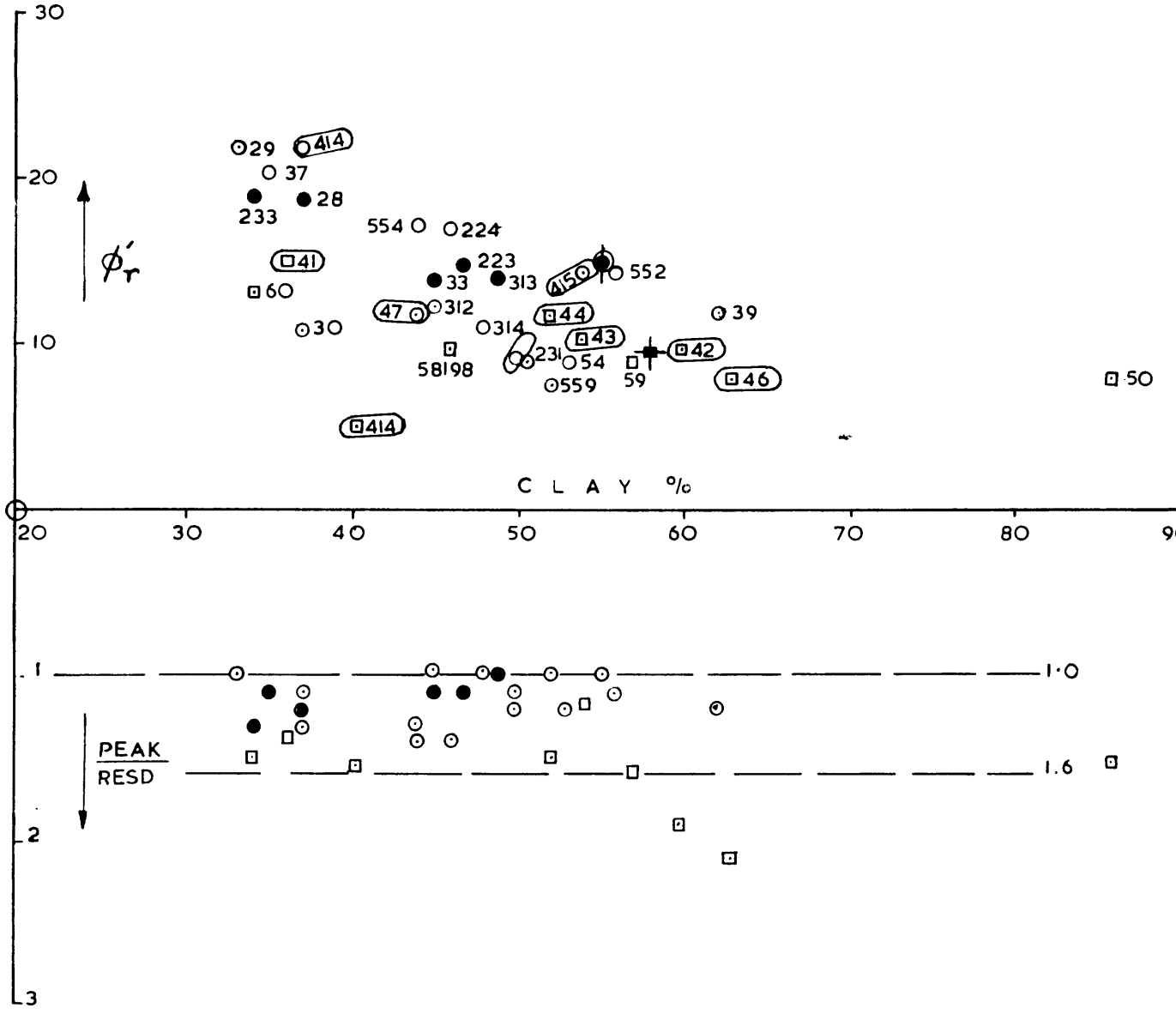
FOUNDATION INVESTIGATION 1965

SHEAR STRENGTH

VS CLAY FRACTION

(T.S.J. & SLIGHT SHEAR ZONES)

(After K.H.H.) FIG. 73.



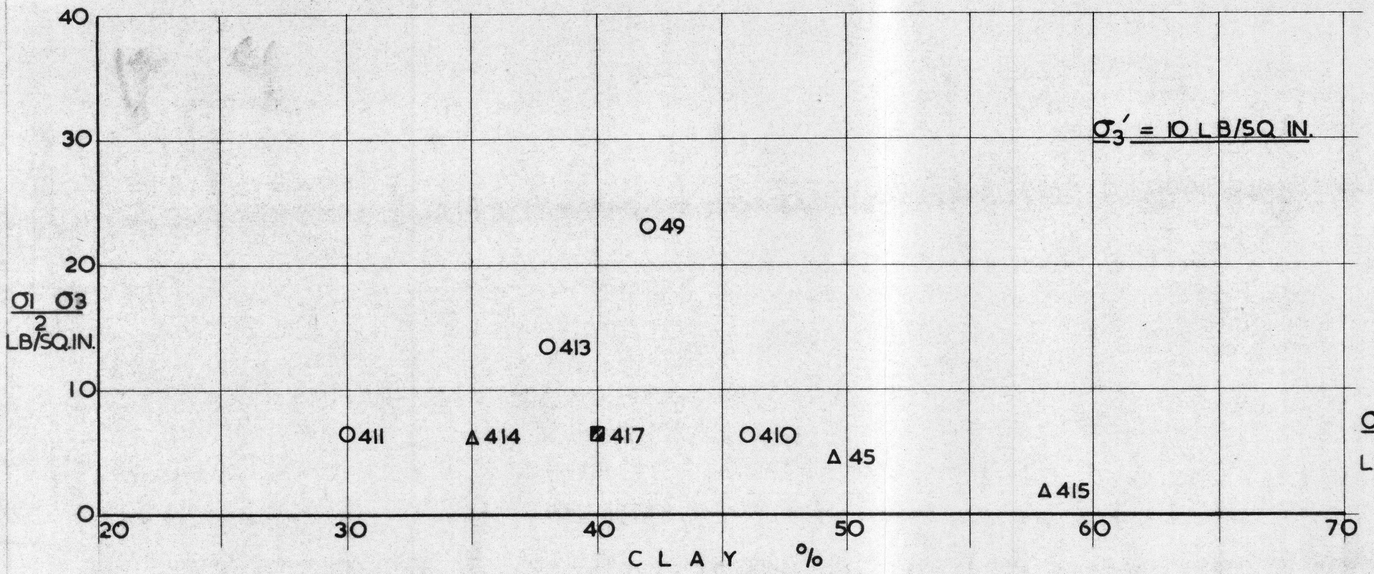
LEGEND

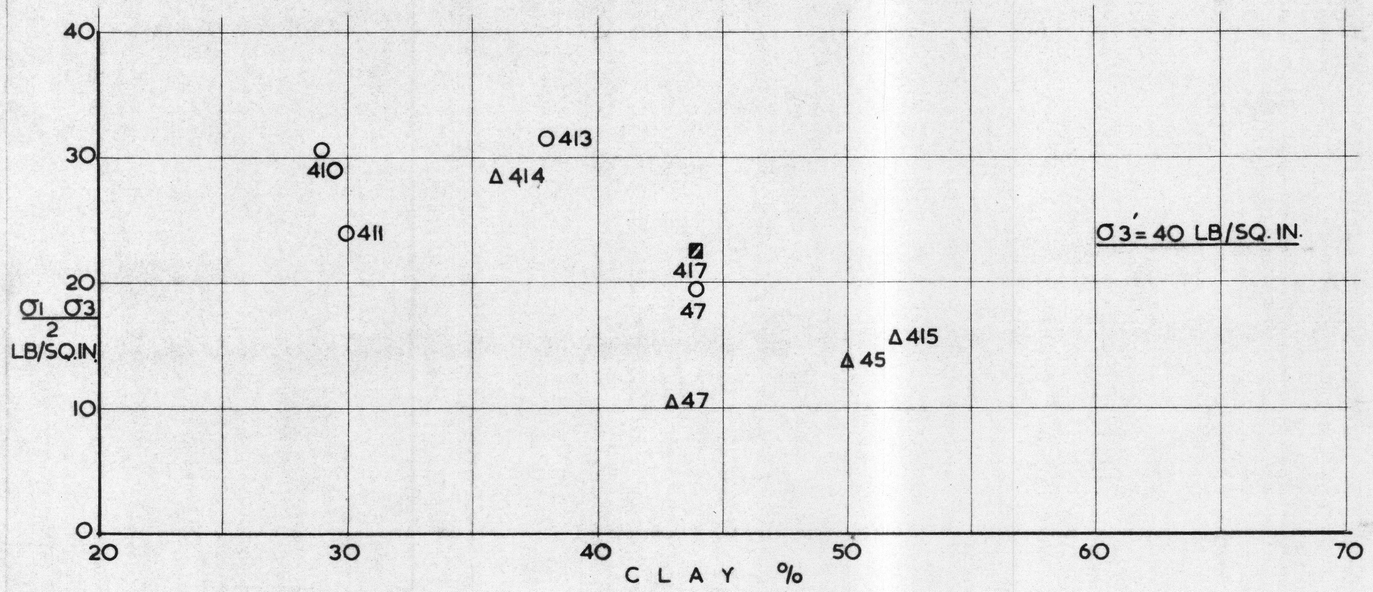
1962/63 TESTS:
SHEAR BOX
4" TXL.

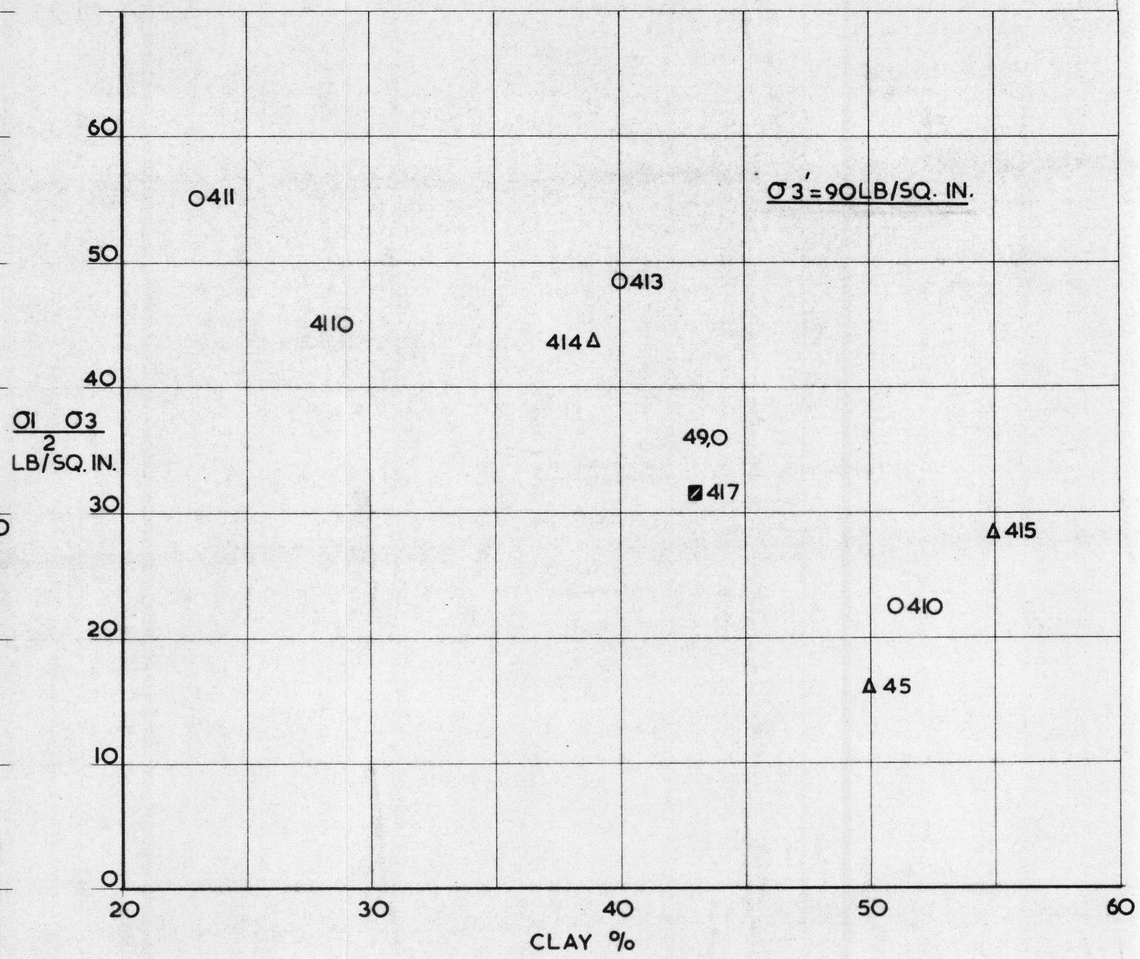
RESIDUAL TXL
RESIDUAL (TXL WITH ROTATING BUSHES)
RESIDUAL (SHEAR BOX)

JARI

FOUNDATION INVESTIGATION 1965
SHEAR STRENGTH VS. CLAY FRACTION (MODERATE & INTENSE SHEAR ZONES)
(After K.H.H.) FIG. 74.







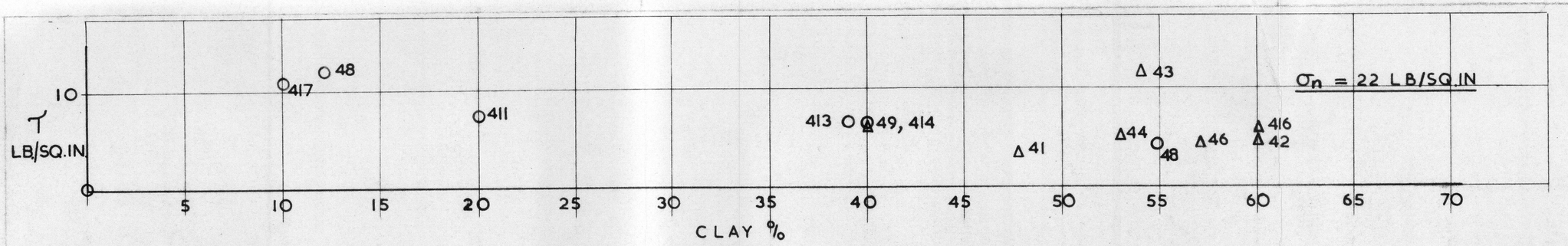
LEGEND

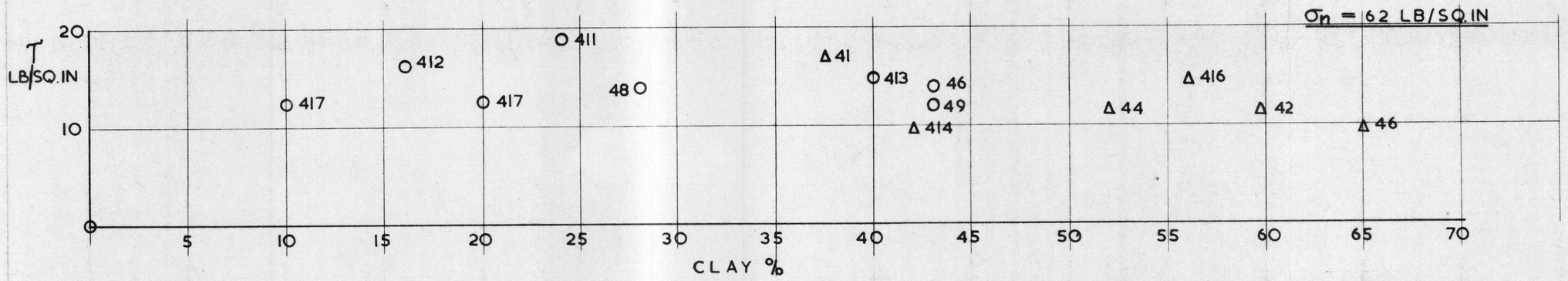
RESIDUAL SHEARED ..... Δ
RESIDUAL UNSHEARED ..... O
SPLIT ..... ◪

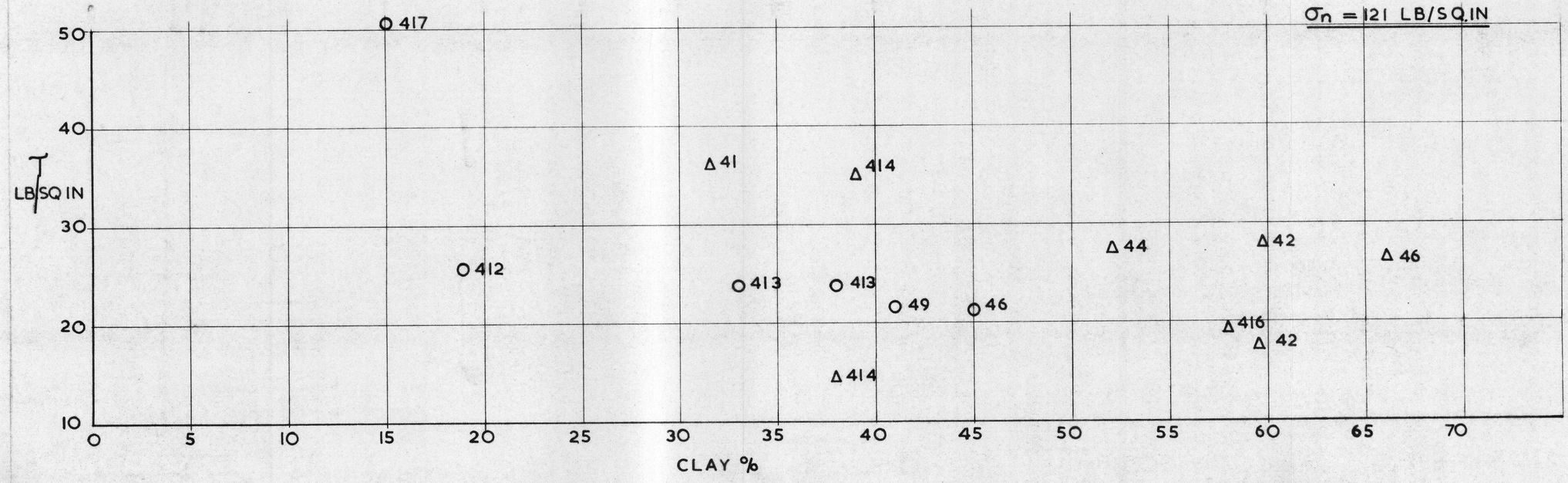
JARI

FOUNDATION INVESTIGATION 1965
TRIAXIAL TESTS
RESIDUAL STRENTH VS CLAY FRACTION

FIG. 75.







LEGEND

RESIDUAL SHEARED Δ

RESIDUAL UNSHEARED O

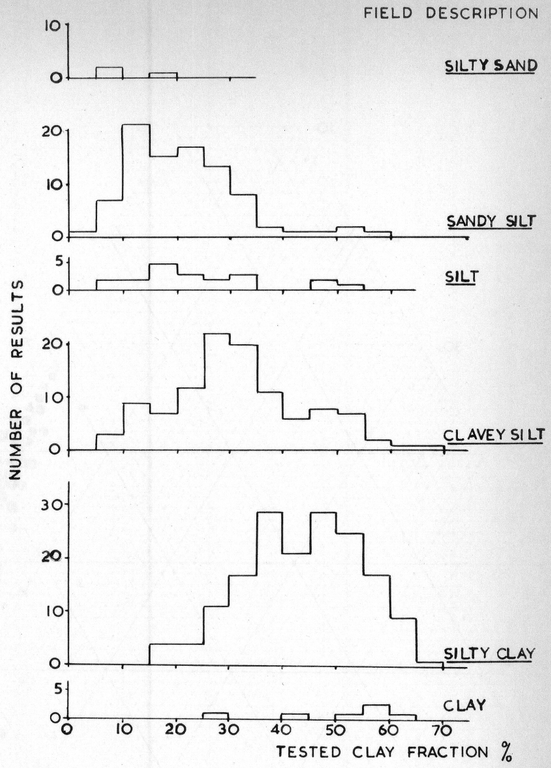
JARI

FOUNDATION INVESTIGATION 1965

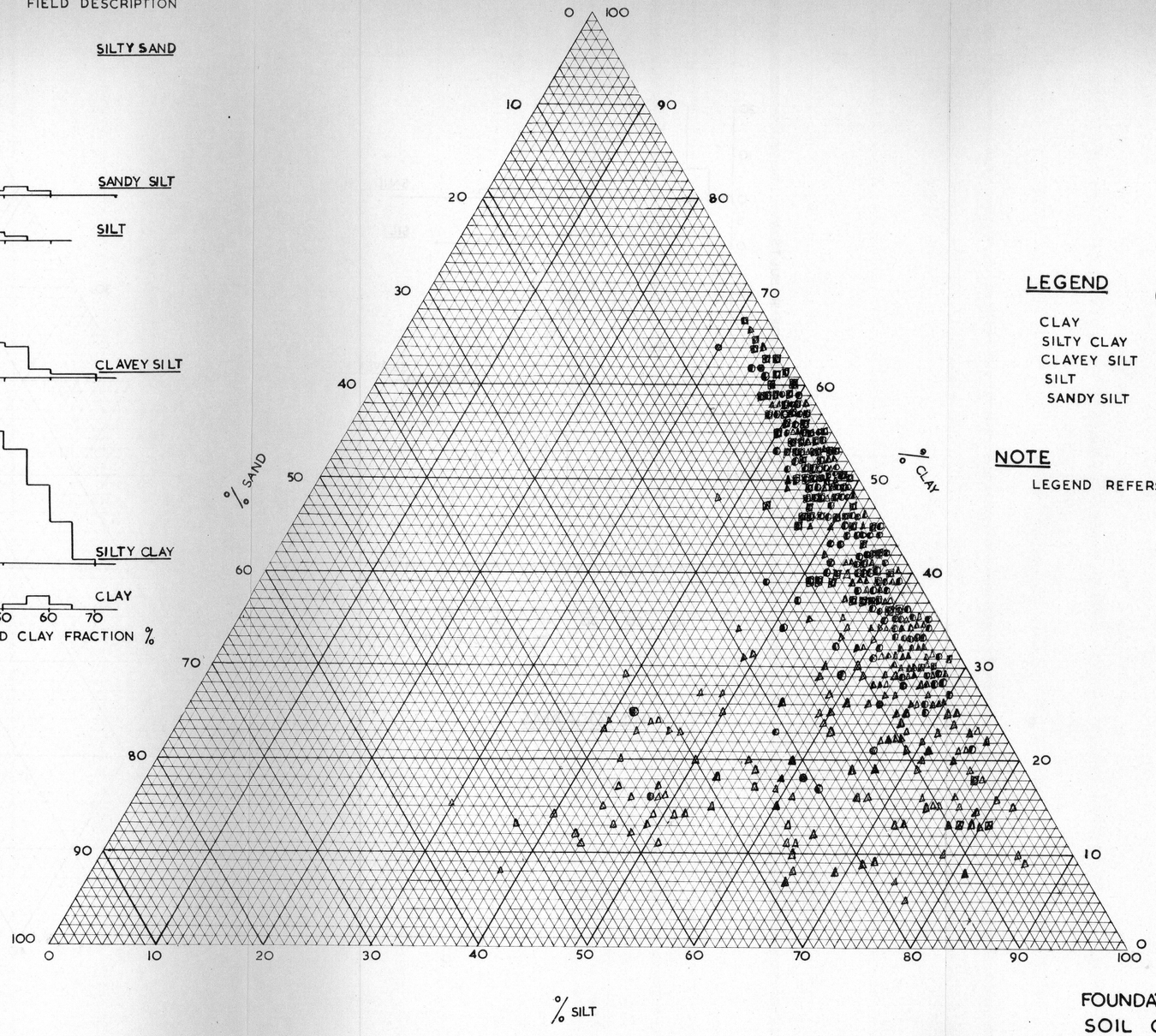
SHEAR BOX TESTS

RESIDUAL STRENGTH VS CLAY FRACTION

FIG. 76.



HISTOGRAMS



LEGEND

	UNSHEARED	SHEARED
CLAY	●	■
SILTY CLAY	◐	◧
CLAYEY SILT	△	▣
SILT	▲	▩
SANDY SILT	△	▨

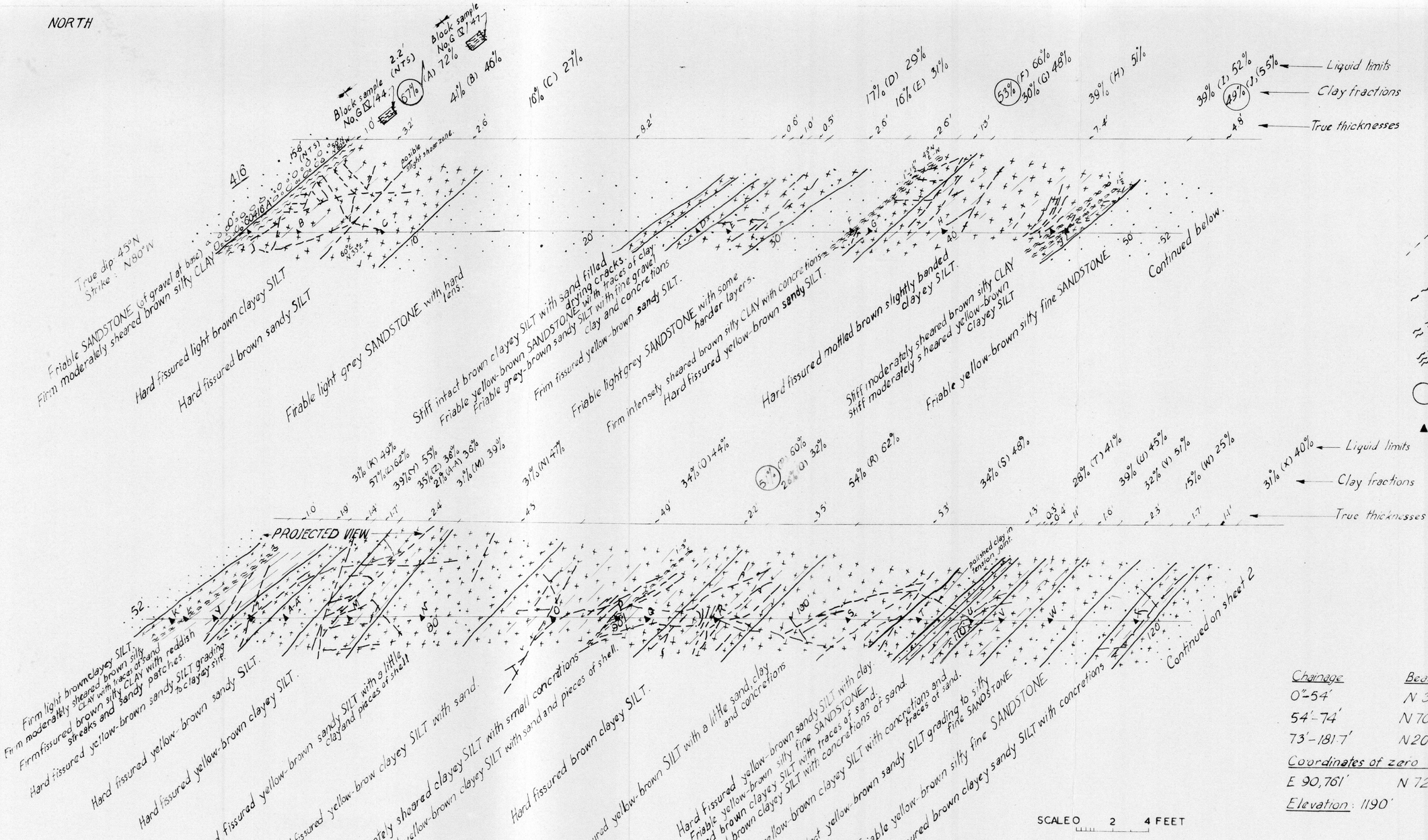
NOTE

LEGEND REFERS TO FIELD DESCRIPTIOIN.

JARI

FOUNDATION INVESTIGATION 1965
SOIL CLASSIFICATION CHART

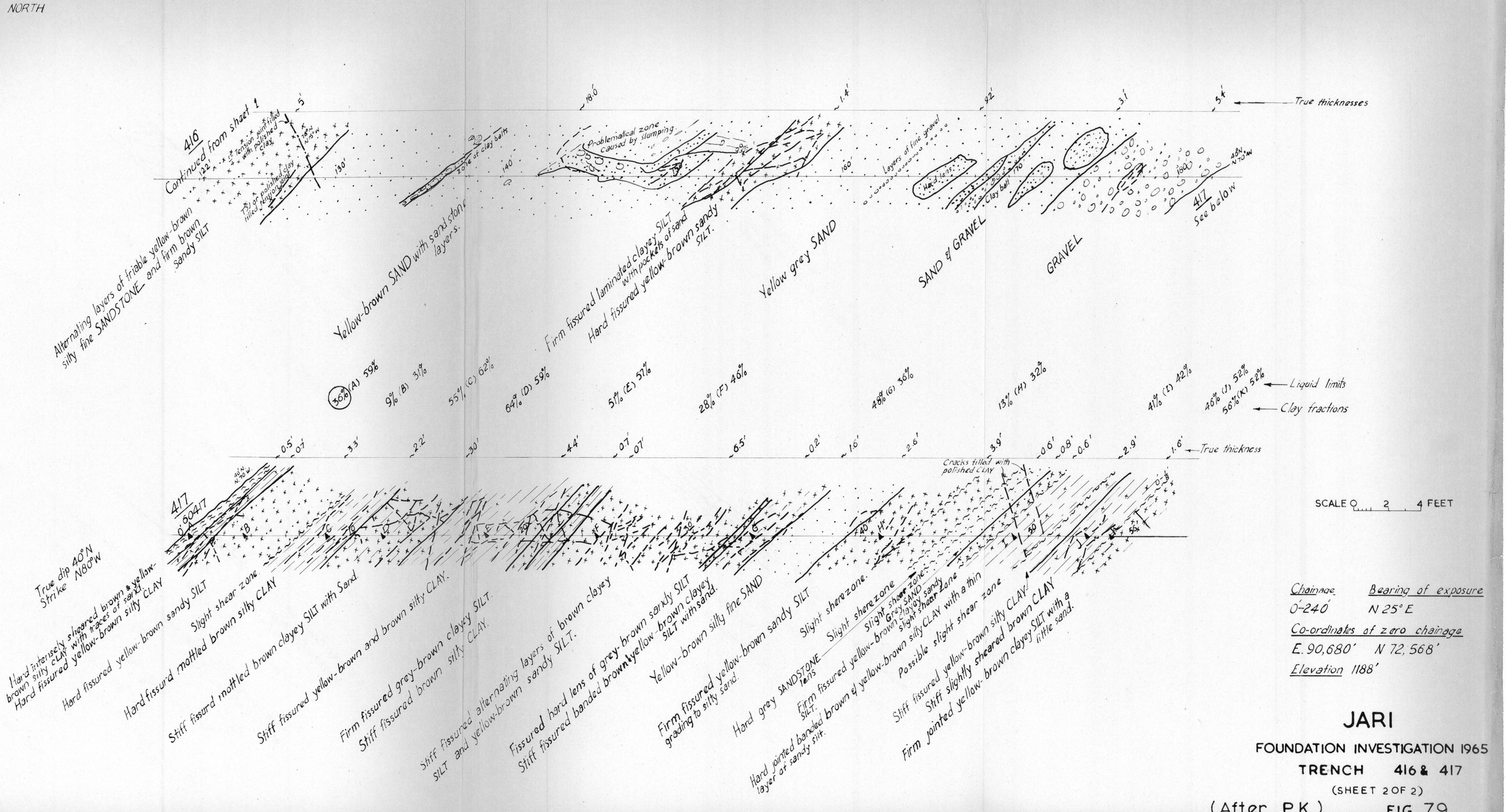
(After P.K.) FIG. 77



Chainage	Bearing of exposure
0'-54'	N 35°E
54'-74'	N 70°E projected on to N 20°E
73'-181.7'	N 20°E

Coordinates of zero chainage
E 90,761' N 72,713'
Elevation: 1190'

JARI
FOUNDATION INVESTIGATION 1965
TRENCH 416 & 417
(SHEET 1 OF 2)
(After P.K.) FIG. 78.



Chainage 0'-240' Bearing of exposure N 25° E

Co-ordinates of zero chainage E. 90,680' N 72,568'

Elevation 1188'

JARI

FOUNDATION INVESTIGATION 1965

TRENCH 416 & 417

(SHEET 2 OF 2)

(After P.K.) FIG. 79.

DISCUSSION OF BEDROCK PROPERTIES

Index Properties and Clay Fraction

Bedrock described as 'clay' contained from ca. 16% to 75% of clay (defined as particles less than 0.002mm. diameter as measured by the standard hydrometer test). The remaining fraction was fine to coarse silt, with a trace of sand and commonly a few small hard concretions (1/8" to $\frac{3}{4}$") which usually did not effervesce with dilute hydrochloric acid. The ranges of gradings of Upper Siwalik Clays from Jari and of Upper/Middle(?) Siwalik clays from Mangla are shown in figs. 38 and 80 respectively. Occasionally the clay was referred to as 'shale' by visitors to the region. However, the term 'clay' was used exclusively though certain horizons of some beds clay/shale would have been appropriate (for example, the foundations of the Weir, U.S.B.). Geologists use the term 'shale' for fissile (easily splitting clay with numerous parallel planes - Amer.Geol.Inst.) hard clay. Only rarely was this property developed at Mangla. The clay could also conveniently be described in 'consistency' terms (C.P. 2001: 1957) and the great majority of clays were stiff or hard; occasionally a soft clay occurred (for example, in the intense shear zone, below water table, in the Tailrace), so that everything considered the term 'clay' was undoubtedly the most appropriate. The clay although geologically correctly labelled 'bedrock' was soil like in its behaviour. The term bedrock was retained to differentiate the Siwalik clays from

the alluvial clays and silts (for example, found in the Jhelum river terrace deposits) which had similar index properties to many of the bedrock clays. This is not surprising as they are generally normally consolidated reworked or recent equivalents of the former.

In the field description of the bedrock clay was given in the following order:

consistency - structure - colour - grading - TYPE - additional information,

for example:- stiff fissured brown silty CLAY

or hard slightly fissured red/brown CLAY with occasional $\frac{1}{4}$" dia. chalky concretions;

or firm yellow/brown clayey SILT *

All the characteristics were estimated by feel and eye; to improve reliability individuals checked their description against laboratory results. Field descriptions of Mangla soils is discussed in more detail by Fookes (1961). Some ranges of estimates by trained field staff has been given earlier in Parts I and II. (e.g. figs. 15, 16, 17 or 77)

Liquid limits varied from ca. 25% to 70% at Mangla (typically 40% to 45%) and when plotted against plasticity index nearly all samples lay within a narrow zone just above the 'A' line but not quite parallel to it (fig. 80). Results from Jari lay in a similar zone (fig. 38), but liquid limits exceeding 70% were not uncommon and in some beds reached 100%. Results from Sukian (shown by crosses in fig. 80), except for five or six thin beds of bentonitic clay of liquid limit 80% to 160%, were generally similar to those at Mangla

* SILTSTONE was used if it was sandy and behaved as a non-cohesive material.

but extended to 75%. The higher liquid limits predominated towards the Jari site, which were of certain Upper Siwalik age.

From mineralogical analysis on sheared clays by various operators, reported by Robertson (1965), the following table XXIV has been drawn. Locations I - IV are those discussed previously under Foundation Investigation of Mangla shear zones, p. 155 and 165, also Fookes & Head (1964).

The index properties were tested from the same block sample as the mineral specimens, but not from the same specimen on which mineral tests were made. The high calcite content from the Location IVB, the fault zone, may be explained by percolation of very slightly lime rich water from the overlying sandstone bed which was known to contain calcareous concretions. Robertson in discussion of the mineralogy and engineering behaviour of the sheared clays concludes that the variation of mineralogy is small and not enough to account for much difference in physical behaviour. He says "the clays contain a high proportion of clay minerals though much of the mica is silt size and greater. The soil mechanical properties of the clays will be determined to an appreciable extent by the quartz and coarse mica contents; especially where these are high, the clays can be held in the voids leaving relatively low liquid limits. But where the clays more than fill the voids, they act as lubricants and all clays with high clay grade content behave in a similar manner rhealogically". He also considers that the clay minerals were essentially derived from the alteration products of detrital minerals brought into the basin of deposition.

Robertson discusses the relation of liquid limits and montmorillonite content and says that in general the montmorillonite is the main contributor to the liquid limit of the Siwalik clays but the relation of liquid limit and montmorillonite content is not very close. The variation in liquid limit is only a little greater than the variation in cation exchange capacity, K_2O content and H_2O+ content. He also considers that the grade of dynamometamorphism reached in the shearing of the clays was not sufficient to alter the existing montmorillonite towards chlorite or existing chlorite to swelling chlorite.

Robertson's discussions are interesting because they:

(i) Tend to favour the probability that shear zones occurred in originally high liquid limit (i.e. weak) clays (fig. 69) by choice and did not substantially increase the liquid limit by shear action;

(ii) Suggest variations in mineralogy are not of dominating importance in accounting for strength variations in the clays. This confirms suggestions derived from correlation curves that strength is more closely related to grain sizes and other mechanical properties.

The activity (as defined by the ratio $\frac{\text{Plasticity Index}}{\text{Clay fraction}}$) of the clays from Mangla and Sukian varied between 0.4 and 1.5 (average 0.7, i.e. just below 'normal' activity). Exceptionally, in the bentonites and associated beds, activities approaching 3.0 were found; otherwise the typical variation appeared to occur at random throughout the site. No

satisfactory relationship between particle size and Atterberg limits was established and this is illustrated by the graphical plot of liquid limit against clay fraction for clays from the Mangla area (fig. 81). This is not out of keeping with the experience of Grim (1962). The activity of Jari clays appeared to be marginally higher ranging between 0.6 to 1.6 (fig. 37).

The activities are in accord with the available mineralogical analysis on unsheared clay.. Bibhuti Mukherjee (1964) reports 40-50% illite, 30-40% kaolinite and 20-30% montmorillonite from the Middle Miocene of the Potwar (see Part I). Robertson for the sheared clays on the basis of H_2O+ and cation exchange and from X-ray results and K_2O calculations based on the assumption that the ratio of muscovite to illite is 19:1, also gives the illite content in the 40-50% range. Table XXII gives Robertson's figures.

The fairly narrow degree of scatter on the plasticity and activity charts from all three damsites together with the few mineralogical analyses and the geological observations do not suggest any dramatic changes of environment of deposition during the Upper Siwalik. The occasional layers of wind blown(?) volcanic material indicate a small exception but this material is obviously transported from outside the area and no other local igneous activity in the area is indicated. The oncoming of the Bala Gala gravels at the top of the System is the first significant change, even so these deposits are still fluviatile. The variation in engineering properties

of the Mangla clays, therefore, appears to be dependent on a few, clear, geological features, viz:-

Primary (deposition)	Secondary (tectonic and diastrophic)
Grain shape and size	Shearing
Mineralogy	Mineral changes
Void ratio	Void ratio changes
Some fissuring	Fissure formation and modification

Variations of index and strength properties can almost without exception be explained (albeit only crudely) in terms of these geological parametersand the basic simplicity of the stratigraphy of the three major damsites, although it took a considerable volume of fieldwork to establish, is confirmed by the laboratory results.

T A B L E XXII

Robertson's Mica Contents for Some Sheared Clays 1965

Location	K_2O	Muscovite	Illite	Mica
I	3.25	27.48	49.86	say 30
II	3.01	25.43	46.18	28
III	2.71	22.90	41.58	25
IV-A	3.25	27.48	49.86	30
IV-B	2.81	23.75	43.11	26
Charlie I	2.91	24.60	44.68	27
Charlie II	3.13	26.47	48.03	29

Strength of Clays at Jari

Although clays of low dry density generally gave a low effective strength, no significant correlation was obtained between strength and density. However, it was found that low strengths were associated with high liquid limit, and a working correlation built up on site was obtained between liquid limit and residual $\emptyset'$ value (fig. 25). The latter was the value deduced from individual specimens calculated from the expression $\text{Sin } \emptyset' = \frac{\sigma_1' - \sigma_3'}{\sigma_1' + \sigma_3'}$. This was considered practicable since groups of Mohr circles for samples of similar properties gave envelopes with zero or very small cohesion in the residual condition. There is a significant difference between the correlation established on site as part of the day to day investigation and the correlation finally derived for assessing the parameters to be used by the design engineers in London*. The former was gradually built up daily from the laboratory results as they became available from each set of three triaxial tests on individual block samples. Thus the average of three strength tests was plotted against the average of three clay fractions (or, for Jari, three liquid limits). This working correlation was a convenient and readily available method for use on site. Figs. 25 and 65 show the relationships which were gradually built up for Jari and Mangla respectively. On the other hand the 'design correlation' with c' = 0 was derived by considering the test results from each specimen separately, and then, as a final step averaging the graphical plot produced.

* For a fuller discussion on strengths used in design, see Binnie, Skempton & Clarke (1967).

This 'site correlation' shows that the value of ϕ' (residual) ranges between 20° and 30° for clays of liquid limit about 50% and falls to 18° to 20° for liquid limit of 80% or more. The scatter of strength results is considerable for clays of liquid limit below 50% but lessens above 70%. Additional work currently in progress with lower rates of strain and shear box tests with reversals are giving lower strengths than presented here.

The range of stress and classification properties of Jari clays is given in Table XXTII. Strength tests were by triaxial equipment and do not represent the current set of shear box tests with reversals now in progress.

T A B L E XXTII

Jari Clays - Soil Properties of Typical Samples 1963

Bedrock type	Clay %	Silt %	LL %	PL %	Peak c' lb/sq.in	Peak ϕ'	Residual c' lb/sq.in.	Residual ϕ'	Remoulded ϕ'
Low LL	17	47	35	18	12	31°	5	22°	-
Medium LL	48	51	64	28	9	19°	0	17°	18½°
High LL	52	46	97	32	9	17°	0	17½°	17°

Strength of Mangla and Sukian Clays

A correlation between effective (residual) shear strength and liquid limit, similar to that found at Jari, was anticipated during the following Sukian investigation, but was not found to be satisfactory. However, both at Mangla and at Sukian a better site correlation was found to exist between residual strength

and clay fraction (fig. 65 gives the 'site' working correlation). It is interesting to note that the envelope shown in fig. 65 is remarkably similar to that shown by Skempton (1964, fig. 7). Skempton's correlation was applied to clays of different geological ages, and sedimentary and tectonic histories whereas those at Mangla and Sukian are part of one System.

Residual strengths from triaxial tests when plotted as a Mohr diagram invariably suggest a curved envelope. For simplicity in arriving at comparative figures the test results were interpreted on site by drawing a straight line envelope to the circles by eye*; this usually gave a cohesion intercept even for residual strengths. Typical Mohr circles for peak and residual conditions are shown in fig. 82 and illustrate the method of interpretation. The difference between the straight line envelope used on site and the possibly more correct curved envelope is also clear.

Typical properties and average results, for Mangla and Sukian clay, are given in Tables XXV and XXVI.

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* Interpretation of lines to circles, on site, was usually done by Mr. K.H. Head.

T A B L E XXV

Mangla Clays - Soil Properties of Typical Samples 1964

Bedrock type	Clay %	Silt %	LL %	PL %	Peak c' lb/sq.in	Peak Ø'	Residual c' lb/sq.in	Residual Ø'
Low clay	17	74	37	17	30	41°	16	32°
Medium clay	32	62	47	22	14	39°	4	27°
High clay	50	48	53	26	14	27°	3	21°

T A B L E XXVI

Sukian Clays - Soil Properties of Typical Samples, 1964.

Bedrock type	Clay %	Silt %	LL %	PL %	Peak c' lb/sq.in	Peak Ø'	Residual c' lb/sq.in	Residual Ø'
Low clay	16	59	37	16	25	36°	6	27½°
Medium clay	36	62	53	25	16	32°	6	22½°
High clay	53	46	57	26	9	18½°	8.5	16°
Bentonitic clay	35	63	121	36	7	15°	5	15°

For an exact comparison of 'typical' and the range of strengths of Jari, Sukian and Mangla clays, more sampling and testing for the Mangla beds would be required on the same basis as the close centre sampling at Jari and Sukian where, within reason, all beds were sampled and tested. In the absence of this work, the best estimates, and this would still be good as a large proportion of the Mangla beds have been or

are being tested; indicate a very slightly higher average strength and corresponding slightly lower average liquid limit and clay fraction. This slight difference in the Mangla and Jari clays has been indicated in Tables XXIII, XXV and XXVI. In addition, the range of activities of Mangla clays is slightly lower and in keeping with the geology.

Discontinuities

One of the fundamental properties of the Mangla type of clay bedrock, i.e. heavily overconsolidated stiff fissured and occasionally sheared clays; is that the overall property of a large mass of the material cannot be directly related to the peak strength properties of small laboratory samples taken from between joints, fissures or other planes of discontinuity within the mass. During the Jari and Sukian site investigations it became apparent that the 'rock' problem had to be differentiated from the 'soils' problem, and study followed techniques used in rock mechanics, for example, where joints, fissures and other discontinuities are investigated in the field by careful mapping and measurement or in the laboratory by carefully orientated strength testing (Fookes & McKenna 1963). This fundamental concept which played an important part at Mangla was not instantly obvious and took many months, even years of field and laboratory work and thought.

Test procedures on remoulded, reconsolidated, natural and 'sliced' samples, described earlier were used to assess the properties on the surfaces of discontinuities within the bedrock. A large-scale insitu shear test would have been

most interesting but was not carried out. Results from the small scale laboratory tests on surfaces of discontinuities gave shear strengths which were about or apparently slightly below(?) the residual strength obtained under similar test conditions on intact material (see curve E, fig. 24).

The only sampling techniques used both on intact and sheared material were by trimming specimens* from blocks (of about 1' cube, though smaller blocks were taken during the foundation investigation) or by trimming specimens from NX rotary diamond cores. With one or two exceptions (e.g. on a thin zone of soft clay in the large Trial Adit, Mangla) no samples were taken by driving U1½" or U4" tubes, so that no comparative work on test results produced by different sampling techniques was undertaken. Block and NX core sampling gave similar strength results although a rigorous analysis was not undertaken. In addition, investigation of effects on strength characteristics caused by removal from the ground were not studied, so in this field much more work remains to be done.

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* Specimen is defined on site by the author as the actual material placed in the test equipment. The specimen is obtained from the sample which is the material collected from the field.

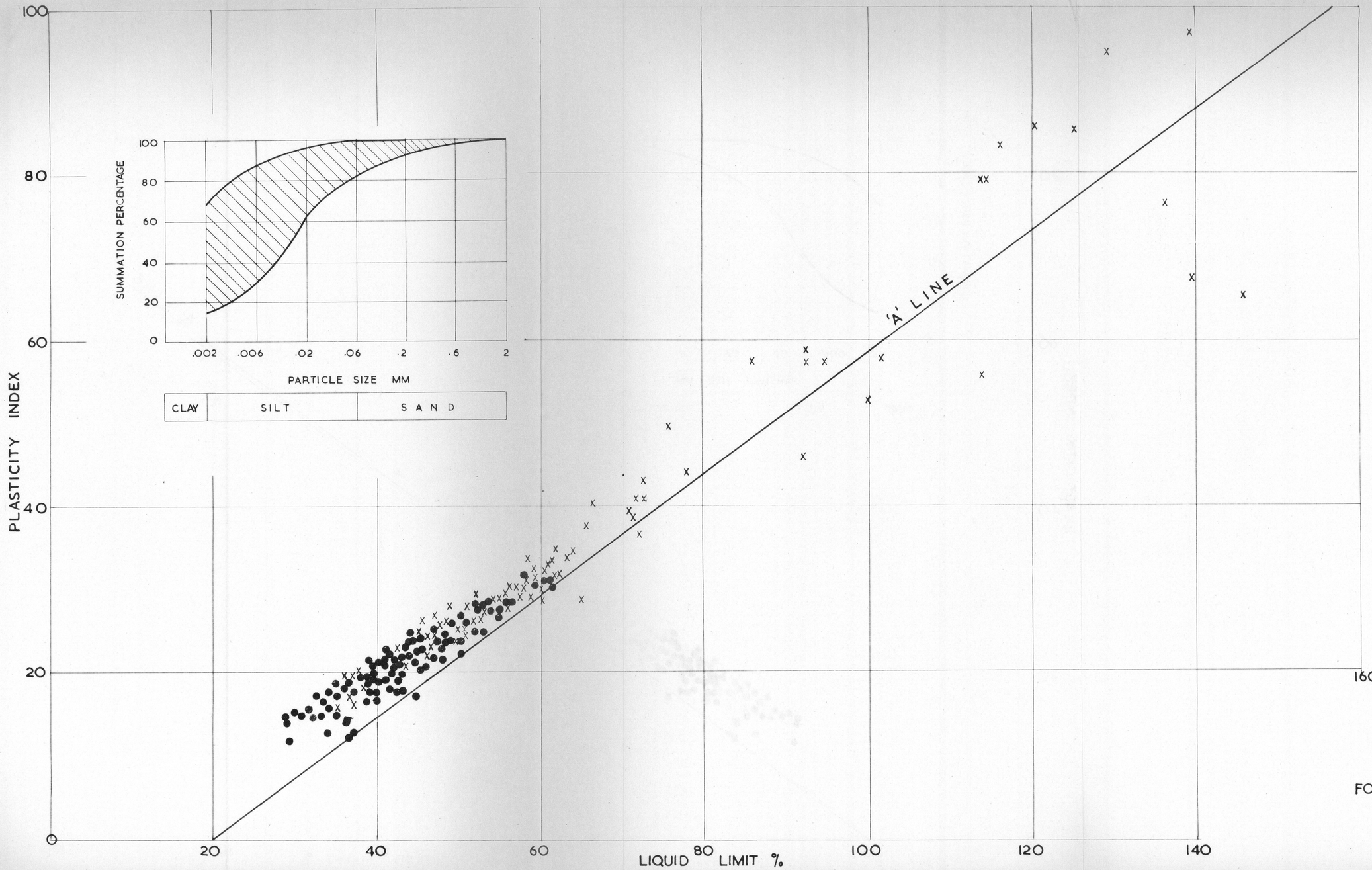
MANGLA

FOUNDATION INVESTIGATION 1964

MINERAL ANALYSIS OF SHEARED CLAYS

Location	Field Classification	C.F. %	L.L. %	Field Density P.S.F.	Moisture %	Montmorillonite %	Mica %	Goethite %	Calcite %	Kaolinite and Chlorite %	Quartz by diff. %
I	Intense	55	56	143.8	16.7	23	30	8	1	15+5	18
II	Moderate	33	47	148.4	12.4	21	28	2	1	15+5	28
III	Slight	32	48	132.9	15.4	21	25	5	1	15+5	28
IV-A	Intense	43	53	143.2	15.0	20	30	3	1	15+5	16
IV-B	Fault zone	53	51	143.0	13.5	14	26	3	17.5	15+5	18.5
Charlie I	Slight	60	55	131.3	18.0	23	27	4	4	15+5	22
Charlie II	'Weak' clay	46	51	145.0	13.2	20	29	(4)	1	15+5	16

TABLE XXIV

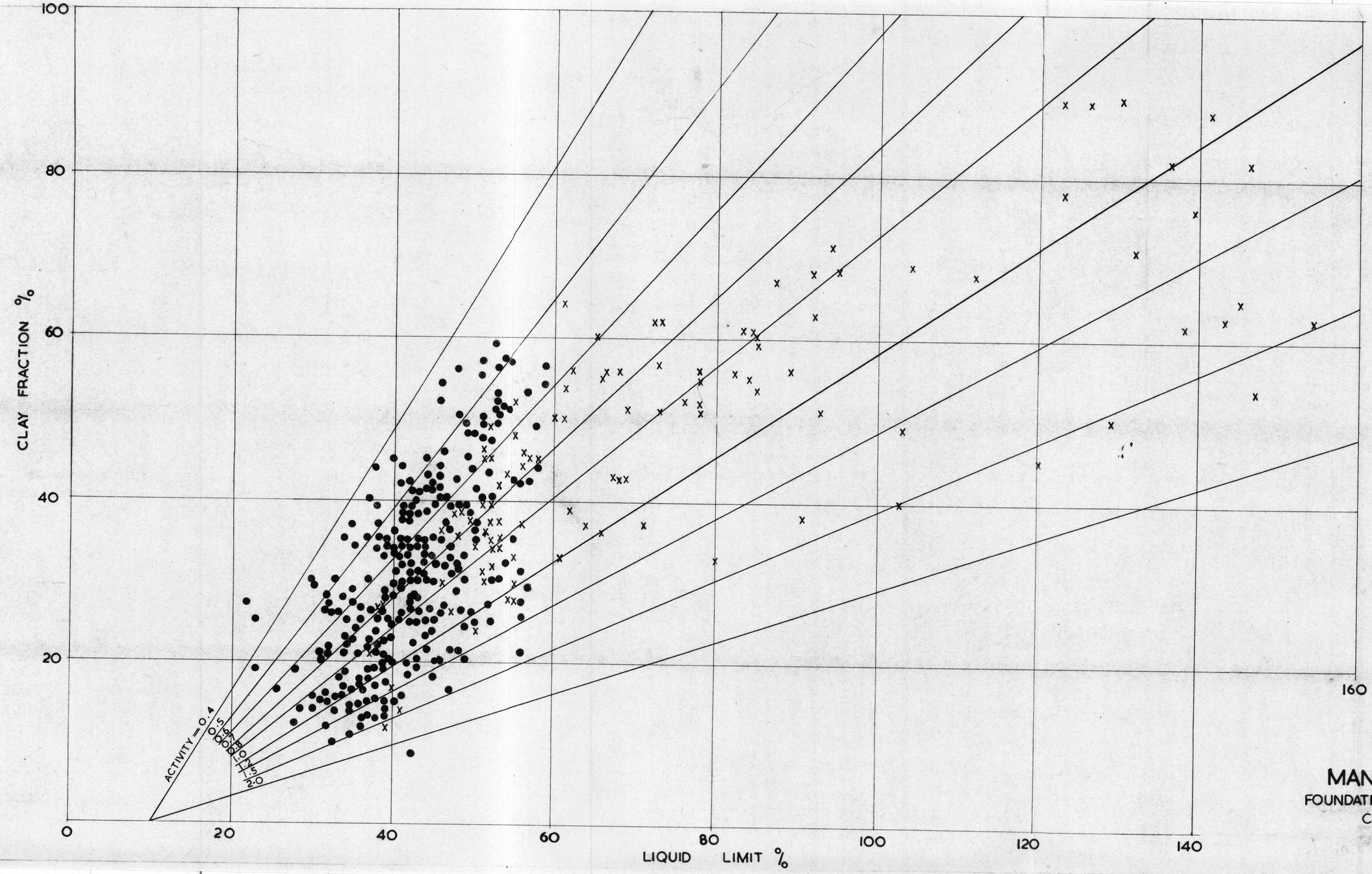


MANGLA/SUKIAN

FOUNDATION INVESTIGATION 1965

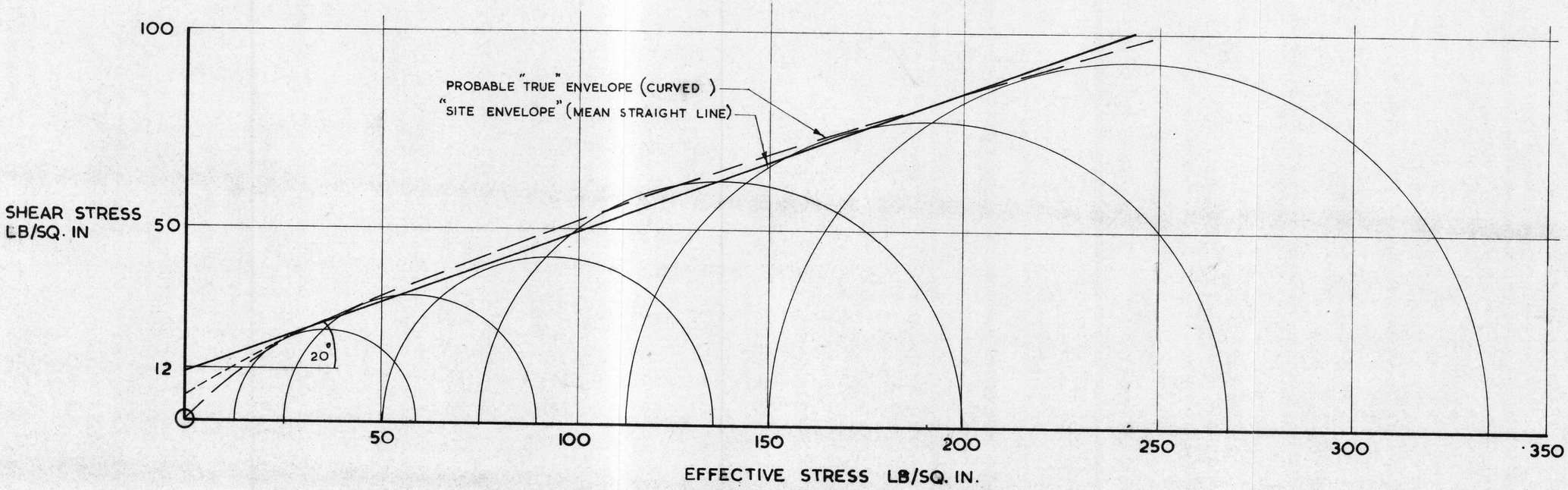
PLASTICITY CHART & PARTICLE SIZE

FIG. 80.



MANGLA/SUKIAN
FOUNDATION INVESTIGATION 1964-65
CLAY FRACTION VS.
LIQUID LIMIT

FIG. 81.



MANGLA CLAYS

MANGLA

TYPICAL MOHR CIRCLES
FOR MANGLA CLAY

(After K.H.H. & M.A.)

FIG. 82.

SUMMARY AND CONCLUSIONS

1. The development is given of the site investigation from 1961 to 1965 for the ca. £150 million Mangla Dam Project. The Project comprises the Mangla, Jari and Sukian earth dams and associated works and forms part of the Indus Basin Scheme, West Pakistan.

2. Bedrock of the project consists of folded clay, sandstone and occasional gravel beds of the Plio/Pleistocene Siwalik System. The geology and structure of the site and adjoining region is discussed and the features of importance to the engineering performance of the foundations are emphasized. The relationship of the important Changhar faulted fold to the site geology was not fully established.

   Results from the investigations on the clay beds are presented and discussed in two parts, viz:

   Part I, which describes and discusses the local geology and principal techniques used in the site investigation, mapping, boring, sampling, insitu and soil laboratory tests.

   Part II, which deals with the chronological development of the various stages of the investigation and presents and discusses results and findings from the work.

3. The location of the principal damsite across the River Jhelum at Mangla is at a point where foothills of the

Himalayan mountains meet the Punjab Plain. In general the site is hilly, with steep scarp faces and gentle dip slopes formed by the beds of sandstone; and degraded slopes by the beds of clay which are themselves usually covered by hill debris. The countryside is semi-arid unless irrigated and dry nullahs are numerous, especially in the Mirpur Silt Basin, which forms most of the reservoir area. The climate is fairly dry, hot in summer and warm to temperate in winter with both summer and winter rainy seasons.

4. 'Investigation' has been divided into three stages, viz:

Site Exploration which is preliminary and less detailed than succeeding work. This early work did not find weak conditions in the clay that were found later after intensive search.

Site Investigation which is the principal investigating stage and consists of mapping, boring, sampling and testing. The programme for this was based on engineering requirement; the geology of the site and test findings as they became known.

Foundation Investigation, investigation carried out during the construction stage when fresh exposed foundation is available.

Owing to the large scale of the project, the stages overlapped and were not taking place on each site at the same time, so that techniques developed for the Jari site (1962) which received the first concentrated site investigation,

were later used and developed at Sukian (1963) and then Mangla (1964).

5. In the field, the situation consisted basically of:

(i) gently folded beds of

(ii) alternating stiff fissured clays and friable sandstone with

(iii) tectonic features such as faults, shear joints and shear zones;

(iv) generally a poor degree of exposure;

(v) often difficult access and

(vi) unusually large areas of site.

To meet the problems during site investigation, standard and new techniques were employed. Geological mapping preceded or went hand in hand with boring, trenching and pitting. In areas where the bedrock was obscured, trenches were cut down to bedrock and laid out in positions related to the depth of cover, water table and geometry of the bedrock. These were supplemented by borings laid out in conjunction with the trenches. Thousands of samples were taken for classification tests from trenches, boreholes, natural exposures and pits, in patterns related to the geometry of the bedrock. Undisturbed samples were also taken from these exposures and an approximate correlation established with the classification properties. In the site investigation stage a working relationship for strength/liquid limit was developed and later in the

foundation investigation stage a strength/clay fraction relation.

From the field and related laboratory work, distribution of strength patterns within the bedrock and significant weak features were resolved, to within the scale of the investigation, and the findings used in design. Properties varied significantly from top to bottom of individual beds but lateral variation was smaller and beds of up to 700' length were shown to have continuity of similar properties. Below the weathered zone (where it existed) shear strengths were found not to alter significantly with depth down dip.

6. Orientation studies were made on fissures in fissured clays for the first time, and although the work was only preliminary it suggests approaches for future work. The following tentative conclusions were made:

(i) Fissures in clays lend themselves to field observation and measurement of their attitude.

(ii) Fissured clays unaffected by weathering or by near-surface changes, in geologically undisturbed areas (e.g. without faulting, shearing or strong folding), have a random orientation of fissures. This type of fissure probably originates at an early stage in the formation of the deposit.

(iii) Unweathered fissured clays in areas adjacent to faulting or in folded bedrock in which there has been some shearing, show preferred orientation of some of the fissures in directions which follow the

fold, fault or shear pattern of the area. These fissures are undoubtedly related to tectonic stresses.

(iv) Unloading, caused by erosion can result in the formation of horizontal fissures or perhaps, more generally, of fissures parallel to the ground surface.

Tectonic fissures had polished or striated surfaces. Four categories of degree of fissuring were used, e.g. 'intact'; 'slightly', 'moderately' and 'highly' fissured.

7. Bedding plane shear zones were discovered and their engineering significance shown for the first time. The shear zones are the result of dislocation caused by bed over bed slip during the folding of the beds and were found only within clays. They can occur as a single plane of shear or in zones of dislocation up to ca. 3' thick. The thicker zones are comprised of numerous shear bounded lenses in which both Riedel and thrust shears were recognised. At the extreme limit of shearing cardboard thin slices of clay are produced. In all zones examined in detail, a continuous principal plane or planes could be discerned. The major amount of bed over bed slip obviously took place on these planes. In all the construction slope failures examined which slid over shear zones, the failure path followed a principal plane. Three divisions of shear zones were recognised

in the field and tested in the laboratory, viz; 'slight', 'moderate' and 'intense'; depending on the thickness of the zone and apparent degree of shearing. Shear zones were traced continuously for over 1,500'.

8. Structural discontinuities in clays caused by tectonic shearing, viz. tectonic fissures, thrust (shear) joints, shear zones and fault zones have polished surfaces. The nature of these surfaces was investigated for the first time both in the laboratory and the field and it was found that they had little or no peak condition. The field geometry of the surfaces was established during the site investigations.

9. The properties of the Upper and Middle(?) Siwalik clays* for the Project show extreme ranges from:

CF%	LL%	PL%	Activity	Field Density	Ø' (c' = 0)	
					Peak	Residual
15-75	25-100	20-40	0.6-1.8	130-145	15-38	7-30

There is a tendency for the Mangla clays, which have been overconsolidated by some 5,000' of overburden to have slightly higher strengths and to have a slightly greater field density than the Jari clays which have only been overconsolidated by some 2,000'. In addition they appear to have on average, slightly lower clay fractions and liquid limits. Apart from the occasional seams of

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* The thin seams of bentonitic clay have higher liquid limits and higher activities.

bentonitic clay the Mangla Project Siwaliks are dominately illitic clays with up to 20% montmorillonite; sufficiently detailed work has not been carried out yet to show a significant mineralogical difference between the Jari and the Mangla clays. Both the Jari and the Mangla clays are products of deposition in fluviatile and lacustrine environments probably analogous to the Alpine Molasse. From the limited sedimentalogical studies made on site, both the Jari and the Mangla clay beds were similar in occurrence and appearance. It is possible that the climate was colder during the deposition of the Jari clays and there is some preliminary work which suggests that clay minerals are slightly more weathered than the Mangla clays. However, on the basis of available evidence it is concluded that the Upper Siwalik (Jari) and the Lower Upper (or Upper Middle(?)) Siwalik (Mangla) clays are both similar geologically and in engineering property and that any difference in strength of these two clay types is within the range of variation found at each site and is consistent with the clay fractions which are controlled by the original state of deposition and the degree of overconsolidation.

10. Work presented here was concluded at the end of 1965 but is continuing both in the field and in the laboratory.

ACKNOWLEDGMENTS

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A P P E N D I X I

HISTORY OF THE PROJECT

Feasibility Report requested	1952
Feasibility Report presented	May 1954
Consulting Engineers appointed	Dec. 1957
Interim Report by Consulting Engineers	Dec. 1958
Consulting Engineer's recommendation reviewed	Oct. 1959
Tenders invited for Civil Engineering work	June 1961
Tenders received	Nov. 1961
Contractors appointed	Jan. 1962
Estimated Date of Completion	Aug. 1968

PRINCIPAL DATA

Mangla Dam and Intake Embankment

Type	Earthfill
Maximum height	380 feet
Crest elevation	1,234 feet S.P.D.
Length of crest	11,000 feet
Excavation	15,000,000 cu.yds.
Fill	73,000,000 cu.yds.

Sukian Dam

Type	Earthfill
Maximum height	100 feet
Length of Crest	17,000 feet
Excavation	6,500,000 cu.yds.
Fill	11,000,000 cu.yds.

Jari Dam and Rimworks

Type	Earthfill
Maximum height	234 feet
Length of Crest	15,000 feet
Excavation	12,000,000 cu.yds.
Fill	39,000,000 cu.yds.

Main Spillway

Type	Submerged Orifice
Capacity	900,000 cusecs (at pool elevation of 1,202 feet S.P.D.)
Type of gates	Tainter
Number of gates	9
Size of orifice	36 ft. wide x 40 ft. high
Excavation	29,000,000 cu.yds.
Fill	1,700,000 cu.yds.
Concrete	1,200,000 cu.yds.

Emergency Spillway

Type	Unregulated
Capacity	230,000 cusecs. (at pool elevation of 1,228 ft. S.P.D.).
Excavation	12,500,000 cu.yds.
Fill	700,000 cu.yds.
Concrete	200,000 cu.yds.

Diversion Tunnels

Number	5
Internal Diameter	30 ft. and 26 ft.
Length	2,000 feet each.

Bong Canal

Capacity	40,000 cusecs.
Length	15,000 feet
Bed width	100 feet
Depth	37 feet

Reservoir

Maximum Conservation level	1,202 feet S.P.D.
Minimum Pool level	1,040 feet S.P.D.
Gross Storage	5.55 M.A.F.
Live Storage	4.75 M.A.F.
Surface Area of Reservoir	100 square miles.

CONTRACT No. 2

Civil Engineering Works

Mangla Dam Contractors — U.S.A.

a consortium of

Guy F. Atkinson Co. (Sponsor)
Chicago Bridge & Iron Co.
S.J. Groves & Sons, Co.
Chas. L. Harney Inc.
C.J. Langenfelder & Son Inc.
Ostrander Construction Co.
R.A. Trippeer Inc.
Walsh Construction Co.

(All data to December 1965).

JARI
SITE INVESTIGATION 1962-63
SUMMARY OF TRIAXIAL RESULTS ON SANDSTONE BEDROCK.

Sample No.	Location	Dry Density lb/cu.ft.	Permeability cm/sec.	Coefficient of Consolidation Cv sq.cm/sec.	Ø' (Peak)	Ø' (Ult.)	Sample Axis	Remarks
45721 A	Adit JA5, Ch. 32' E. Wall.	106	$3x10^{-4}$	2.6	40^{o}	40^{o}	Vertical	
B		111	$12-10^{-4}$	-	44^{o}	41^{o}	Vertical	
45722 A	Adit JA5, Ch. 61', W. Wall.	109	$4x10^{-4}$	3.5	37^{o}	36^{o}	Vertical	
B		114	$6x10^{-4}$	(7) *	(35^{o})	(32^{o})	Vertical	Faulty
45723 A	Adit, JA5, Ch. 96' W. Wall.	111	$4x10^{-4}$	(4) *	41^{o}	35^{o}	Vertical	Sample
C		108	$5x10^{-4}$	-	42^{o}	37^{o}	Vertical	
45701	Density Pit No. 4	107	$4x10^{-4}$	-	(32^{o})	(33^{o})	Vertical	Faulty Sample
45705 A	Trench ABC,	109	$12x10^{-4}$	7.7	40^{o}	40^{o}	Vertical	
B		113	$5x10^{-4}$	3.5	47^{o}	43^{o}	Parallel to bedding	
C	Ch.172' from North end.	110	$16x10^{-4}$	17.6	44^{o}	40^{o}	Parallel to bedding	
D		115	$6x10^{-7}$	0.01	31^{o}	-	Normal to bedding	
E		117	$6x10^{-6}$	0.20	37^{o}	35^{o}	Normal to bedding	

(* = Approximate values)

APPENDIX II. TABLE I.

APPENDIX II. TABLE II.

JARI
SITE INVESTIGATION 1962-63
SUMMARY OF TRIAXIAL SAMPLES ON SANDSTONE BEDROCK.

Sample No.	Location	Dry density lb/cu.ft.	Permeability cm/sec.	Coefficient of Consolidation Cv sq.cm/sec.	ϕ' (Peak)	ϕ' (Ult.)	Sample axis
45707 A	Trench ABC, Ch.323 ft.	116	$2x10^{-4}$	4.3	49°	44°	Vertical
B	From North end.	115	$4x10^{-4}$	16	45°	38°	"
C		120	$3x10^{-4}$	8.8	40°	39°	"
E		118	$4x10^{-4}$	6.8	38°	37°	"
F		117	$6x10^{-4}$	10.1	40°	38°	"
45710 A	Trench ABC, Ch.435 ft.	119	$1.3x10^{-5}$	0.4	53°	41°	Near vertical
B	from North end	121	$6x10^{-5}$	4.9	42°	38°	Vertical
C		120	$3.5x10^{-7}$	-	38°	35°	Vertical
D		116	$1.2x10^{-5}$	2.5	41°	38°	"
E		119	$12x10^{-5}$	4.2	37°	38°	"
45711 A	Trench ABC, Ch. 489 ft.	120	$0.3x10^{-4}$	3.5	45°	39°	Vertical
B	from North end.	117	$2x10^{-4}$	12.5	42°	40°	"
C		112	$4x10^{-4}$	2.2	42°	37°	"
D		122	$0.7x10^{-4}$	11.3	38°	37°	"
E		118	$2.8x10^{-4}$	5.7	36°	35°	"
F		119	$1.7x10^{-4}$	3.4	38°	37°	"

NOTE: Cv (sq.ft./month) = Cv (sq cm/sec) x 2,831

SUKIAN

SITE INVESTIGATION 1963-64

FIELD PERMEABILITY TEST RESULTS ON SANDSTONE BEDROCK

Hole No.	Location	Depth of Test	Permeability k Cm/Sec.
SK-732	E. 39,337 N. 78,431 G.L. 1173.3	25' - 30'	2.42×10^{-5}
SK-733	E. 39,400 N. 78,557 G.L. 1165.6	5' - 15' 15' - 25'	9.33×10^{-5} 2.39×10^{-5}
SK-734	E. 39,324 N. 78,784 G.L. 1181.6	5' - 15' 15' - 25'	1.13×10^{-5} 5.32×10^{-5}
SK-735	E. 39,374 N. 78,837 G.L. 1173.3	15' - 25' 25' - 35'	1.48×10^{-5} 8.84×10^{-6}
SK-736	E. 39,591 N. 79,182 G.L. 1153.9	5' - 15' 15' - 25'	3.31×10^{-5} 5.15×10^{-5}
SK-737	E. 39,636 N. 79,249 G.L. 1149.2	5' - 15' 15' - 25'	1.13×10^{-4} 1.96×10^{-5}
SK-738	E. 39,815 N. 79,464 G.L. 1142.0	5' - 15' 45' - 55'	6.35×10^{-5} 8.59×10^{-6}
SK-741	E. 41,525 N. 79,140 G.L. 1198.9	10' - 15' 15' - 25'	6.07×10^{-4} 5.42×10^{-4}
SK-742	E. 41,610 N. 79,220 G.L. 1201.2	9' - 15' 15' - 25'	2.05×10^{-5} 8.73×10^{-5}
SK-743	E. 41,780 N. 79,505 G.L. 1227.2	35' - 44'	4.84×10^{-4}
SK-744	E. 41,810 N. 79,595 G.L. 1212.3	41' - 50'	7.71×10^{-6}
SK-745	E. 41,875 N. 79,892 G.L. 1242.4	10' - 20' 20' - 30'	1.37×10^{-4} 2.97×10^{-4}
SK-746	E. 41,910 N. 80,045 G.L. 1205.5	10' - 20' 20' - 30'	1.56×10^{-4} 4.46×10^{-4}
SK-747	E. 41,955 N. 80,240 G.L. 1175.3	10' - 20' 20' - 30'	8.86×10^{-4} 6.71×10^{-4}
SK-748	E. 42,000 N. 80,465 G.L. 1167.3	40' - 50' 50' - 60'	6.45×10^{-5} 4.31×10^{-6}
SK-749	E. 42,020 N. 80,565 G.L. 1164.3	25' - 35' 35' - 45'	5.97×10^{-4} 4.76×10^{-4}

E. = Easting G.L. = Ground surface level N. = Northing

APPENDIX II. TABLE III.

SUKIAN
SITE INVESTIGATION 1963-64.
FIELD PERMEABILITY TEST RESULTS ON SANDSTONE BEDROCK

Hole No.	Location	Depth of Test	Permeability k Cm/Sec.
SK-721	Ch. 208 + 00	5' -15' 15' -25'	5.46×10^{-5} 4.43×10^{-5}
SK-722	Ch. 210 + 00	5' -15' 15' -25'	2.41×10^{-5} 7.6×10^{-6}
SK-723	Ch. 221 + 00	5' -15' 15' -25'	9.78×10^{-5} 2.55×10^{-5}
SK-724	Ch. 226 + 00	5' -15' 15' -25'	1.32×10^{-4} 6.07×10^{-5}
SK-725	Ch. 229 + 00	5' -15' 15' -25'	1.71×10^{-4} 1.94×10^{-5}
SK-726	Ch. 236 + 00	5' -15' 15' -25'	3.64×10^{-4} 3.82×10^{-5}
SK-727	Ch. 241 + 00	5' -15' 15' -25'	6.59×10^{-5} 1.39×10^{-5}
SK-728	Ch. 248 + 00	5' -15' 15' -25'	4.46×10^{-4} 8.46×10^{-5}
SK-729	Ch. 251 + 00	5' -15' 15' -25'	2.87×10^{-4} 3.74×10^{-5}
SK-730	Ch. 259 + 00	5' -15' 15' -25'	1.31×10^{-4} 6.40×10^{-5}
SK-731	Ch. 268 + 00	5' -15' 15' -25'	1.26×10^{-4} 3.32×10^{-5}

Ch. = Centreline Chainage.

APPENDIX II.

TABLE IV.

SUKIAN

SITE INVESTIGATION 1963-64

SUMMARY OF TRIAXIAL RESULTS ON SANDSTONE BEDROCK.

Trench No.	Sample No.	Coordinates	Grading Clay+ Silt %	Fine Sand %	Med. Sand %	Field Density lb/cu.ft. (& M/C%)	Unconf. Compr. Strength lb/sq.in.	Disintegration Time Mins.	Class	Shear Strength C' lb/sq.in.	Ø'	Permeability Cm/Sec.
SK-20	58103	E. 41130 N. 79500 El. 1149.3 Depth 13.5'	16	26	58	109	3.6	1/2	E	11 0	$31\frac{1}{2}^{o}$ Peak $37\frac{1}{2}^{o}$ Ult	0.18 to 1.0 x 10^{-4}
Exc.	58105	Ch. 268+47' Off. 75' U/S El. 1187.3 Depth 5.7'	15	14	65	124 (7.8)	17	1% in 10 min. 1% in 24 hrs. + crack	A^{-}	12 4	36^{o} Peak $35\frac{1}{2}^{o}$ Ult	1.2 to 8.2 x 10^{-4}
SK-22	55344	Ch. 334+50' Off. 540 El. 1166 Depth 21'	26	24	50	122 (5.4)	21	120	B	13	34^{o} Peak	1.5 to 3.9 x 10^{-4}
SK-12A	58101	Ch. 304+30' Off. 295' U/S El. 1149.5 Depth 8.5'	11	8	78	118 (6.8)	3.9	10% in 24 hrs. 45% in 72 hrs.	B^{+}	0 0	38^{o} Peak $35\frac{1}{2}^{o}$ Ult	0.4 to 1.2 x 10^{-4}
Exc.	58110	Ch. 248+89' Off. 34' U/S El. 1191.5 Depth 10.5'	7	16	65	113 (3.4)	22	72 hrs. nil	A	30 14	34^{o} Peak $32\frac{1}{2}^{o}$ Ult	0.7 to 1.5 x 10^{-4}

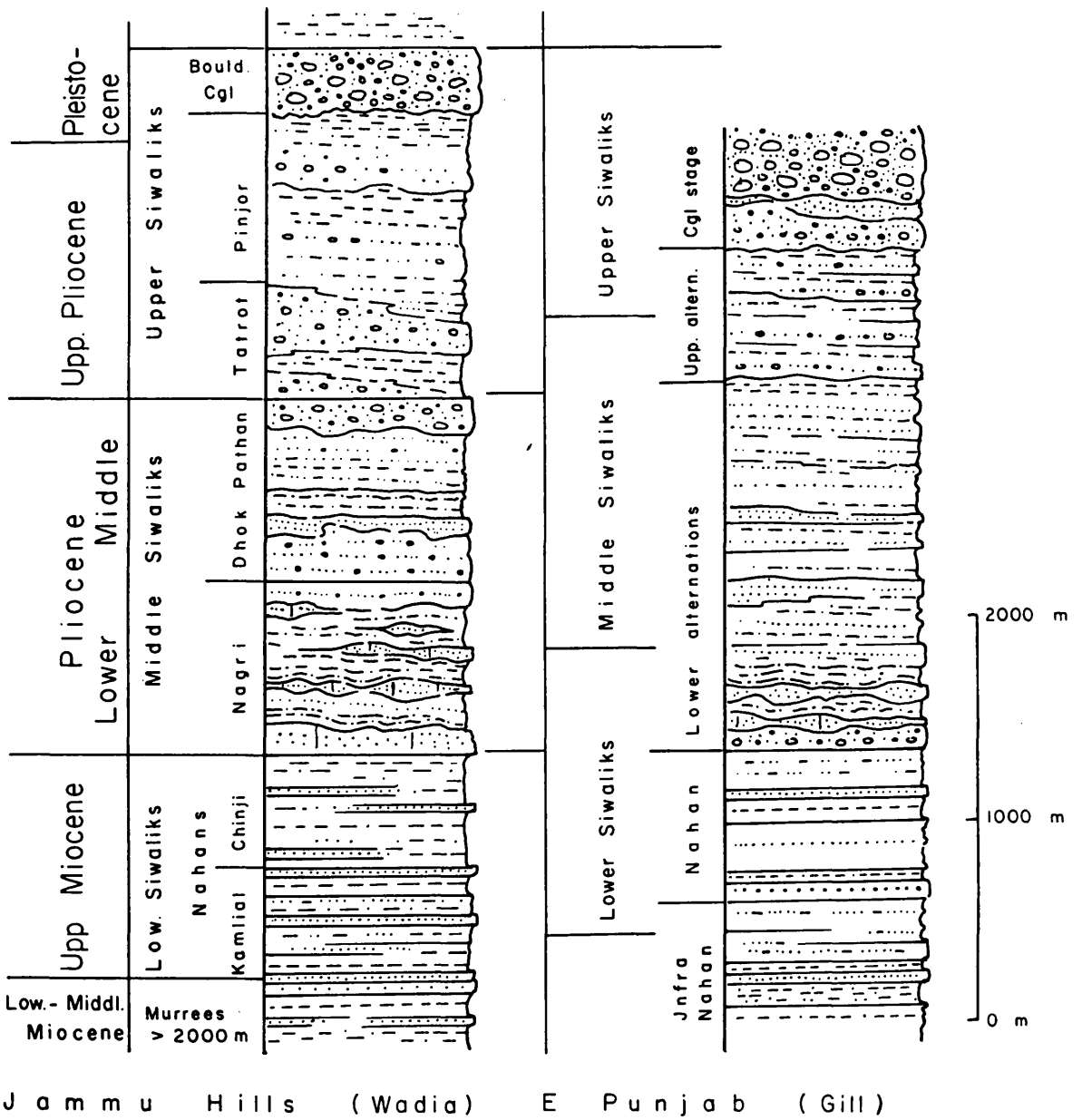
APPENDIX II. TABLE V.

A P P E N D I X III

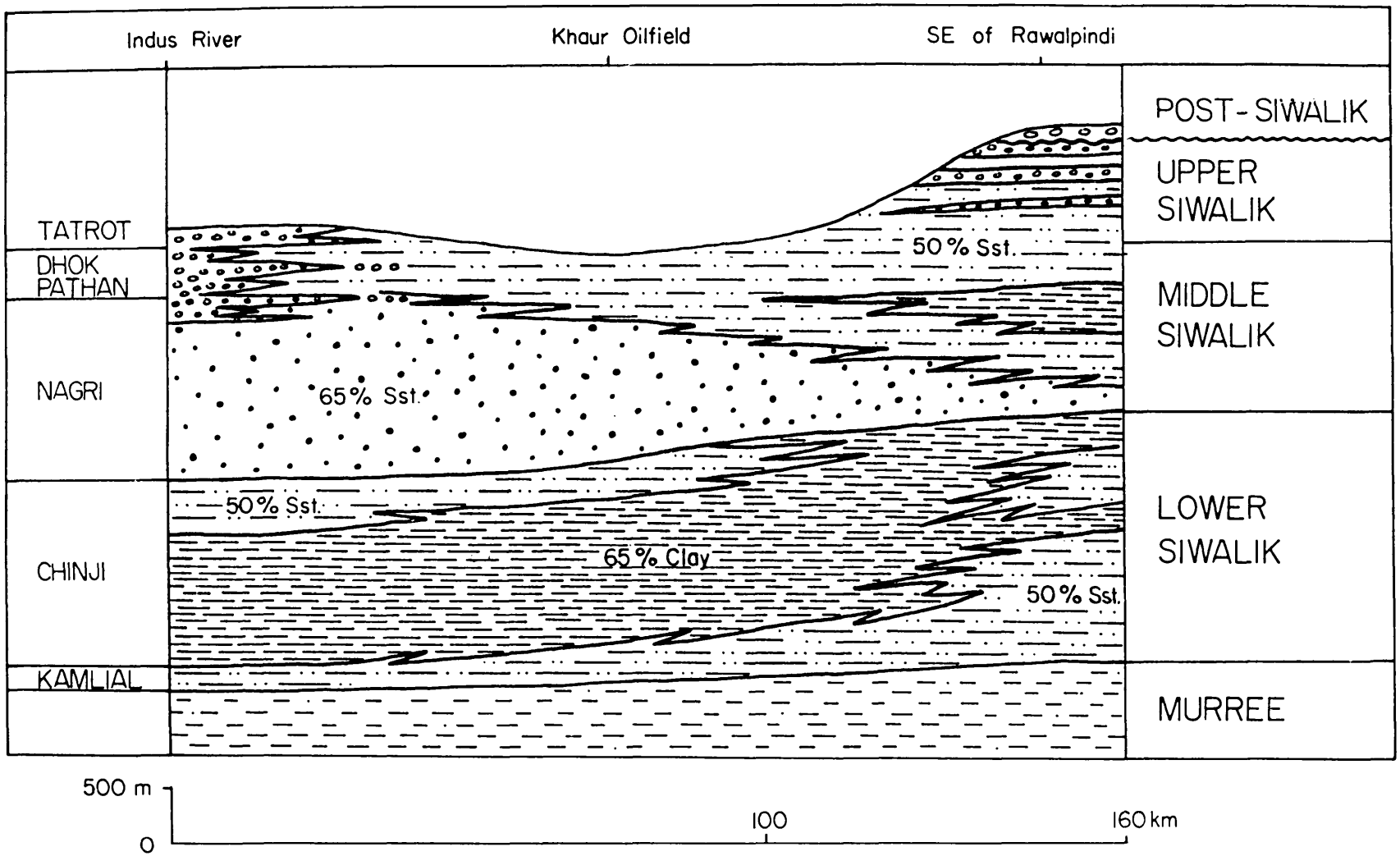
Both figures reproduced from GANSSER, A., 1964

(i) Stratigraphy and correlation of the Siwaliks in the Punjab Sub-Himalayas, mainly compiled after D.N. Wadia (1928, 1953) and W.D. Gill (1951).

(ii) Schematic correlation and facies table of the Siwaliks in the Potwar Basin. Redrawn after W.D. Gill. The Mangla sequence approximates to the upper right hand side of the section.



APPENDIX III



APPENDIX III

A P P E N D I X IV

MANGLA FOUNDATION INVESTIGATION 1964

Detail of Shear Zone Locations I to IV

LOCATION I (Intake)

Approximate Co-ordinates: E. = 26620'
N. = 75125'
El. = 1055'

Figs. 61 and 55 show some detail of the area studied.

One set of shear box samples and one 4" triaxial sample were taken from the shear zone immediately below the sandstone/clay contact. The sandstone is almost certainly Alpha sandstone and the clay is 11 minus.

The shear zone itself (at the location studied) can be divided into two portions - an upper moderate zone and a lower intense zone (plate 37). The upper zone consists of a tight mass of clay lenses with polished and striated faces. The lineations on the clay faces give an overall picture of movement in the dip direction of the bedrock, i.e. in a north-east/south-west direction. The lenses form an 'imbricate' pattern giving a sense of movement also in the dip direction. The junction with the base of the sandstone above and the top of the sheared clay below is sharp and polished and the clay fragments in the basal breccia of the sandstone are full of small joints and slickensided fissures. The base of the sandstone shows small bottom structures (ripple marks, current channels, rill marks and small basal deformations) so that although the junction is sharp, it is irregular. The irregularities in general protrude no more than an inch or so into the clays beneath and the clay at the junction with the irregularities is polished.

The intensely sheared zone consists of a tight mass of polished leaves (mille feuilles) and it was from this zone that the $\emptyset'$ 10° (ult.) results were obtained during the 'Orange' investigation. Individual leaves of clay are typically 2 to 5 mm. thick and 10 to 30 cm. long. They can easily be moulded within the fingers and the shear box specimens were trimmed from this material. The intensely sheared zone passes abruptly down into stiff fissured clay. Joints in this clay pass into but not across the shear zone. The

4" diameter triaxial sample contained the intensely sheared clay in a layer orientated at 61° to the sample axis, between the stiffer clays above and below it.

The larger joints (fig. 1 of fig. 61) were measured and their attitudes shown on a contour diagram (fig. 7). The joint faces are polished and sometimes lineated in their dip direction. Two principal sets were apparent - one dipping with the dip of the bedding, and the other opposite to the bedding dip. The two sets intersect to give a 'diamond' pattern

LOCATION IA (Intake)

The shear zone sampled at Location I has been traced from the intake east slope to the intake embankment core trench. Fig. 55 shows the area studied.

Samples were also taken from this shear zone during the 'Orange' site investigation programme from locations Orange III and IV.

Descriptions and photographs of scrapes B.10 to B.17 illustrate the relative degree of shearing, and curves of liquid limit and clay fraction across the shear zone show the soil properties of the shear zone in relation to the surrounding clays. The shear zones are characterized by a higher clay fraction and liquid limit percentage. The intensity of shearing diminishes in a southerly direction which agrees in general with the lessening of shear expected along bedding as the crest of the Tailrace fold is approached. Upstream from scrape B.12 the sheared clay is overlain by sandstone as the sandstone has eroded the upper portion of clay bed II minus, but the shear zone itself maintains a constant horizon within the clay.

LOCATION II (Intake Core Trench)

Approximate Co-ordinates Ch. 134 + 00
Offset 36' Downstream ℄
El. 935'

One set of shear box and one set of 1½" triaxial samples were taken from the shear zone within clay bed 8 minus. The shear zone is the same one which was exposed in the intake tunnel portals, No. 4 and No. 5. The block from which the 1½" dia. triaxial samples were taken broke into pieces and three specimens were trimmed from the three separate pieces. The orientation of each specimen is therefore not known.

The shear zone itself is moderate and occurs within a clay horizon between siltstones. It consists of a tight

mass of polished lenses of clay with their long axes parallel to the bedding dip so that no imbricate structure is developed. The lineations on the lens faces are also in the bedding dip direction indicating movement parallel to the bedding dip. The contact with the siltstones above and below the shear zone is fairly sharp and the zone gives the impression of being contained within the siltstones. The siltstones themselves are slightly fissured and much jointed. The dominant joints were measured and plotted on a contour diagram which gives a similar pattern to the contour diagram of joints from Location I. Some of the larger joints cross the shear zone but the majority pass into it or abut against it. Again the joints exist in two principal sets which intersect to give a diamond pattern.

LOCATION III (Lower Stilling Basin)

Approximate Co-ordinates Sta. 62 + 36'
Offset 505' RT of $\mathrm{C_L}$
El. 907'

Fig. 62 shows the detail of the location.

One shear box sample was taken from the clay immediately below the sandstone contact. The sandstone is the alpha bed and the clay bed is No. 201. One 4" dia. triaxial sample was taken at the contact and orientated so that failure occurred along the contact surface.

Because the sheared clay zone is thin, i.e. one principal plane by the sandstone/clay contact, the 4" dia. triaxial sample was trimmed so as to include the contact zone as well as the shear zone. However, the shear box samples were thin enough to contain sheared clay without the contact zone affecting the surface of the shear in the test.

The shear zone is classed as slight and occurs immediately below the contact. The contact is polished and slickensided - the clay below the contact is highly fissured for 3 to 6" beneath the contact. The term 'shear zone' even when prefixed by 'slight' may be a little generous for this feature, nevertheless the term is retained as it fits at the end scale of shearing intersities used for the Project. 'Slightly sheared contact' is a more accurate description. Neither lenses or leaves of clay are formed. The base of the sandstone bed shows bottom structures similar to those described for Location I.

The clay below the shear zone was fissured and the larger cracks, joints and fissures are shown on the drawing together with their attitudes. The shear zone itself has been noted wherever it has been exposed in the Lower Stilling Basin. No sense of movement was determined for the shear zone.

LOCATION IV (Lower Stilling Basin)

Approximate Co-ordinates Sta. 59 + 45
Offset 105' Rt of ℄
El. 804'

Two shear box samples, one in the shear zone and one in the fault zone, were taken. One 4" triaxial sample was taken in the fault zone and one in the shear zone each with axes orientated. Both fault and shear zones were within clay bed 201. Plate 43 shows details of the sampling location.

The shear zone (IVA) occurs between thin bedded clays and silts. It shows the same characteristics as the shear zone at Location II and is classed as moderate/intense. It has been traced across the whole width of the Lower Stilling Basin.

The shear zone is composed of clay lenses with their long axes parallel to the bedding dip. Lineations on the lens faces indicate sense of movement in the bedding dip direction. The contact of the shear zone with the containing clays is not sharp and the zone grades into them over a distance of a few cm. All the clays and silts on the drawings in Fookes & Head (1964) are highly fissured; only larger cracks, joints and fissures are shown, together with their attitudes.

The shear zone is cut by a thrust(reverse) fault zone (IVB). This fault has been traced continuously from the Spillway Tailrace. Where the fault crosses sandstone beds it is similar to fault RF A or B from the Fort Hill and is a fracture with fault gouge developed at some places in the sandstone and thin black clay smear developed at other places. Where it crosses clay beds features similar to intense and moderate shear zones are developed. In Location IVB the leaves and lenses are flexed against the walls of the fault in a manner similar to small drag folds and indicate a sense of movement along the dip of the fault plane. This sense of movement is in agreement with the lineations on the clay lenses and leaves when the fault is passing through clay and on the black clay smear when the fault is passing through sandstone.

Fuller details are given in Fookes & Head (1964).

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ORIENTATION OF FISSURES IN STIFF OVERCONSOLIDATED CLAY OF THE SIWALIK SYSTEM

by
P. G. FOOKES

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ORIENTATION OF FISSURES IN STIFF OVERCONSOLIDATED CLAY OF THE SIWALIK SYSTEM

by

PETER G. FOOKES*

SYNOPSIS

Measurements of the attitude of fissures in stiff-fissured overconsolidated clay bedrock are described together with the technique of stereographic projection, point and contour diagrams to portray their attitude. This technique was used on Siwalik clay to investigate directions of orientation of fissures which could act as paths of weakness for failure surfaces in dam foundations and deep excavations.

Both random and preferred orientations of fissures were found, the latter appearing to be related to the local fault, shear and fold pattern of the bedrock. The working hypotheses of fissure formation, used during the investigation, are given.

On décrit des mesures sur la disposition des fissures dans des assises rocheuses d'argile surconsolidée fissurée raide ainsi que la technique de projection stéréographique, des diagrammes de points et de contours pour décrire leur disposition.

Cette technique a été utilisée sur des argiles Siwalik pour faire des recherches sur les directions d'orientation des fissures qui pourraient agir comme lignes de faiblesse pour les surfaces de rupture dans les fondations de barrage et les excavations profondes.

On a découvert des orientations aléatoires comme des orientations préférées, ces dernières semblant être apparentées à la faille locale, au type de cisaillement et de pli de l'assise rocheuse. On présente les hypothèses admissibles sur la formation des fissures qui ont été utilisées au cours de l'enquête.

INTRODUCTION

No previous work has been found on the orientation of fissures† in fissured clay. This Paper is presented to show that fissures lend themselves to the study of their orientation in the field. From such a study, both random and preferred orientation patterns were discovered and some tentative conclusions made on their relation with larger scale geological structures. Formation of fissures and the modification of existing fissures some time after their formation are briefly discussed.

The influence of fissures on the strength of clays has occupied much attention in the literature since Terzaghi's classic paper (1936)[1] on the stability of slopes in natural clay. He described stiff fissured clay in a fashion that has been little improved since, viz. 'When it is dropped a big chunk of such clay breaks into polyhedric, angular or sub-angular fragments with dull or shiny surfaces. The diameter of the fragments may range between less than one centimetre and more than twenty centimetres. In some cases the jointing has been produced or intensified by preceding natural slides'. However, little work has been done subsequently on the field character or origin of such fissures. Text books on soil mechanics only briefly discuss them and use 'fissure' as a portmanteau term for several geological features of similar appearance and of possibly different origin, though they do recognize that one or several agencies may have produced the 'fissures'. Tschebotarioff (1951, p. 20) states that overconsolidation by temporary pressure, drying or chemical action weakens stiff clays and produces fissures and slickensides. Terzaghi and Peck (1948, p. 257) say slickensides are smoothly polished surfaces that may be the result of volume changes produced by chemical processes or of deformations produced by gravity or tectonic forces. Casagrande (1947) writing on fissure formation in clays suggests the influence of electric streaming potentials, while Skempton and Northey (1952) on the basis of experimental evidence suggest syneresis.

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† In this Paper fissures are defined as small fractures existing in clay and siltstone beds but not crossing the boundary of the bed or horizons within the bed. Slickensides are defined as polished and striated (or grooved) fissures.

[1] The references are given on p. 206.

White (1961) in a paper on colloid phenomenon in clays and shales develops the ideas of syneresis and the chemical environment of deposition, which he considers may be responsible for forming small scale structures like slickensides and fissures. More recently Skempton (1964) considers that slickensided fissures may form as a result of tectonic movements or unequal expansion during the erosion cycle.

It is worth mentioning further some of the points made by White as he deals at length with the possible origin of fissility,* syneresis cracks and fissures. He shows from his laboratory studies on clay mineral suspensions that syneresis cracks are fissures that develop in a suspension, where water is expelled from a clay/water system by internal forces, and they may resemble mud cracks commonly found in present-day sediments. Also, cracks within the suspension have completely random orientation from vertical to horizontal, and shrinkage by syneresis takes place in all directions. In fissile clays such as shales the clay minerals are orientated with their longest dimensions more or less parallel to the bedding. Such clays generally contain few slickensides. In contrast, clays with no or poor fissility have randomly orientated clay minerals; they are generally more fissured than fissile clays.

FIELD TECHNIQUES

For several decades geologists have been using the technique of petrofabric analysis† to investigate rock deformations. One of these techniques, called stereographic projection, is used to portray diagrammatically the attitude or orientation of geological planes (e.g. fissures, faults or joints‡) or lineations (e.g. ice striae or elongated minerals). Recently petrofabric analysis has been increasingly used in the study of problems in rock mechanics, for example, by John (1962). These methods have yet to be reported in extensive use as an aid in soil mechanics, but their development should be helpful in problems where deformations such as faults, joints or folds make analysis unrealistic if foundation properties are considered to be isotropic (Fookes and McKenna, 1963).

It was found during a detailed site investigation of Siwalik clay bedrock in West Pakistan that the attitudes of fissure planes lend themselves readily to the interpretative techniques of stereographic projection. The dip and strike of individual fissures were carefully measured in the field with the aid of a compass and clinometer. Usually up to a hundred readings were taken at one location, from an area of approximately 200 sq. ft on one bed. Measurements were made from within adits or pits whenever possible so that the fissure planes of any direction could easily be seen, and so that there was no selection of any one particular set of fissures preferentially exposed by one face only. Methods of measurement of fissures were essentially the same as for standard joint studies (Wise, 1964). Only fresh unweathered clay was measured, since after drying or weathering on exposure local stress conditions are set up that cause cracking related only to the local condition. An example of this is columnar jointing in clays resulting from drying on exposure.

For engineers not familiar with stereographic projection, the technique is briefly described as follows: Lines drawn normal to each fissure plane are plotted on a point diagram (Fig. 1). The fissures are imagined to be planes passing through the centre of a sphere. The line drawn normal to the fissure is projected as a point onto the lower half of the sphere which, when viewed from above, is represented as a circle on the plane of the paper, using an 'equal area'

* Fissility (White, p. 560) 'is the characteristic that causes a rock to split into thin layers lying parallel as, for example, along bedding planes'.

† The study of spatial relationships of the units that comprise a rock and the movements that produced these relationships. It is a branch of structural petrology, which deals with all aspects of deformed rocks and their tectonic history. Several textbooks treat this subject, for example, Billings (1954, p. 363).

‡ Joints are defined by Billings (1954, p. 106) as planes or surfaces that divide rocks, and along which there has been no visible movement parallel to the plane or surface. Although some joints are planes, some are curved surfaces. Faults are defined as planes with visible movement parallel to the surface.

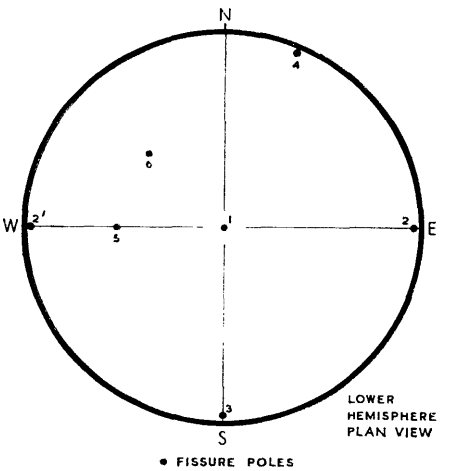


Fig. 1. A point diagram

projection. For example, horizontal fissures will project onto the centre of the circle (point 1, Fig. 1) and vertical fissures onto the circumference (points 2, 2′, 3 and 4) at a position given by the strike direction of the fissure. All vertical fissures can be plotted in two positions, for example points 2 and 2′ represent one vertical fissure with a north–south strike. In practice one point only is plotted so as not to give double the abundance of vertical fissures. Point 3 is a vertical fissure striking east–west and point 4 a vertical fissure striking N 75° W. Inclined fissures plot out between the centre and the edge of the circle (points 5 and 6). Thus fissures dipping east plot out on the western half of the circle (point 5) and fissures dipping south-east plot out in the north-western quadrant (point 6) and so on.

From a point diagram (Fig. 2(a)) a contour diagram (Fig. 2(b)) is then prepared by use of a grid in the manner described by Billings (*op. cit.*) so that the density of points can easily be read and an analysis of the density pattern made.* The contour diagram quickly indicates by the density of contouring any preferred orientation of fissures, for example, in Fig. 2(b), the contours indicate a 'peak' of fissures dipping north and striking east–west.

ORIENTATION OF FISSURES

Field observations were made at two sites, Jari and Mangla, over 100 miles north of Lahore, West Pakistan.

Jari

At Jari measurements on fissures were made from eight locations in an area of $\frac{1}{4}$ mile by 1 mile (Fig. 3). Within this area the bedrock conditions appeared to be reasonably uniform and only one small fault was found, but the beds were dipping rather steeply at 30° to 50° N with an east–west strike.

All the point and contour diagrams showed a remarkable similarity of pattern. None showed purely random orientation; all showed one or two pronounced peaks.

Figs 2(a) and 2(b), and 4(a) and 4(b) show two typical locations. The contour diagrams show some scatter, together with a marked peak of preferred orientation dipping north approxi-

* Referring to Fig. 2(b), a contour of 8%, for example, means that 8% of all points lie within a unit area. The unit area is defined as 1% of the total area of the diagram.

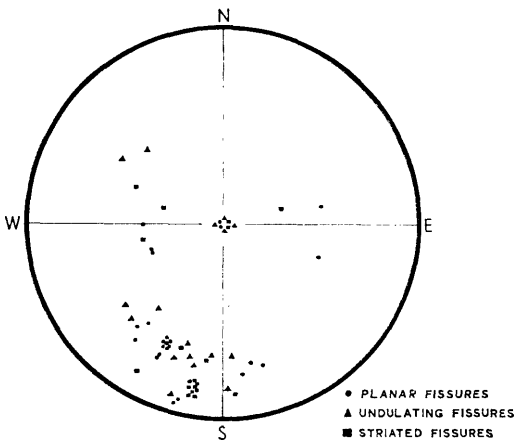


Fig. 2(a). Jari. The point diagram from location JA. 3

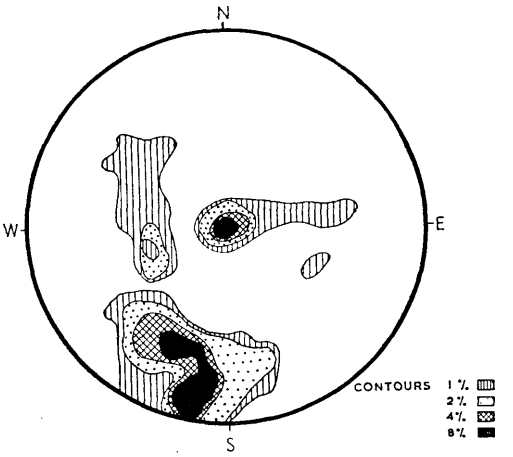


Fig. 2(b). Jari. The contour diagram derived from Fig. 2(a)

mately parallel to or a little steeper than the bedding; they also show secondary peaks corresponding to horizontal fissures. The fissures dipping parallel to the bedding were found to be cut by the horizontal fissures, so were considered to have been formed earlier than the horizontal fissures. The dipping fissures appear to be related to shear zones in the clay as they are parallel or nearly parallel to them. The shear zones themselves are parallel to the bedding and are considered to be 'flexural-slip shears'* developed by beds slipping over each other during the folding of the bedrock. They consist of a tight mass of flattened rhomb-shaped disks of polished and striated clay giving the appearance of having been elongated in the direction of shear movement along the dip direction.

The minor peaks of horizontal fissures were found in near-surface exposures in flat lying areas. It is thought that they had been formed by the unloading of the clay parallel to the present day ground surface. Subsequent to the folding and shearing of the bedrock, rapid erosion has been taking place and approximately 2000 ft of bedrock have been removed. It was considered, though not fully investigated, that in hilly areas the attitude of near-surface fissures formed by expansion when overconsolidated clay is unloaded by erosion, would be influenced by the topographic form of the hills and valleys resulting from the erosion.

The findings at Jari are summarized by Fig. 5(a) (point diagram) and Fig. 5(b) (the contour diagram drawn from Fig. 5(a)) which show the readings from all the Jari locations added together. They clearly indicate a somewhat random pattern overlain by two peaks, one peak of dipping fissures approximately parallel to the bedding planes and shear zones, the other approximately parallel to the ground surface. For comparison, the average dip of the shear zones and bedding planes is also plotted in Fig. 5(b).

Mangla

The bedrock at Mangla is in some areas more disturbed by folding and faulting than at Jari. It is also considerably older, though of the same system as at Jari. It is estimated from geological considerations that at least 5000 ft of bedrock has been removed to form the present land surface. Several locations were measured, some near to and others at some distance from

* An alternative name is 'bedding plane slips'.

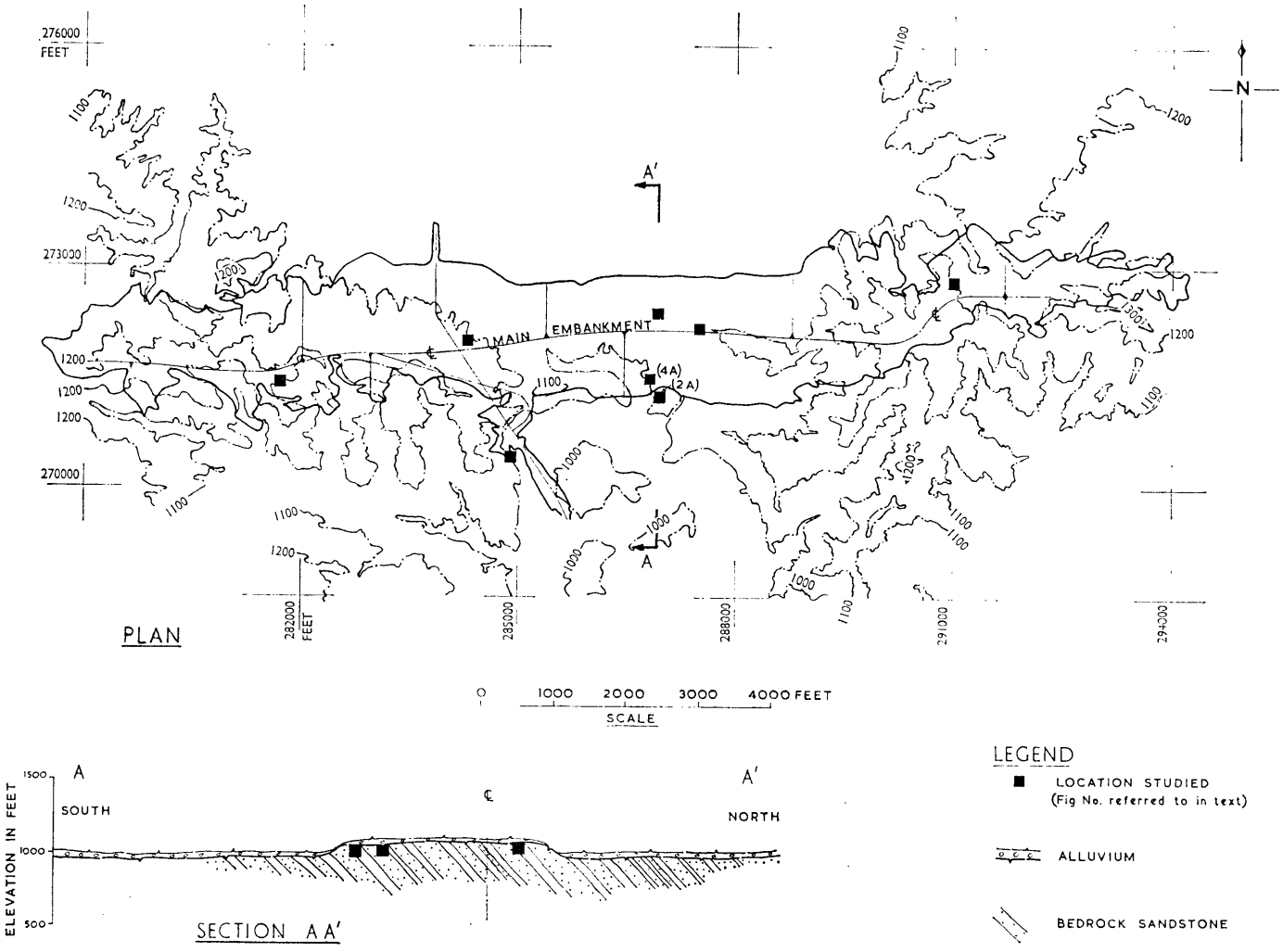


Fig. 3. Jari dam. Plan of site and diagrammatic geological section

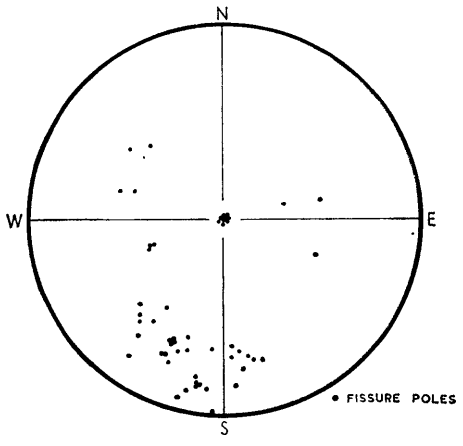


Fig. 4(a). Jari. Location JA. 11

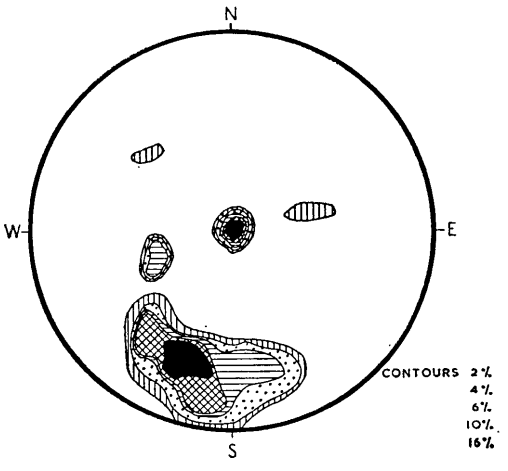


Fig. 4(b). Jari. Derived from Fig. 4(a)

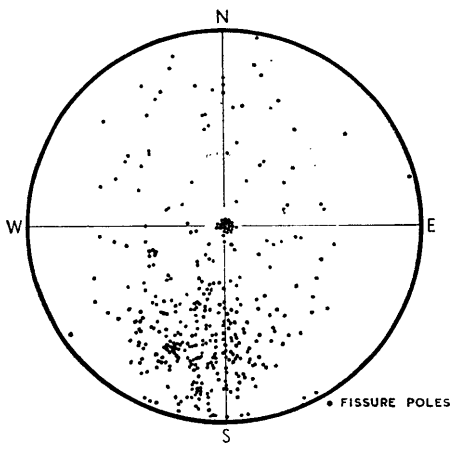


Fig. 5(a). Jari. Composite diagram from all the locations studied

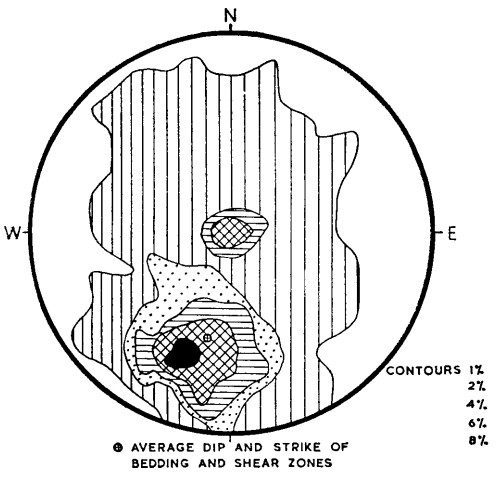


Fig. 5(b). Jari. Derived from Fig. 5(a)

relatively strongly folded or faulted areas (Figs 6 and 7). After study, a general picture emerged showing that fissures appeared to be of random orientation except within approximately 100 ft of a locally large fault (with a relative displacement of several feet) or within a fold limb. In these latter conditions some fissures showed preferred orientation with an attitude similar to that of the fault or fold.

Fig. 8 is an example of a point diagram indicating randomly orientated fissures. Measurement for this diagram was made at a location in which no nearby faults or shear zones were found. In contrast, Fig. 9(a) shows a contour diagram of a location adjacent to a fault. The diagram shows a marked peak of fissures dipping at a shallow angle south-east approximately

Text continued on p. 203

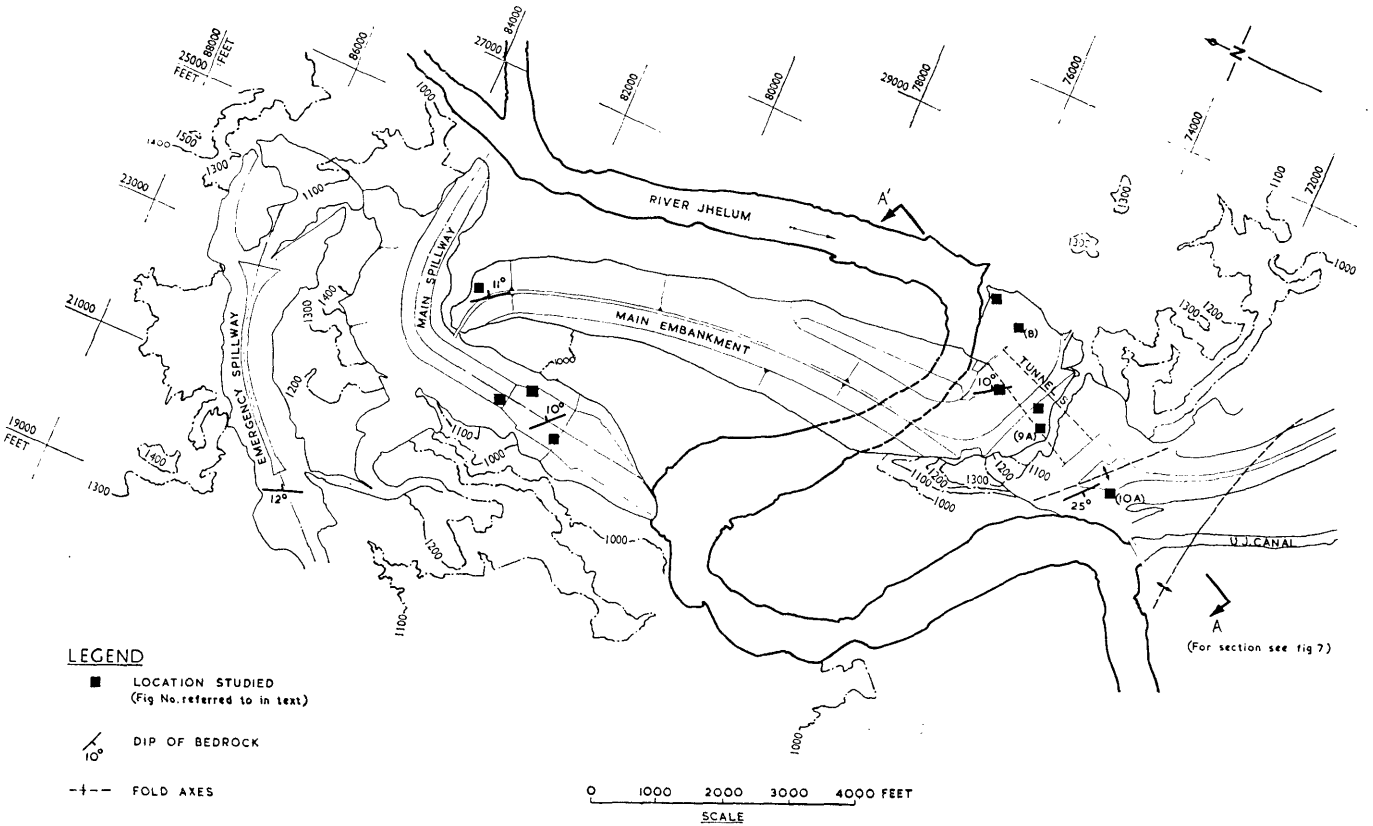


Fig. 6. Mangla dam. Plan of site

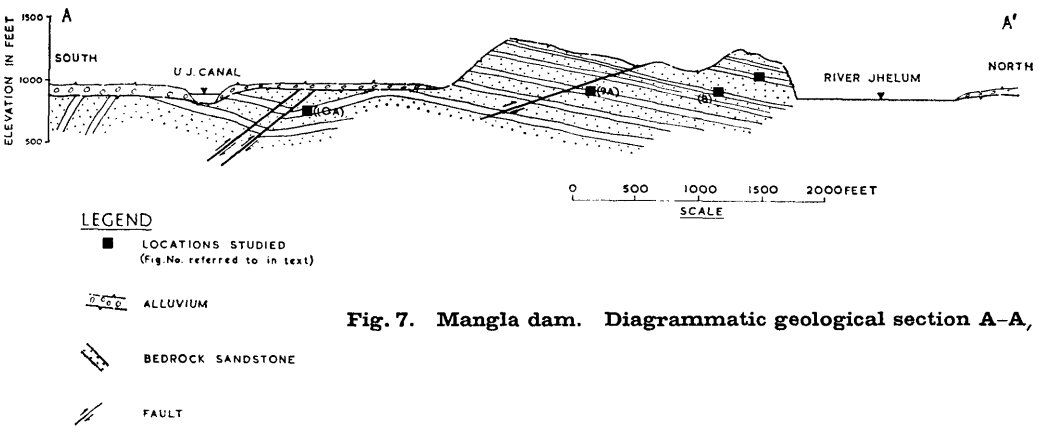


Fig. 7. Mangla dam. Diagrammatic geological section A–A,

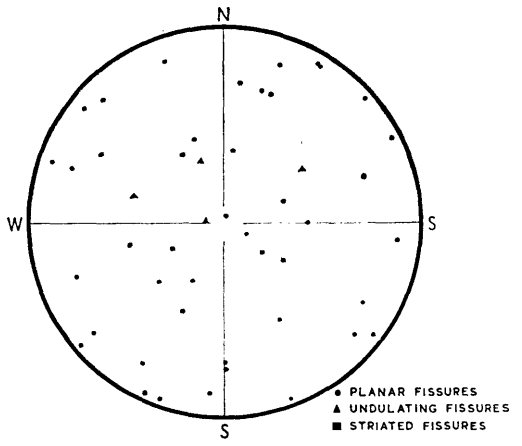


Fig. 8. Mangla. Location 217

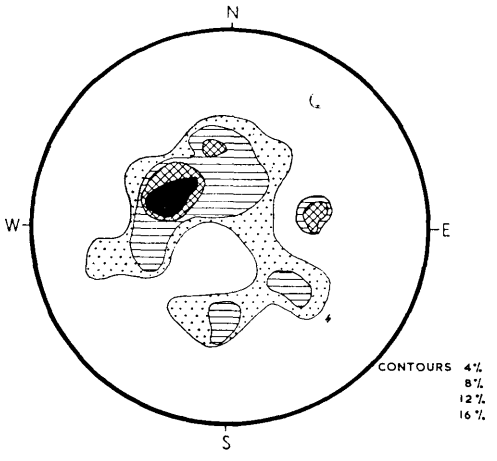


Fig. 9(a). Mangla. Location T. 43

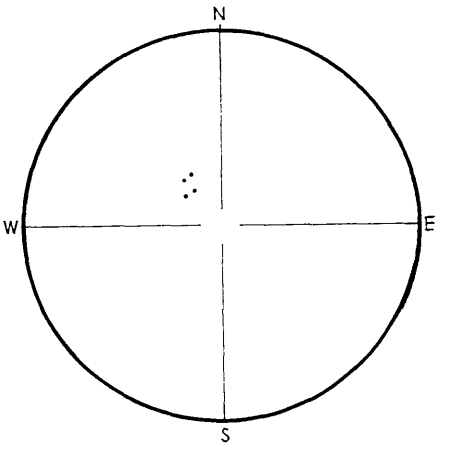


Fig. 9(b). Mangla. Point diagram of faults near location T. 43

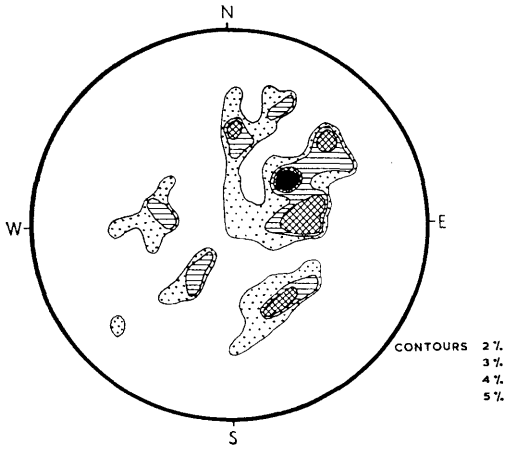


Fig. 10(a). Mangla. Location 2/1, all fissures measured

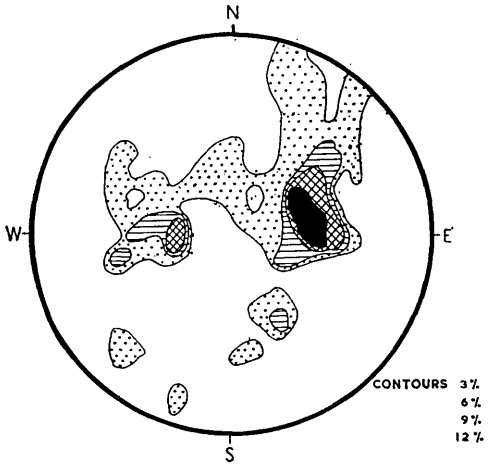


Fig. 10(b). Mangla. Location 2/1, striated fissures only

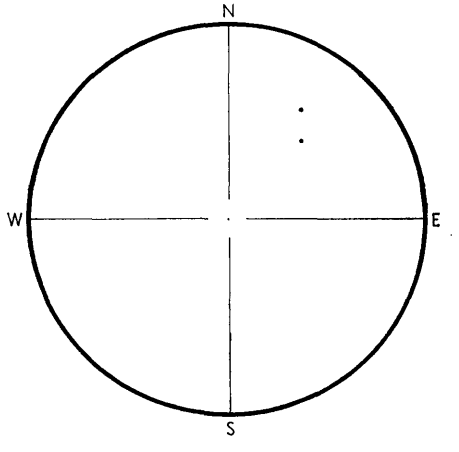


Fig. 10(c). Mangla. Point diagram of faults near location 2/1

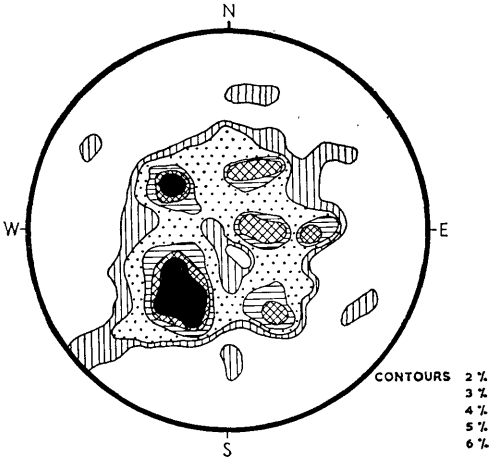


Fig. 11. Mangla. Composite diagram of fissures from all the locations studied

parallel to the fault. Measurements of the attitude of the fault are given as a point diagram (Fig. 9(b)); the similarity of the fissure and fault pattern is immediately apparent. Figs 10(a) and 10(b) are from another locality and both show peaks of fissures dipping south-west in the same direction as nearby faults. These are shown as a point diagram (Fig. 10(c)). Fig. 10(b) is of striated fissures only and shows a higher peak than Fig. 10(a). From inspection of the striated surfaces, it was concluded that the striations indicated relative movement of the opposite faces of the walls of the fissures parallel to the dip direction of the faults.

Fig. 11 is a composite contour diagram produced from all the point diagrams made at Mangla. It indicates a fairly random scatter of fissures dipping at a low angle (less than 40°), together with two peaks, one dipping north-east, parallel to the local folding, and the other south-east parallel to the major directions of faulting. The apparently large proportion of low angle fissures is due to the concentration of measurements from near fault locations.

GENERAL CHARACTERISTICS OF THE CLAYS AND FISSURES

The dam at Jari is founded on Upper Siwalik bedrock of Plio-Pleistocene age consisting of alternating beds of overconsolidated stiff fissured clays and weakly cemented sandstones. In order to accommodate the deformations during folding, intensive shear zones of up to 2 ft thick (but typically 4 in.) have developed in the clays parallel to the bedding. Individual clay beds range from 10 ft to 100 ft in thickness and shear zones occur every 20–60 ft. The clays have been described in general geological terms by Wadia (1957, Ch. XX) and in soil mechanics terms briefly by Skempton (1964). Typical soil properties are given in Table 1.

Table 1

Jari clays

Clay %	L.L.	P.L.	Activity	Field density: lb/cu. ft	ϕ'	
					Peak	Residual
20–60	35–90	20–35	<1	135	20°–35°	15°–25°

The site of Mangla dam lies some 20 miles west of Jari. It is founded on Middle Siwalik bedrock of Miocene age, consisting of alternating beds of stiff fissured clays, silts and sandstones. The beds are folded and faulted, with moderately frequent shear zones. The joint pattern is concordant with the fold and fault pattern, and it is hoped to discuss the tectonics more fully in a later paper. The bedrock has been only briefly described (Little *et al.*, 1963) to date. Typical properties are given in Table 2.

Table 2

Mangla clays

Clay %	L.L.	P.L.	Activity	Field density: lb/cu. ft	ϕ'	
					Peak	Residual
25–50	30–60	20–30	<1	142	25°–35°	18°–25°

In general, at Mangla and Jari all bedrock clays, silty clays and clayey silts are fissured, while true silts are unfissured; though some intact clay and some fissured silt can be found. The fissured clay can be described exactly as by Terzaghi (1936). The diameter of the blocks bounded by fissures typically ranges from 1 in. to 3 ft. Several different fissure types were recognized and were assigned to one of three loosely defined groups (Fig. 2(a)); 'plane' fissures, 'striated' (slickensided) fissures and 'undulating' fissures. Plane fissures formed approximately 60% of the fissures measured. They were flat and usually of the widest extent, and often fell within the geological definition of a 'joint'.* The undulating and striated groups formed about 25% and 15% respectively. The average steepest dip of the undulating fissure was taken for the purpose of measuring the dip of the surface. Some undulating fissures were striated, the striations or slickensides usually being aligned parallel to the steepest dip direction. Where the striations were not parallel to the steepest dip, the dip reading was made parallel to the steepest dip of the surface.

* All fissures are either joints or tiny faults if they have some visible movement parallel to their surface; but not all joints are fissures as they may be too large in extent to accord with the working definition of fissures.

In the Mangla laboratory a limited number of tests on scrapings of no more than 2 mm thick of the slickensides surfaces of plane fissures showed liquid limits about 5% higher than the parent clay. The striations on fissures occasionally indicated movement direction (in the same fashion as ice striae on glaciated hard rocks) and a contour diagram of the striated fissures from one location (Fig. 10(b)) indicated the majority of striated fissures as being parallel or sub-parallel to a relatively large fault nearby. This suggests that slickensides are formed by relative movement on the opposite walls of the fissure in the same way as slickensides on fault planes or slickensides developed on clay faces in shear box tests (Skempton, 1964, Figs 5 and 20). White (p. 569) states, 'slickensides probably have as their origin, the same factors that produce syneresis cracks. The unit concerned, however, is thicker and slickensides are formed under continuous deposition and compaction of a clay . . . the clay would probably reach a point where (syneresis) cracks would begin to close by plastic flow, as one side of a crack would move against the other. The clay minerals would orient, giving the slick surface of the slickensides'.

As working hypotheses prior to the orientation study, it was considered that slickensides and fissures in general could be formed and modified by one or more different processes, viz.:

(i) formed at the time of deposition or soon after by syneresis and/or changes in the salt chemistry of the environment and deposit;
(ii) formed or modified some time later than (i) by in-situ physicochemical changes brought about by such agencies as ground-water, weathering or ion exchange;
(iii) formed or modified by tectonic (or earthquake) stresses during folding, faulting or shearing of the beds;
(iv) formed or modified by non-diastrophic processes,* e.g., drying, hill creep, rebound on unloading or stress release during erosion.

Modification was considered to mean reactivation of existing fissures by rubbing of opposite walls of the fissure surfaces against each other or chemical changes in their mineral composition; either or both of these processes causing change or the beginnings of change in alignment of the mineral grains on the walls of the fissure (cf. Skempton, 1964, p. 83).

A tentative classification of fissures was attempted on the basis of the orientation studies and it was found that three patterns could be recognized, and related to the possible methods of formation:

(*a*) random patterns, i.e. (i) and (ii) above;
(*b*) patterns with 'peaks' parallel or nearly parallel to relatively large folds, faults or shear zones, i.e. (iii);
(*c*) patterns with 'peaks' parallel or nearly parallel to the existing ground surface, i.e. (iv).

CONCLUSIONS

The following conclusions were drawn. They are only tentative, but are believed to hold good for the areas studied. More work should be done before they can be applied elsewhere:

(1) Fissures in clays lend themselves to field observation and measurement of their attitude.
(2) Fissured clays unaffected by weathering or by near-surface changes, in geologically undisturbed areas (e.g. without faulting, shearing or strong folding), have a random orientation of fissures. This type of fissure probably originates at an early stage in the formation of the deposit.

* Diastrophism: all the processes of deformation of the earth's crust, including folding, faulting, elevation and subsidence, related to mountain building. Non-diastrophic processes are those not directly related to mountain building, for example, weathering, hill creep or rock fall under gravity.

(3) Unweathered fissured clays in areas adjacent to faulting or in folded bedrock in which there has been some shearing, show preferred orientation of some of the fissures in directions which follow the fold, fault or shear pattern of the area. These fissures are undoubtedly related to tectonic stresses.

(4) Unloading caused by erosion can result in the formation of horizontal fissures or perhaps, more generally, of fissures parallel to the ground surface.

ACKNOWLEDGEMENTS

The work was undertaken as part of the programme of investigating the Mangla and Jari clays by Messrs Binnie & Partners, Consulting Engineers, Mangla Dam Project.

The author wishes to record his thanks to Messrs Binnie & Partners, Mr J. R. Gwyther, Chief Resident Engineer, and Mr Mir Bashar Khan, Project Director and Chief Engineer, for permission to publish the Paper, to Mr D. D. Wilson and other members of the laboratory and field investigation staff at Mangla for their enthusiastic assistance and to Professor A. W. Skempton for stimulating discussions and field visits.

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ABSTRACT

Part of the site investigation on the clay bedrock of the Mangla Dam Project from 1961-65 is described. The Project consists of an approximately $150 million civil and electrical work comprising the Mangla, Sukian and Jari dams and associated hydro-electric and flood control schemes.

The thesis is divided into two parts. Part I deals with the descriptive aspects, local and regional geology and field and laboratory techniques used during investigation. Special geometric techniques were evolved for study of the bedrock. Part II deals with the chronological development of the investigation programme and presents results and discusses findings.

The clay bedrock is part of the Middle (?) and Upper Siwalik System of the south-eastern region of the Potwar Plateau, West Pakistan. The clays occur as beds which may be up to 100' thick and continuous over many 1,000s of feet. They are interbedded with beds and lenses of sandstone or occasionally, of gravel. The Siwaliks were deposited in a freshwater environment, and in places have been overconsolidated by some 20,000' of sediment; they are folded and faulted by early Quaternary earth movement.

Clays are typically stiff to hard, fissured and heavily overconsolidated. Typical clay fractions range from 20-50% for the older clays on the west of the site and 20-60% for the younger clays on the east of the site. Activities are

usually less than 1. Of considerable interest and engineering significance is the tectonic shearing associated with the folding of the beds. The field and laboratory characteristics of the surfaces of tectonic shear planes and other discontinuities was extensively studied and results are presented for the first time. The sheared surfaces of clays usually show little or no peak strength.

Engineering properties of the Sukian clays, occurring midway between the Jari and Mangla clays, show both Jari and Mangla characteristics although differences are small Some weathering of the clays has occurred at Sukian where little erosion is taking place unlike Mangla and Jari where there is river action which is constantly removing surface clay.

20/2/1967

N

INFERRED FAULT

SUTUH ANTICLINE

THAROCHI

PUNCH RIVER

DADIAL

CHAOMUKH

HTL

KANGAR

JHELUM RIVER

1250

1200

1300

MIRPUR BASIN

SYNCLINE

KHAD RIVER

MIRPUR

SANDHAR

KANSHI RIVER

GADARI KALAN ANTICLINE

GADARI KALAN

DHANGROT

KUNBLI

THER CHAK

PLOT

KHUMAL

KALIAL BENS

MIRPUR GAP

LEHRI RESERVED FOREST

BABYAM

PEL KARIM

SULTANPUR

MANGLA

SUKIAN DYKE

MANGLA DAM

SPRINGS

JARI

KAS GUMA

JARI DAM

Fig. No. 8

CHANGHAR FAULTED FOLD

KALRI

JALTI

INDUS GANGES PLAIN

LEGEND

ALLUVIUM

- FLOODPLAIN TERRACE
- RIVER JHELUM TERRACES
- INDUS GANGES PLAIN ALLUVIA
- 'MIRPUR SILT'

BEDROCK

- 'BALA GALA GRAVEL' UPPER SIWALIK
- UNDIFFERENTIATED SIWALIK CLAYS, SILTS AND SANDSTONES

STRUCTURE

- INFERED FAULT
- FOLD OR FAULT/FOLD AXIS
- DIP / STRIKE OF BEDROCK
- VERTICAL BEDS
- GEOLOGICAL BOUNDARIES

TOPOGRAPHY

- VILLAGE
- TOPOGRAPHIC CONTOUR
- SEASONAL STREAM 'NULLA'
- PERMANENT RIVER

SCALE

0 5

MILES

(MAINLY AFTER THE GEOLOGICAL SURVEY OF PAKISTAN)

MANGLA PROJECT GEOLOGY PLAN

Fig. 4.