A study of hafir linings in Darfur Province, Western Sudan

Report No OD/10
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Hydraulics Research Station
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ABSTRACT The Democratic Republic of The Sudan, in common with many other countries, suffers from the major problem of maintaining adequate water supplies for both domestic and agricultural use. In the western Sudan, the wet season lasts for about four months. For the remaining two-thirds of the year, water is only available from a few shallow open wells and reservoirs, both natural (fulas) and man-made (hafira).

An experimental investigation was started in 1969 to assess the performance of four polythene and two compacted-earth linings as methods of reducing seepage in small hafira. It was set up under the auspices of the United Kingdom Ministry of Overseas Development in conjunction with the Rural Water Corporation of The Sudan.

Data were collected at the site at Lunya, near El Fasher in Darfur Province, from 1969 to 1976. Analysis of the data was performed in the Overseas Unit of the Hydraulics Research Station and the results are presented in this report. The seepage control capability of each type of lining is evaluated and the results are related to lining conditions observed during a site inspection carried out in 1976. An estimate is made of the useful life of each type of lining.

CONTENTS Page

TABLES

FIGURES

PLATES

CONTENTS (Continued)

PLATES (Continued)

1 INTRODUCTION

Geography of The Sudan 1.1

1.1.1 The Republic of The Sudan (Fig 1) is the largest country in Africa with an area of just over 2.5 million square kilometres. It extends from the northern boundaries of Uganda, Kenya and Zaire in the south to Egypt and Libya in the north. To the east lie Ethiopia and the Red Sea and to the west, the Republic of Chad and the Central African Republic. In 1966, it had a population of about 14 million people.

1.1.2 The southern Sudan consists essentially of a vast, shallow depression covered by a superficial deposit of clay. Beyond the clay plain is a plateau along which runs the country's southern boundary. The plateau is drained by numerous tributaries of the White Nile which flow generally north-eastwards across the clay plain.

1.1.3 To the north of the plain, across the central part of the country, an upland zone culminates in the highlands of Darfur on the west and the Nuba mountains to the east. Between these two lies an extensive region of sand-dunes (known as goz) which is an area of short savanna grass and acacia shrub.

1.1.4 To the north of the goz are the extensive Libyan and Nubian Deserts which are sandy and rocky respectively. These cover most of the country to the north of Khartoum.

1.1.5 This report describes some experiments into methods of water storage which were carried out in the western Sudan at Lunya, about 20 km from El Fasher in Darfur Province.

The need for water storage 1.2

1.2.1 According to data published in January 1977[1], the annual drinking water requirements for human and animal populations in 1975 amounted to 335 x 10^6 cubic metres. From this amount about 86 x 10^6 cubic metres were needed for human supply, and the remaining 249 x 10^6 cubic metres for animals. The supply available from boreholes came to about 16 x 10^6 cubic metres per annum. A similar quantity was available from hafira and small dams, and shallow wells supplied about 2 x 10^6 cubic metres. An additional supply of 30 x 10^6 cubic metres from natural sources brought the total amount then available to 64 x 10^6 cubic metres, ie 20 per cent of the demand. The deficit was partially reduced in three ways:-

a) During the wet season, water was available from fulas (natural depressions) for human and animal consumption.

b) In the dry season (November to May) nomadic communities migrated to areas of permanent natural water such as the Nile.

c) Some water was available during the dry season from shallow, open wells.

However, these sources could not remove the deficit entirely with the result that there was (and still is) a serious water shortage in the region.

Development of hafira in The Sudan 1.3

1.3.1 A Hafir (from the Arabic Hufra – a hole; plural – Hafira) is by definition a small depression or excavation where water is stored during a wet season for use during the following dry season. Organised hafir construction started in The Sudan in about 1946. They were shallow excavations dug in natural clay pans which were subject to seasonal flooding. About 500 hafira were constructed to this design during the first 20 years, many of which were shown later to have only a short useful life.

1.3.2 In 1966, responsibility for the hafir construction programme was taken over by the newly created Rural Water and Development Corporation (RWDC). Many advances in design and construction techniques were made by the Corporation which by 1969 had in Darfur Province alone, 88 hafira with a gross capacity of 3.3 million cubic metres[2]. (The corresponding figures for the whole of The Sudan were 684 and 13.8 respectively). By 1976, this had further increased to 850 unlined and 7 lined hafira. The storage capacities of the lined hafira ranged from 15 to 60 x 10^3 cubic metres.

Background to the project 1.4

1.4.1 In 1968 a group of consultants, assigned by the Ministry of Overseas Development (ODM) of the United Kingdom, visited the western Sudan to study the water supply problem. They formulated a survey and development programme for central Darfur which was published the same year[3]. The terms of reference required the provision of new water supplies from underground sources where possible. Only where these were not available were dam and hafir schemes to be investigated. It was anticipated that the surface-water development would comprise three dams and ninety-nine hafira.

1.4.2 It was agreed that more details were required of the behaviour of a number of possible hafir lining techniques. A seepage-control experiment was therefore included in the programme of surface-water investigations. It was proposed that the research installation be sited at Lunya near to the project headquarters at El Fasher.

1.4.3 A description and the results of these studies were published in a series of reports [3, 4, 5, 6] between 1968 and 1970, with a further special report in 1973[7].

1.4.4 In 1975, ODM suggested that the Overseas Unit of the Hydraulics Research Station (HRS) would be interested in the final results of the Lunya experiments. In collaboration with the RWDC (now the Rural Water Corporation (RWC)), a brief preliminary visit was made by a member of the Unit in January 1976. This was followed by an inspection of the hafira linings in March 1976 in the presence of another member of the Unit's staff. Analysis of all the site data obtained during the 6 years of the experiment was started at HRS in May 1976 and the results are given in this report.

2 DESIGN AND CONSTRUCTION OF THE EXPERIMENTAL HAFIRA

Hafir construction details 2.1

2.1.1 A total of 7 hafira were constructed at Lunya. Details of the layout together with a typical cross-section are shown on Fig 2. Hafira A, B, C, D and E were nominally of 3.5 m finished depth with top dimensions of 31 metres by 27 metres, side slopes of 3:1 and end slopes of 4:1. Hafira F and G had a nominal finished depth of 4.0 metres with top dimensions of 40 metres by 32 metres, side slopes of 2½:1 and end slopes of 4:1. The distribution channels were brick-lined and laid to ensure that the hafira were filled by gravity. The hafir supply was diverted from wet-season run-off that ponded behind an existing weir and bund on the main wadi. Some settling of sediment was provided for in an excavated forebay. The inlet pipeline could be closed by a sluice valve to prevent loss of water from the hafira.

2.1.2 Details of the types of linings are given in Table 1 and a description of the methods employed to lay them is given in Ref 4. Photographs in Plate 2 were taken during the construction and are included by permission of ICI.

Lining design 2.2

2.2.1 The installation was designed to test three types of membrane lining (hafira A, B and C), two types of clay lining (hafira F and G) and one combination clay and polythene lining (hafir D). Hafir E was unlined and acted as a control.

2.2.2 Hafir A was lined according to the recommendations of the polythene manufacturer. These have since been amended and the current practice is to use 381 micron sheet as the waterproofing (top) membrane [8].

2.2.3 Particular attention was paid to the problem of termite attack. A relatively non-toxic chemical insecticide (Gammexane 26DP) was used in hafira A, B and

C to minimise any termite activity near the membranes. Application of the insecticide was limited to below the waterproofing membrane – for safety reasons, the insecticide was not applied above the top membrane at any time.

2.2.4 The top membranes of these hafira (A, B and C) were also protected from accidental damage by a 0.25 m thick layer of silty or clayey sand.

2.2.5 The "sandwich" design, with an insecticide slurry retained between two membranes, was investigated in hafira A and C. The insecticide was expected to remain active until released by a puncture in the lower membrane. It was hoped that the process would be gradual and that it would give some measure of long-term protection.

2.2.6 The compacted earth linings (hafira D, F and G) were tried because at, or near most potential hafir sites there is some clay available. It should be noted, however, that this type of massive clay lining in hafir F requires strict control of the moisture content during laying. This is necessary to counteract any shrinking or cracking. Hafira D and G used thinner clay layers with either polythene (hafir D) or silty sand to stop the clay from drying out too fast.

Comparison of design and survey geometry 2.3

2.3.1 The hafira were surveyed prior to the exposure of the linings in March 1976. The surveys were conducted by RWC and observed by a member of the Overseas Unit who returned with the original survey drawings. Levels were taken at half-metre intervals across the major (x) and minor (y) axes of hafira A, B and C and across the minor axes of D, E, F and G. Inspection of these sections showed that the trapezoidal design had changed to a broad Vee shape, although the side slopes away from the bases were near to the design.

2.3.2 Base levels and hafir dimensions provided by the surveys are presented in Table 2. Throughout this report, full or maximum depth is the difference in level between the hafir base and the top of the inlet pipe well (see Fig 2b).

2.3.3 Survey data obtained in 1969 by the engineering consultants was compared with that obtained in 1976. The data consisted of spot heights at the top and bottom of the slopes for all hafira, except B and C. The comparison confirmed that the hafir shapes had not changed since their construction. The earlier data could therefore be used to supplement that obtained in 1976 where required.

Numerical analysis of bed level data 2.4

2.4.1 Using the survey data, various geometrical quantities were computed on the assumption that the open-water surface approximated to an elipse at all levels. These values are given in Tables 3 and 4 together with the design values. It can be seen that all the hafira were made larger than was required by the design. Use of the survey rather than the design data made the computation more difficult, but it is believed this resulted in a more realistic water-balance equation.

3 LABORATORY ANALYSIS OF LUNYA SUB-SOILS

Grain size analysis 3.1

3.1.1 No in-situ testing was performed but indirect estimates were derived using data from disturbed samples. Some samples were collected in 1969 specifically for grain size analysis[4]. More samples were obtained in 1976 from intermediate depths in three hafira and each set of samples was subjected to standard particle size analysis (Figs 3 and 4). The silt and clay fractions (below 0.002 mm) ranged between 20 and 65 per cent by weight. Particle sizes of the silt fraction were determined by the "fall-velocity" method[9]. The results of this analysis are summarised in Table 5 from which it is apparent that the residual clay fractions were high, 10 to 25 per cent by weight.

3.1.2 It is important to appreciate the distinction between particle size and grain size, for it is the latter which controls the hydraulic conductivity. In the sand fraction, grain and particle size are equivalent but this is not the case for the silt and clay fractions. For the Lunya soils it is probable that most of the clay particles would be present in either an aggregated or cemented form. This would tend to reduce the ability of these fractions to control the hydraulic conductivity and hence reduce seepage.

Analysis of clay fractions 3.2

3.2.1 Two samples with clay fractions of 20 and 25 per cent by weight (numbers A3 and B2 in Table 5) were selected for analysis. The samples were examined by standard techniques [10] in the Sedimentology Laboratory at HRS.

3.2.2 The first determination was cation-exchange capacity (C) which provides a crude differentiation between the major types of clay minerals. For consistency, two successive size fractions were separated from each sample. The results are given in Table 6a. Each of the size ranges contained a proportion of non-active minerals such as quartz; to obtain values of C for the pure clay, the determined values must be increased in proportion to the quantity of clay per sample. The pure clay or "adjusted" values are also given in Table 6a. Exchange capacities of the major clay groups[11] are presented in Table 6b for comparison. This shows that there is a high proportion of montmorillonite clay in the Lunya sub-soils. This group is characterised by volumetric expansion with the absorption of water – a "swelling" clay.

3.2.3 A further laboratory examination found that the dominant cation in the samples was calcium. It is therefore probable that the main clay type in the Lunya sub-soils is calcium montmorillonite.

4 ANALYSIS OF SEEPAGE DATA

Acquisition of basic data 4.1

4.1.1 The primary experimental measurement was the water level in each hafir. This was taken by putting a dip-stick into the inlet-pipe well until a stop on the stick rested on the well lip (see Fig 2b). The end of the stick was 3.4 m below this point. For hafira F and G, the minimum depth recorded was 0.5 m because the dip-stick was too short to reach the water below this level.

4.1.2 No measurements were taken during the wet season from about June to October. Daily readings were started when the supply valve was finally closed, and these continued until the start of the following wet season. At the same time, meteorological data were collected from the following instruments:-

a) Class "A" evaporimeter, standard open pan

b) Class "A" evaporimeter, standard screened pan

c) Piché atmometer

d) Totalising anemometer

e) Hygrometer, wet and dry bulb thermometers (unsheathed type)

f) Maximum and minimum thermometers

Temperatures of the air and the open-pan water were also measured, and an estimate was made of cloud cover. All this data were collected at about 0930 every day.

4.1.3 The evaporimeters were filled to a prescribed level (indicated by a fixed point gauge) each day using large and small cups. The large cup was 11 cm in diameter and 11 cm deep, the figures for the small cup were 6 cm and 4.2 cm respectively. Items (c), (e) and (f) were placed in a standard meteorological screen. All the meteorological instruments were placed approximately in the centre of the site within a few metres of each other (Plate 1).

Calculation of seepage losses 4.2

4.2.1 In order to determine the seepage losses through each hafir lining, the following relation was used:

$$(V_{i-1} - V_i) = \Delta V_i = B_i + E_i + G_i + Q_i \qquad \text{...... (1)}$$

where:

ΔV_i is the incremental change in stored volume on day i

B_i is the total domestic abstraction

E_i is the open-water evaporation

G_i is the capillary (or closed-water) evaporation

Q_i is the seepage

This equation describes the water balance in any hafir.

4.2.2 The volumetric term was computed from the equation

$$\Delta V_i = (Ao_{i-1} + Ao_i)\ (HW_{i-1} - HW_i)/2 \qquad \text{...... (2)}$$

in which the values of Ao (water surface area) were obtained from the survey data and HW was the water level reduced to site datum. The values were found for incremental steps of HW of less than 0.1 m.

4.2.3 The abstraction term, B_i, was taken from the observer's records. He noted the number of "tins" of water which he used each day and the hafir from which they were taken. (1 tin is approximately 4½ litres).

4.2.4 E_i, the open-water evaporation term, was computed using daily evaporimeter data collected by the observer. The problem of estimating E_i for the experimental hafira was a severe one. A number of methods were considered before finally deciding to use the pan data with a suitable coefficient:-

$$Eh_i = Co_j\ Ep_i \qquad \text{...... (3)}$$

where h_i denotes values for a hafir on day i, p_i denotes values for a pan on day i and Co_j is the pan coefficient for month j. The values for Co_j were based on evidence from larger evaporimeters. The evaporation from pans has been found to reach a limiting value at a diameter of about 4.7 m (12 ft). It is considered that, at this size, the evaporation approximates to that from a lake of up to 5 to 10 hectares and 5 m deep. Table 7 gives results comparing mean monthly conversion factors for the Class "A" pan to 12 ft diameter sunken tanks[12, 13]. The site at Lunya is on latitude 14°N and it has a very similar climate to that of Khartoum, – the maximum variation occurs between May and August when the experimental hafira were dry. The monthly pan coefficients recorded at Khartoum may, therefore, be applied to the Lunya data. (Using a constant value of 0.7 throughout the dry season would result in a maximum error of only 13 per cent in February).

4.2.5 An empirical formula for the capillary evaporation term given by the consultants [6] and converted to present notation, showed that

$$G_i = K\ \overline{P}_i\ Co_j\ Epo_i \qquad \text{...... (4)}$$

where $\overline{P}_i$ is the mean water surface perimeter during day i. In their final report in 1973[7], the consultants calculated a value of K = 0.70 from data collected at hafir B. For this, they assumed that the seepage was zero. A detailed study of the processes involved in the natural drying of a soil surface has shown that, for the backfill used at Lunya, K = 0.72. The equation for capillary evaporation therefore becomes:

$$G_i = 0.72\ \overline{P}_i\ 0.65\ Epo_i \qquad \text{...... (5)}$$

5 DISCUSSION OF RESULTS

Definition of terms 5.1

The results of the water-balance computations (see equation 1) are summarised in Tables 8 and 9. The various column headings are defined as follows:-

a) Volume: the initial stored volume at the start of the season expressed as a percentage of the hafir capacity at maximum water level.

b) Evaporation, open: the total volume lost from the hafir during the season by evaporation from its open-water surface, expressed as a percentage of the initial stored volume for that season.

c) Evaporation, closed: the total volume lost from the hafir during the season by capillary evaporation from the exposed margins of the hafir bed, expressed as a percentage of the initial stored volume for that season.

d) Seepage: the total volume lost from the hafir by seepage through the lining, expressed as a percentage of the initial stored volume for that season.

Performance of polythene-lined hafira 5.2

5.2.1 The results are given in Table 8. They are also plotted in Fig 5 in which the values for hafira A, B and C are shown in green. (Hafir D is included in the clay-lined group since the polythene was intended to stop the clay from drying and not act as the waterproof membrane).

5.2.2 These values show that the proportion of seepage increased annually in all three hafira. At the start of each season these hafira were more than three-quarters full, the progressive trends therefore relate to the lining of the entire hafir basin rather than to different parts of it.

5.2.3 In the first season of tabulated results, 1970-71, the seepage losses were less than a quarter of the original stored volume. For hafir A this was the first dry season after filling, and the second season for hafira B and C. The latter two were filled during the 1969 wet season when the seepage losses were 32 and 21 per cent respectively. Hafir B required extensive repairs during the 1970 dry season before its second filling. For hafir C, the 1969-70 result was the lowest recorded from it, implying that subsequent repairs were either not carried out or negligible for this hafir. The lining efficiencies for all three hafira were therefore greater than 75 per cent in their original reference states.

5.2.4 In 1974 the rainfall was well above average and, more significantly, it was concentrated in two months. This can be correlated to the anomalous reversals in the lining performance of hafira B, C and E. For the latter, the reduction in seepage is attributed to temporary crack closure of the loosely compacted sub-soil. In hafir C the effect was quite marked and is considered due to swelling of the silty clay soil. This effect of an expanding clay fraction was less pronounced in hafir B but bulk differences in soil cover were noted during the lining inspection.

Performance of clay-lined hafira 5.3

5.3.1 The results of data analysis for the clay-lined hafira are given in Table 9 and Fig 5 (red lines). The true clay-lined hafira, F and G, had capacities of approximately two and a half times that of the control. At the start of the first two seasons, F and G were only partially filled. For comparison purposes, the seepage data has been extrapolated up to that which could have occurred had the hafira been full. Fig 5 shows that hafir F, with 0.75 m of sandy-clay, behaved in a similar fashion to the unlined control, hafir E. Hafir G, lined with a mixture of sandy and compacted clay 0.5 m thick, had an even greater seepage rate for the first four seasons. In 1974-75 and 1975-76 the seepage losses from hafira E, F and G are all within a range of 15 per cent. This implies that there is no advantage to be gained by lining a hafir with imported clay.

5.3.2 Hafir D shows a steady deterioration throughout its operating life (1974-75 was the last working season for this hafir). Up to the 1974-75 season, hafir D followed the same basic trend as the polythene-lined hafira. It is thought that after 1974-75 the membrane would have deteriorated to such an extent that the clay lining would have the major effect and the values of seepage loss would be similar to F and G.

Relative lining efficiencies 5.4

5.4.1 Consideration of relative efficiencies for all the hafira must refer to the seepage from the unlined control hafir E (shown in black on Fig 5). At the start of the 1970-71 and 1971-72 seasons this hafir was only 18 and 37 per cent filled respectively. The seepage rates which could have occurred had the hafir been full have been calculated by extrapolation based on the data for the remaining four seasons. Fig 6 shows the efficiencies for the various linings relative to the unlined control (hafir E). For the hafira with polythene membrane linings, the average initial gain was approximately 50 per cent. After the third dry season, their relative efficiencies were reduced to only 25 per cent. The last two seasons gave further reductions with all three linings at about 10 per cent efficient. For all practical purposes it is evident that the advantage gained by even the best lining was negligible after only five seasons of undisturbed use. (Hafira F and G showed a slight improvement after 1974).

5.4.2 The combination polythene and clay-lined hafir follows a similar pattern to that described above. This figure demonstrates even more clearly that the two clay linings were completely ineffective in controlling seepage. During the final season the performance of all the linings was practically identical.

5.4.3 The variation of net gain with time during two dry seasons is shown in Fig 7 for hafir A. The relative net gain was found by subtracting the percentage of original stored volume remaining in the control hafir E from the corresponding value for hafir A. This was done at 5-day intervals throughout the 1972-73 and 1974-75 seasons. The figure shows that the seepage pattern is approximately the same for both seasons with a difference of 15 to 20 per cent between the two. It can be seen that the maximum gain to storage occurs about one month after filling. After this, there is a steady reduction to the end of the dry season.

Summary 5.5 There was no real advantage achieved by a lining of any type within five years from construction. It has been demonstrated that total seepage losses eventually matched that from the unlined hafir for all lining designs. The progressive deterioration of the polythene-lined hafira ultimately reduced their relative efficiency to only 10 per cent. The clay linings appeared to permit even higher seepage losses than the unlined control, except in the last two seasons of the experiment.

6 INSPECTION OF LININGS, MARCH 1976

General comments 6.1

6.1.1 The first visit to the site in March 1976 gave the impression that it had been allowed to deteriorate to some extent. A high proportion of the land surrounding the hafira, within the perimeter fence, was covered with grass and a thistle-like plant which produced sharply spiked seeds about 5 mm in diameter. There were also a number of plants with stems up to 30 mm thick growing more than a metre high. These were spread all over the site and were also found to be growing in the hafir backfill in some places.

6.1.2 The original report from Sir Murdoch MacDonald and Partners[4] suggested that the area should be kept free from plant growth. The site, however, reproduced fairly closely the conditions which prevailed at a working hafir. It is therefore thought that the seepage data are much closer to the true hafira than would have been the case had the site been totally cleared.

6.1.3 The original plan had been to remove all the backfill from the hafira and to make a detailed survey of the damage. It was soon apparent, however, that in order to minimise accidental damage to the buried linings during these operations, the work would be very slow. It was therefore decided that diagonal strips of backfill about one metre wide would be removed across each hafir. The backfill varied in each hafir but was generally baked hard and required a variety of metal tools for its removal (Plate 3). The following notes were compiled for each hafir:

Hafir A 6.2 In two places the backfill had slipped to expose the upper membrane. One slip covered about 1 m^2 (Plate 4) and the other was half this size. Removal of the soil cover was apparently due to erosion during the wet season since, at the time of the inspection, the backfill was baked hard. In the exposed strip of lining, two roots were found growing through the membrane at about 5 m and 14 m from the top of the hafir (Plate 5). The growth seemed to have started below the membranes within the sub-soil. A number of joints (for details of joint construction see Fig 2c) were uncovered throughout the length of the inspection trench. Most of these joints were intact with the internal mastic-polythene joint unbroken, but the adhesive tape was generally degraded (Plate 6). In some places, adhesion between the mastic tape and the polythene was negligible. The joint between the plastic membrane and the inlet/outlet pipe showed no signs of deterioration. At one of the joints, some fine roots had grown up through the overlap between two adjacent plastic sheets. Removal of the upper membrane exposed an extensive root system in the insecticide slurry layer (Plate 7). The eastern quarter of the lining was eventually uncovered exposing the pattern of jointing (Plate 8). This uncovered a joint which had obviously been damaged during laying and had subsequently been repaired (Plate 9). It was concluded that observations in the initial trench were representative of the whole area.

Hafir B 6.3 The general impression of the lining exposed in the trench was that the single membrane was more damaged than in hafir A. A view of the trench cut along the western diagonal is shown in Plate 10. There were seen to be a large number of small holes in the polythene with fine roots growing through them; these holes appeared to be enlarged round the roots. Seven large roots had grown through the membrane on the eastern diagonal compared with three on the same slope in hafir A. In each case the hole appeared enlarged in relation to the root size (Plate 11). A sample of the holed lining was taken from a further site 12 m down the diagonal (Plate 12). Three of the five joints which were uncovered had pulled apart. As in hafir A, the edges of the adhesive tape were degraded. At the top of the trench a joint had completely opened (Plate 13) and a sample of the mastic tape was taken from this site (Plate 14). At the inlet/outlet pipe, the condition of the plastic-to-concrete seal was found to be very good (Plate 15).

Hafir C 6.4 The inspection trench was excavated transversely in this hafir. Both membranes were found to be in an extremely damaged state. A general view is given in Plate 16 and a closer view of the north-west face is shown in Plate 17. A sample of the upper membrane, taken from near the top of the slope, is shown in Plate 18. The degree of damage appeared to increase upward from the base of the hafir and it was so severe that even the location of joints was difficult.

Hafir D 6.5 This hafir had ceased to function during the 1975-76 season due to complete blockage of the inlet pipe by backfill. Plate 19 shows the north-east face of the hafir where the polythene membrane was uncovered as a result of erosion of the backfill. An area of large holes was found about 3.5 m down the hafir, one of which is shown in Plate 20. Another group of holes was found on the floor of the hafir. Most of the joints had failed to some extent and there was noticeable stretching of the membrane near them. A sample of the adhesive tape, showing considerable damage along its edges, is shown in Plate 21.

Hafir E 6.6 A general view of the control hafir is shown in Plate 22. The surface was covered with plant growth and there were a number of places where the surface material had cracked and slipped (Plate 23). No excavation was performed in this hafir.

Hafira F and G 6.7 In each hafir, the surface had cracked and could be lifted in pieces about 30-50 cm^2 and 2-4 cm thick. A hole was dug in each lining (Plate 24) about half-way down the slope. It proved very difficult to distinguish the boundary between the imported clay and the natural sub-soil. No large cracks were noticed in the lining material and digging obscured any smaller ones.

7 MEMBRANE LININGS : FAULTS AND FAILURES

Construction faults 7.1 From the observations reported above it is possible to identify a number of different types of lining damage. It is not, however, possible to place them in any order of relative importance. There were inevitably some punctures made in the lining during the installation and, where detected, these had been repaired. The repairs had obviously remained intact, except where the adhesive had been uncovered for a long period, as had those to faulty joints. The degree of unrepaired puncturing of the membranes is indicated by the seepage calculated for hafira A, B and C during their first year of operation. It may be assumed that 10 to 20 per cent seepage loss represents the maximum effect of construction faults.

Mechanical failure 7.2

7.2.1 Mechanical damage to the joints and membrane may be related to the stability of the backfill. An increase in the water content of the soil would decrease the shear strength and ultimately result in a slide. Conversely, a decrease in water content would increase the shearing stress transmitted to the membrane, which could be ruptured if the backfill moved. The presence of water as an external hydrostatic load would, however, increase stability of the backfill.

7.2.2 Intense rainfall on an empty hafir could therefore result in a catastrophic failure of the backfill. This, in fact, occurred in hafir D during August 1975. The relatively thin and sandy soil was removed from large areas near to the top (Plate 19). The many joint failures observed in the hafir are assumed to date from this event. Hafira A, B and C remained stable during this period and opened joints were confined to areas near the top of the hafira (eg hafir B, Plate 13).

7.2.3 To minimise the chances of mechanical failure, most of the sheets were placed loosely with many creases. The failures in hafir D were, however, of major importance and emphasise that slope design must be based on established methods of stability analysis.

7.2.4 A sample of the buried lining collected from hafir B was tested by the manufacturer's laboratory. It was found to be in practically perfect mechanical condition with an average tensile strength of 151 kg/cm^2 and elongation of 73.0 per cent. This showed that no mechanical or chemical degradation had occurred after seven years service in the Sudan climate. To maintain this high standard, it is essential that the plastic be protected from ultra-violet radiation.

Biological failure: plants 7.3

7.3.1 Typical plant damage is shown in Plate 11. Most of the larger plants appeared to have originated below the membranes and to have grown through the loosely-compacted backfill. In all the hafira, the membranes were penetrated by a network of fine roots. Samples from the insecticide slurry contained a significant proportion of organic matter including seeds that were not decayed or eaten.

7.3.2 The question of whether the plant growth created perforations in the lining or only occurred through existing holes, remains unresolved.

Biological failure: termites 7.4

7.4.1 There are basically two types of termite, "dry wood" and "soil". It was known at the start of the experiment that sub-surface membranes were liable to be damaged by soil termites and that the degree of damage depended largely on the hardness of the material. It was anticipated that the polythene membranes at Lunya would be attacked and destroyed sooner or later. This stimulated the use of insecticides to give protection for as long as possible. However, no estimate could be made of the effective life of this protection[14].

7.4.2 It was assumed that termites were responsible for most of the holes found in the membranes although no termites were found during the excavations. The only identifiable traces of termite activity were tunnels above and below the membranes and rudimentary (unoccupied) nests. Microscopic examination of a thick-gauge sample of polythene from hafir B (Plate 12) revealed well defined jaw marks which could have been made by either a coleopteran (beetle) or isopteran (termite)[15]. It was noted that the jaw marks were evenly distributed around the hole, consistent with it being chewed rather than perforated. Damage to the thin membranes of hafir C was superficially different. Expert examination of a large sample (Plate 18) confirmed that it was typical of large scale, termite damage.

7.4.3 In all hafira, the adhesive tape was found to have been damaged in a way which suggested termite attack (Plate 21). Damage to the mastic tape was not so obvious (Plate 14). It was noted that the exterior adhesive tape was, in places, degraded while still attached to undamaged polythene. This suggests that the termites could be attracted to it for food, a possibility which requires further expert investigation.

7.4.4 All the on-site observations were reported by non-specialists in termite life-history and were based on comments made by the resident Sudanese engineers. In spite of these uncertainties, the balance of evidence shows that termites were the dominant cause of membrane lining failure.

Insecticidal protection 7.5

7.5.1 The specifications (produced between 1963 and 1968) were based on the known persistence of insecticides in domestic and agricultural applications[4]. Chlorinated hydrocarbons (such as DDT) are widely used to prevent termite attack of both crops and buildings. The basic idea behind this method of control is to make a soil environment in which termites cannot exist. This concept was extended to membrane protection on the assumption that the termite attack would originate below the linings.

7.5.2 Samples of hafir slurry and sub-soils were obtained after the linings were partially exposed in March 1976. They were analysed by ICI Ltd to determine the level of residual active insecticide. The results are produced in Table 10 where the concentrations are expressed in parts per million of dry weight of soil (ppm). Residuals of gamma-BHC were detected in all samples but at generally "low" levels. Estimates were made of the initial concentrations of insecticide using data from the Interim Report[4]. These indicated that the initial insecticide concentration in the slurry was approximately 760 ppm and in the sub-soil, between 40-70 ppm. The low levels found in 1976 were not unexpected since gamma-BHC was chosen because of its gradual environmental decomposition. It is also probable that the insecticide was dispersed vertically by seepage water passing through the linings. It is, however, unlikely that the concentration would have reduced sufficiently during the first three years to allow a termite attack from below the membrane capable of making a three-fold increase in the seepage (see Table 8).

7.5.3 A second mode of termite attack occurs at the founding of a colony. A pair of winged adults may fly many kilometres before establishing a new nest in soft, moist soil. From the nest, passages are dug vertically down for a distance of 1 to 2 metres. It is suggested that the Lunya membranes were also attacked in this way. The attack would occur spasmodically during all wet seasons and would obviously not be repelled by insecticide below the membranes. At the start of each wet season all the hafir beds were exposed after the rain and so this mode could be randomly distributed throughout the depth. Although the lining inspections were limited, it is unlikely that any potential termite colony survived the inundation at the end of the wet season.

7.5.4 If this general hypothesis is accepted, it is impossible to protect any flexible, buried membrane from termite attack.

8 CLAY LININGS: FAULTS AND FAILURES

Construction faults 8.1

8.1.1 Figure 6 shows that the clay linings of hafira F and G did not significantly control seepage at any time. This is thought to be mainly due to incomplete compaction of the clay during construction. Soil compaction is normally controlled by reference to a standard laboratory test such as Procter. These procedures do not appear to have been followed with a significant degree of precision at Lunya for various practical reasons. There remains little doubt that the initial state of the clay linings was seriously impaired as a result. Prior to the 1974 wet season the conductivity of the thick clay lining (hafir F) exceeded 0.004 m/day compared with a properly compacted value of about 0.00005 m/day. For the thin clay (hafir G) the value exceeded 0.008 m/day. This is further evidence that compaction was undeveloped in the clay layers, a construction fault which dominated their subsequent performances.

8.1.2 After completion in 1969, the entire linings were exposed to atmospheric drying for almost a year. The upper zones were not submerged until more than four years after construction and this prolonged exposure evidently produced some penetrative cracking of the upper zones. In 1974 the rainfall was well above average and was concentrated in two months. The upper zones experienced prolonged wetting during this period of low evaporation and the cracks formed in 1969 apparently closed. This reversal was maintained, notably in the lining of hafir G, which signifies that this type of lining is not irreversibly damaged by drying.

Hafir D – composite lining 8.2

The explanations developed for the deterioration of the membrane and clay linings must apply equally to this hafir. The gross performance of this combination lining was parallel (in most respects) to that of hafir A, except that its initial reference state was considerably worse. The rate of seasonal degradation was, however, much slower in hafir D.

9 GENERAL DISCUSSION AND SUMMARY

Membrane linings: discussion 9.1

9.1.1 The Lunya experiments have demonstrated that the useful life of these linings in small hafira is less than five years. They proved to be extremely vulnerable to termite attack in spite of the use of insecticide. The results have shown that only a small degree of perforation of the membrane is needed to reduce the control of seepage to minimal proportions. The intensity of damage by termites and plants varied considerably between the hafira but the net effects were identical. The thickness of the membrane did not prevent penetration but did reduce the scale of attack.

9.1.2 Previous experience in The Sudan includes failures of polyvinyl chloride, polythene and butyl linings that were all attributed to termites. A 1.25 mm thick butyl lining failed in a prototype hafir of 7500 m^3 capacity[16] and there is no obvious reason why the modes of attack identified at Lunya should not occur in even larger hafira.

Membrane linings: summary 9.2

9.2.1 The polythene membrane linings installed in four of the experimental hafira at Lunya deteriorated progressively and rapidly.

9.2.2 Their initial gross seepage losses were 10 to 20 per cent of storage capacity – these increased to final values of 60 to 70 per cent after 7 wet seasons.

9.2.3 The advantages gained by the best linings were negligible compared to the unlined hafir after 5 seasons of continuous use.

9.2.4 A regular increase in seepage rates from all water depths in the hafira occurred from season to season.

9.2.5 Inspection of sections of linings exposed in March 1976 revealed a variety of membrane perforations.

9.2.6 The polythene fabric was found to be in perfect structural and mechanical condition after 7 years service.

9.2.7 Joint rupture was restricted and confined largely to one hafir whose thin soil cover was probably moved by intense rainfall in August 1975.

9.2.8 The membranes were damaged and perforated by termites.

9.2.9 Termite attack was amplified by plant attack – root and stem systems were seen to have penetrated membranes and joints.

9.2.10 Insecticidal protection provided no defence against termite attacks in successive wet seasons.

9.2.11 Residual insecticide concentrations were 0.1 to 1 per cent of those originally applied 7 years previously. Dispersion by seepage water probably occurred in addition to chemical degradation.

Clay linings: discussion 9.3

9.3.1 The linings of hafira F and G and the compacted earth element of hafir D cannot be described as failures because they did not deteriorate. Their failure to function as seepage control layers resulted more from inadequate compaction during construction. The most notable feature of these linings were their ability to reduce seepage by slow swelling of the clay. They also resisted structural disruption and loss of shear strength during a long series of wetting and drying cycles.

9.3.2 Previous reported experience with compacted earth linings in The Sudan is limited to that from an experimental hafir near Semieh in Kordofan Province[17]. A 7500 m^3 hafir was constructed in sandy soil to a depth of 6 m. It was lined with a 0.75 m layer of clayey sand. The optimum moisture content (determined by laboratory testing at Khartoum University) was very low and was maintained during field compaction. The performance of the hafir during its first dry season was such that two-thirds of its stored volume was lost by seepage[16] – a similar result to that obtained in the last two seasons in hafira F and G at Lunya.

9.3.3 It can be concluded that a compacted earth lining may be feasible and that a fine sand mulch (type G) could prevent cracking during the dry seasons. However, unless proper construction practices are evolved and rigidly adhered to, these linings will have little effect on the control of seepage.

Clay linings: summary 9.4

9.4.1 The compacted earth linings in two of the experimental hafira at Lunya did not produce useful seepage control at any time.

9.4.2 Their lining efficiency relative to the unlined hafir never exceeded 10 per cent and was virtually zero in all seasons but the last.

9.4.3 Hydraulic conductivity at high levels above the base of these hafira reduced by a factor of almost 5 after the abnormally high rainfall in 1974-75.

9.4.4 A major factor contributing to the failure of the earth linings was the result of failing to follow established construction practices, eg compaction procedures.

9.4.5 Penetrative cracking of the linings was not responsible for their inefficiency. Prolonged wetting in 1974 produced closure of the surface cracks developed by desiccation.

9.4.6 Performance of the composite lining, – clay protected by an anti-drying polythene membrane – was better than the exclusive membrane or clay. The backfill was, however, too thin and was unstabilised during the heavy rain of 1975.

9.4.7 Application of established principles of foundation engineering confirm that construction of efficient earth-lined hafira is technically possible.

9.4.8 Laboratory analysis of clay fractions from Lunya sub-soil reveal that the dominant clay mineral is a calcium montmorillonite of high ion exchange capacity.

9.4.9 If systematic research confirms the general distribution of this mineral in The Sudan, the production of artificial "bentonites" is a distinct possibility.

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DDB. Dd 650449 9/77

TABLES

TABLE 1

Hafir elements tested at Lunya

(Taken from reference 5)

Hafir	Description of Lining		
A	Ground Treatment	–	240 grams of Gammexane 26DP in 227 l of water per 100 square metres.
	Lower membrane	–	63.5 μm polythene taped at joints.
	Slurry/insecticide	–	320 grams of Gammexane 26DP in 150 l of mud slurry per 100 square metres.
	Top membrane	–	254 μm polythene mastic sealed and taped at joints.
B	Ground treatment	–	400 grams of Gammexane 26DP in 227 l of water per 100 square metres.
	Lower membrane	–	None
	Slurry/insecticide	–	None
	Top membrane	–	254 μm polythene mastic sealed and taped at joints.
C	Ground treatment	–	240 grams Gammexane 26DP in 227 l of water per 100 square metres.
	Lower membrane	–	63.5 μm polythene taped at joints.
	Slurry/insecticide	–	320 grams Gammexane 26DP in 150 l of mud slurry per 100 square metres.
	Top membrane	–	63.5 μm polythene mastic sealed and taped at joints.
D	A two layer lining comprising:		
	Lower layer	–	0.15 m compacted clay
	Membrane	–	254 μm polythene mastic sealed and taped at joints.
	Upper layer	–	0.15 m sandy material.
E	Unlined control hafir		
F	A thick clay lining comprising:		
		–	0.75 m compacted sandy clay.
G	A three layer lining comprising:		
	Lower layer	–	0.25 m sandy clay
	Middle layer	–	0.25 m compacted clay
	Upper layer	–	0.25 m silty sand

TABLE 2

Hafir dimensions and levels from 1976 survey

HAFIR	BASE LEVEL †	LWT ‡	MAXIMUM DEPTH	MAJOR AXIS	MINOR AXIS
A	96.95	99.90	2.95	37.40	26.75
B	96.90	99.96	3.06	36.70	25.40
C	96.95	99.92	2.97	36.00	24.20
D	97.50	100.16	2.66	(40.20)	30.10
E	97.10	100.08	2.98	(34.00)	27.20
F	95.90	99.78	3.88	(47.80)	37.10
G	96.30	100.20	3.90	(51.10)	35.00

† levels in metres relative to site Datum (100.50m)

‡ Level of inlet pipe well top

( ) not surveyed – values derived from 1969 surveys.

TABLE 3

Comparison of design and survey geometry for small hafira

Water Depth D(m)	Water surface perimeter P (m)						Water surface area Ao (m^2)						Submerged area As (m^2)						Hafir volume V (m^3)					
	Design	Survey					Design	Survey					Design	Survey					Design	Survey				
		A	B	C	D	E		A	B	C	D	E		A	B	C	D	E		A	B	C	D	E
0.2	24	21	22	25	32	24	33	35	39	48	77	42	34	35	39	49	75	41	5	4	5	6	12	6
0.4	29	30	32	32	38	29	52	70	78	79	113	66	53	73	81	82	111	66	14	14	16	18	31	17
0.6	35	39	39	40	44	36	75	114	116	118	151	99	77	119	125	126	150	98	26	33	36	38	57	34
0.8	40	47	47	45	51	41	102	167	161	151	199	132	105	175	179	162	199	133	44	61	63	65	92	57
1.0	46	53	55	51	57	47	132	219	225	192	252	170	136	228	243	207	253	172	67	100	102	99	137	87
1.2	52	58	60	55	62	53	166	258	266	225	301	218	172	269	289	243	305	221	97	147	152	141	193	126
1.4	57	62	64	59	67	57	204	295	305	261	349	256	212	309	334	282	357	261	134	203	209	189	258	173
1.6	63	66	68	64	72	62	246	339	348	306	397	299	256	356	379	330	409	306	179	266	274	246	332	228
1.8	68	71	73	68	77	67	292	388	397	347	455	348	303	407	430	374	471	358	233	339	349	311	417	293
2.0	74	75	77	72	82	72	342	439	443	394	519	411	355	461	480	426	539	422	296	421	433	385	515	369
2.2	80	79	81	77	87	77	396	491	493	445	585	464	411	516	536	481	610	478	370	514	526	469	625	456
2.4	85	84	86	81	92	82	453	551	570	499	659	523	471	581	610	540	688	541	454	618	631	564	749	555
2.6	91	89	89	85	98	86	514	616	610	554	741	587	534	649	653	599	774	608	551	735	749	669	889	666
2.8	96	75	93	90	104	91	579	695	663	616	833	653	602	734	713	664	869	677	660	866	876	785	1046	790
3.0	102	101	98	95	110	96	648	785	732	683	951	727	674	830	785	735	987	754	783	1014	1016	916	1224	928

TABLE 4

Comparison of design and survey

GEOMETRY FOR LARGE HAFIRA

Water depth D(m)	Water surface perimeter P (m)			Water surface area Ao (m)			Submerged area As (m^3)			Hafir volume V (m^3)		
	Design	Survey		Design	Survey		Design	Survey		Design	Survey	
		F	G		F	G		F	G		F	G
0.2	33	32	35	62	81	94	62	79	83	10	12	14
0.4	38	40	42	86	125	135	88	123	124	25	33	37
0.6	44	45	47	114	163	171	118	162	163	45	62	67
0.8	49	52	54	146	211	227	150	210	218	71	99	107
1.0	54	57	60	180	255	279	186	257	273	103	146	158
1.2	59	62	65	218	303	329	226	306	325	143	202	219
1.4	64	67	69	258	349	375	268	356	376	191	267	289
1.6	70	71	74	302	395	431	314	405	435	247	341	369
1.8	75	75	79	350	438	484	364	454	494	312	425	461
2.0	80	79	85	400	488	566	417	509	578	387	517	566
2.2	85	84	91	454	552	645	473	577	660	472	621	687
2.4	90	89	96	510	618	711	532	648	732	568	738	822
2.6	96	94	101	570	635	794	595	728	819	676	869	973
2.8	101	100	106	634	787	870	662	822	902	797	1017	1139
3.0	106	106	111	700	870	950	731	910	989	930	1182	1321
3.2	111	111	116	770	957	1041	805	1001	1086	1077	1365	1521
3.4	116	116	121	842	1041	1127	881	1091	1180	1238	1565	1737
3.6	122	121	126	918	1131	1222	961	1188	1282	1414	1782	1973
3.8	127	126	131	998	1237	1315	1044	1298	1384	1605	2018	2226
4.0	132	133	135	1080	1393	1405	1131	1452	1484	1813	2278	2498

TABLE 5

Summary of particle size determinations of Lunya sub-soils

Sample No. 1969	1976	Sand %	Silt %	Clay %	Median (D_{50}) mm
1		81	9	10	0.4
4		69	19	12	0.1
2		55	27	18	0.05
6		50	32	18	0.05
5		49	38	13	0.05
3		36	44	20	0.025
9		36	34	30	0.02
(1)	C3	78	13	9	0.25
(4)	B1	72	17	11	0.15
(2)	B3	60	23	17	0.09
(5)	C4	56	32	12	0.08
(5)	B4	55	36	9	0.07
(2)	B2	52	28	20	0.07
(2)	A4	50	33	17	0.06
(3)	A3	36	40	25	0.03

TABLE 6

Cation exchange capacities of soils

a. LUNYA SUB-SOILS

Sample	Fraction		Cation exchange (meq/100g)	
	Size	Total (%)	Actual	Adjusted
	< 63 μ	62.7	32	80
A3	< 20 μ	45.4	44	80
	< 2 μ	25		
	< 63 μ	46.4	30	87
B2	< 20 μ	33.4	39	80
	< 2 μ	16		

b. MAJOR CLAY MINERAL GROUPS

Group	Type	Cation exchange (meq/100g)
Kaolinite	non-expanding	3 - 15
Illite	non-expanding	10 - 40
Chlorite	non-expanding	10 - 40
Smectite (Montmorillonite)	expanding	80 - 150

TABLE 7

Monthly ratios of 12 ft diameter pan to Class "A" pan evaporation

LOCATION	Khartoum (Sudan)	Lod (Israel)	Fullerton (USA)	Poona (India)
LATITUDE (°N)	16	32	34	17
JANUARY	0.67	0.73	0.65	0.86
FEBRUARY	0.62	0.73	0.77	0.84
MARCH	0.65	0.75	0.76	0.82
APRIL	0.62	0.74	0.80	0.76
MAY	0.61	0.73	0.81	–
JUNE	0.64	0.74	0.82	–
JULY	0.65	0.76	0.81	–
AUGUST	0.69	0.76	0.81	0.82
SEPTEMBER	0.69	0.75	0.76	0.82
OCTOBER	0.68	0.73	0.75	0.97
NOVEMBER	0.65	0.74	0.76	0.92
DECEMBER	0.66	0.70	0.66	0.91
ANNUAL	0.65	0.74	0.76	0.86
DEPTH (m)	1.2	1.0	0.9	0.25 †
COEFF. OF VARIATION (%)	5.0	1.5	7.5	7.0
YEARS OF RECORD	2	6	4	1

† Elevated (not sunken).

TABLE 8

Water-balance results for polythene lined hafira

Hafir	Season	Volume %	Evaporated Open %	Volume Closed %	Seepage † %
	1970-71	83	74	10	16
	1971-72	88	68	9	23
A	1972-73	98	61	8	30
970 m^3	1973-74	100	44	5	49
	1974-75	100	40	5	54
	1975-76	84	36	5	58
	1970-71	82	77	10	13
	1971-72	84	57	8	35
B	1972-73	96	41	5	53
1050 m^3	1973-74	100	33	5	62
	1974-75	100	35	5	60
	1975-76	100	28	4	68
	1970-71	79	65	8	25
	1971-72	83	48	8	44
C	1972-73	97	35	5	59
880 m^3	1973-74	99	31	5	64
	1974-75	100	43	6	51
	1975-76	100	30	5	65
Unlined					
control	1970-71	18	52	12	37(72)
	1971-72	37	49	10	42(63)
E	1972-73	83	23	4	73
910 m^3	1973-74	98	25	4	71
	1974-75	100	32	5	63
	1975-76	93	25	4	71

† brackets denote extrapolated values.

TABLE 9

Water-balance results for clay lined hafira

Hafir	Season	Volume %	Evaporated Open %	Volume Closed %	Seepage † %
	1970-71	52	62	10	29
	1971-72	76	57	8	35
D	1972-73	98	49	6	45
920 m^3	1973-74	100	45	6	49
	1974-75	99	40	5	54
	1975-76		NO RECORD		
	1970-71	28	45	6	49(69)
	1971-72	52	31	4	65(80)
F	1972-73	76	25	3	72
2060 m^3	1973-74	98	24	3	73
	1974-75	100	34	4	61
	1975-76	100	32	3	64
	1970-71	19	31	5	64(90)
	1971-72	31	35	5	60(75)
G	1972-73	71	17	2	82
2240 m^3	1973-74	96	16	2	82
	1974-75	100	31	3	66
	1975-76	94	33	6	64
Unlined control	1970-71	18	52	12	37(72)
	1971-72	37	49	10	42(63)
E	1972-73	83	23	4	73
910 m^3	1973-74	98	25	4	71
	1974-75	100	32	5	63
	1975-76	93	25	4	71

† brackets denote extrapolated values.

TABLE 10

Insecticide concentrations in hafir soils

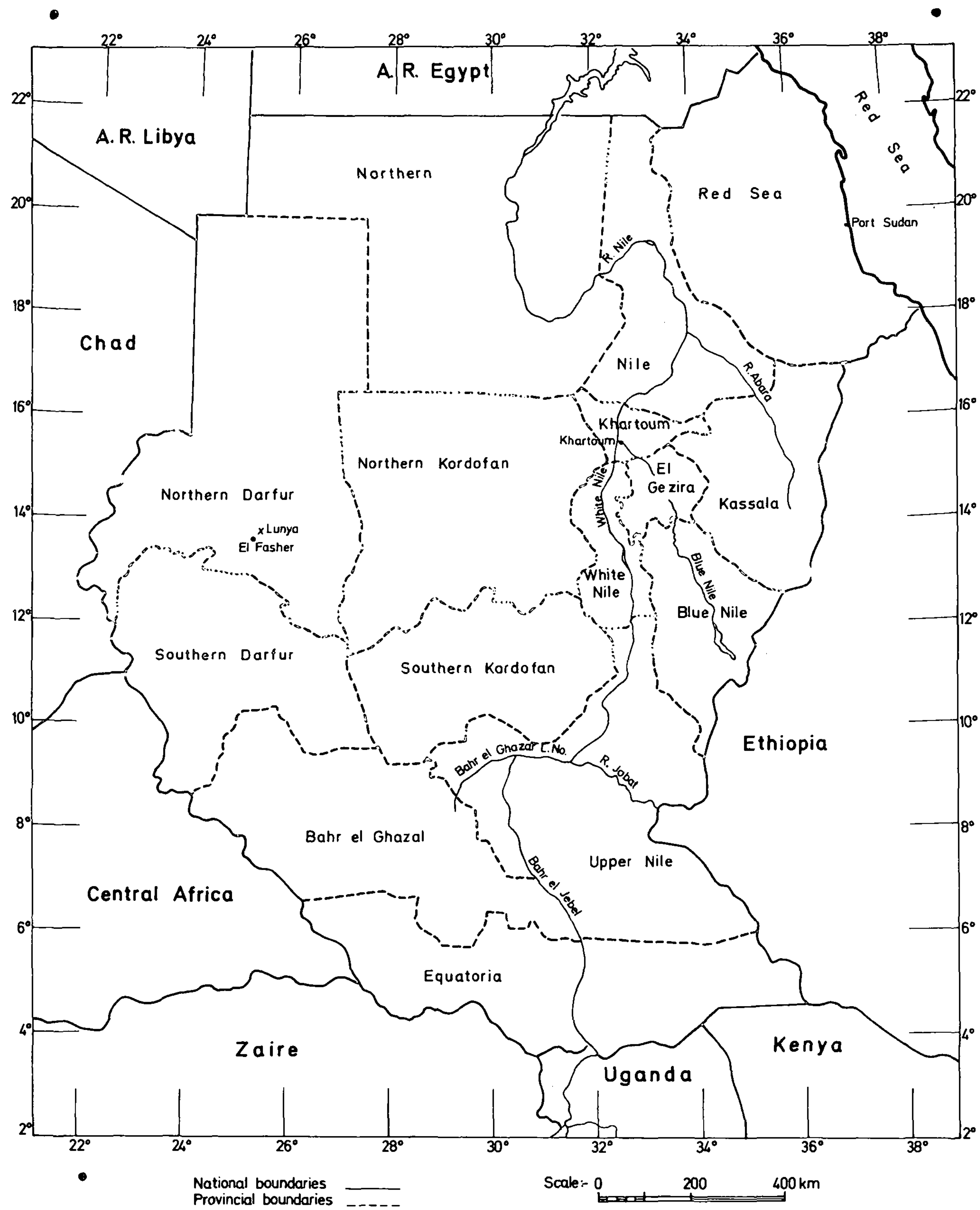
Sample No.	Sub-Soil † (ppm)			Soil ‡ (ppm)	
	A	B	C	A	C
1	0.02	0.03	0.05	0.12	0.76
2	0.02	0.02	0.02	0.02	0.15
3		0.09			
4		0.03			

† below lower membranes.

‡ between membranes.

(data supplied by ICI Plant Protection Ltd; August 1976).

FIGURES



Provincial Map of the Sudan Showing Location of Lunya Site

Fig.1

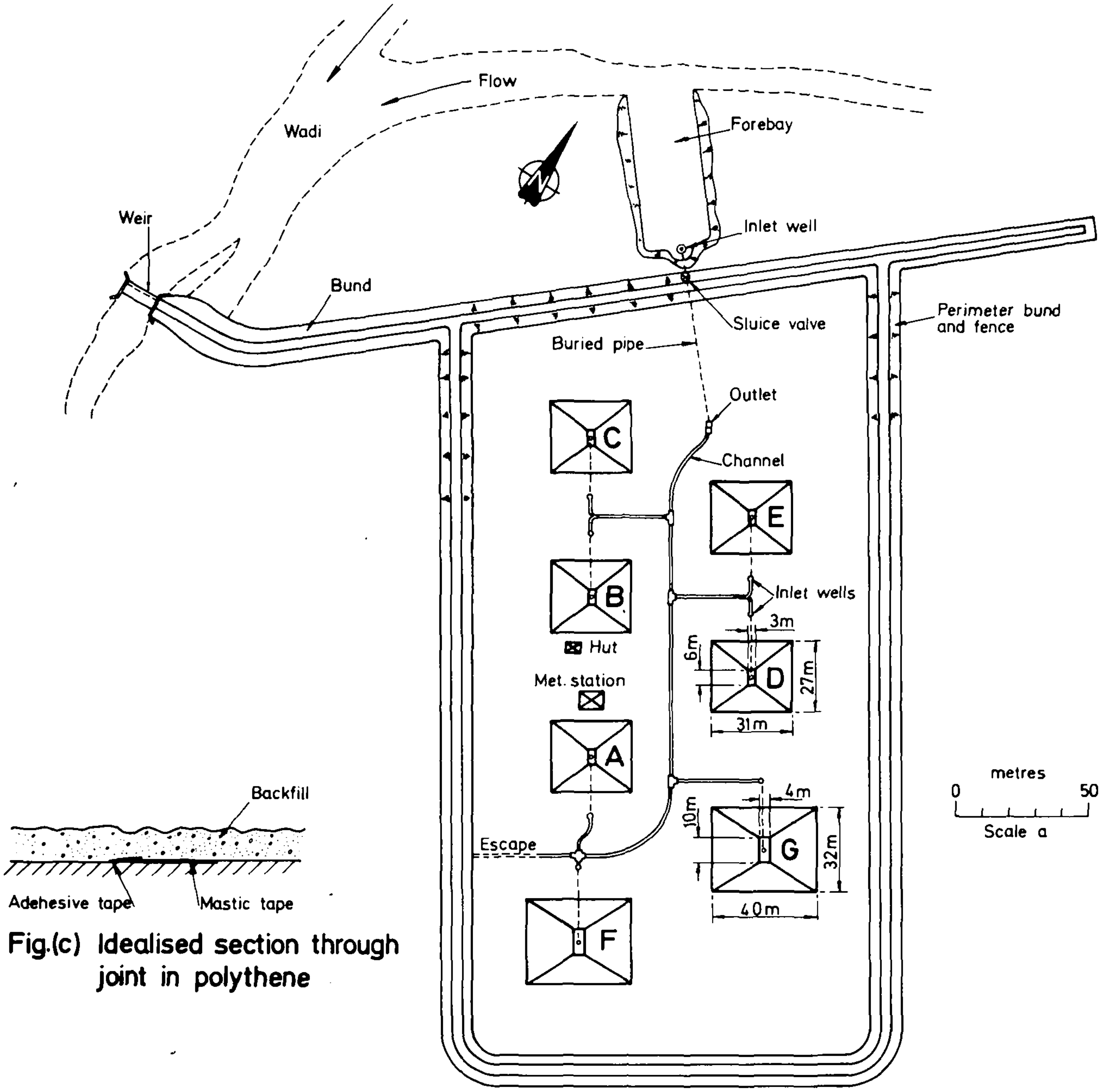


Fig.(a) Layout of experimental facilites

Fig.(c) Idealised section through joint in polythene

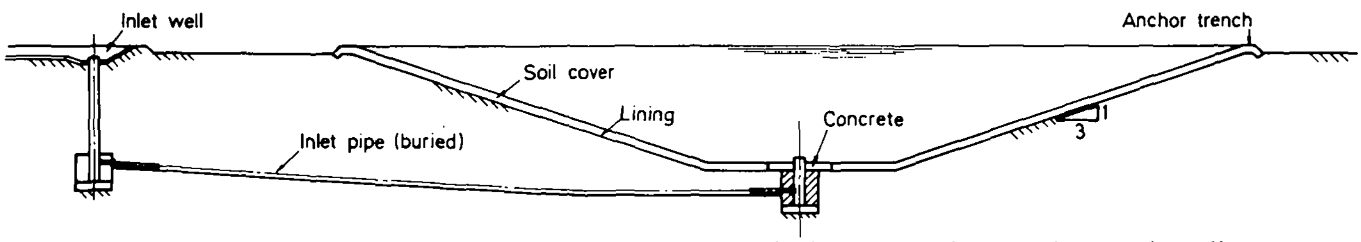
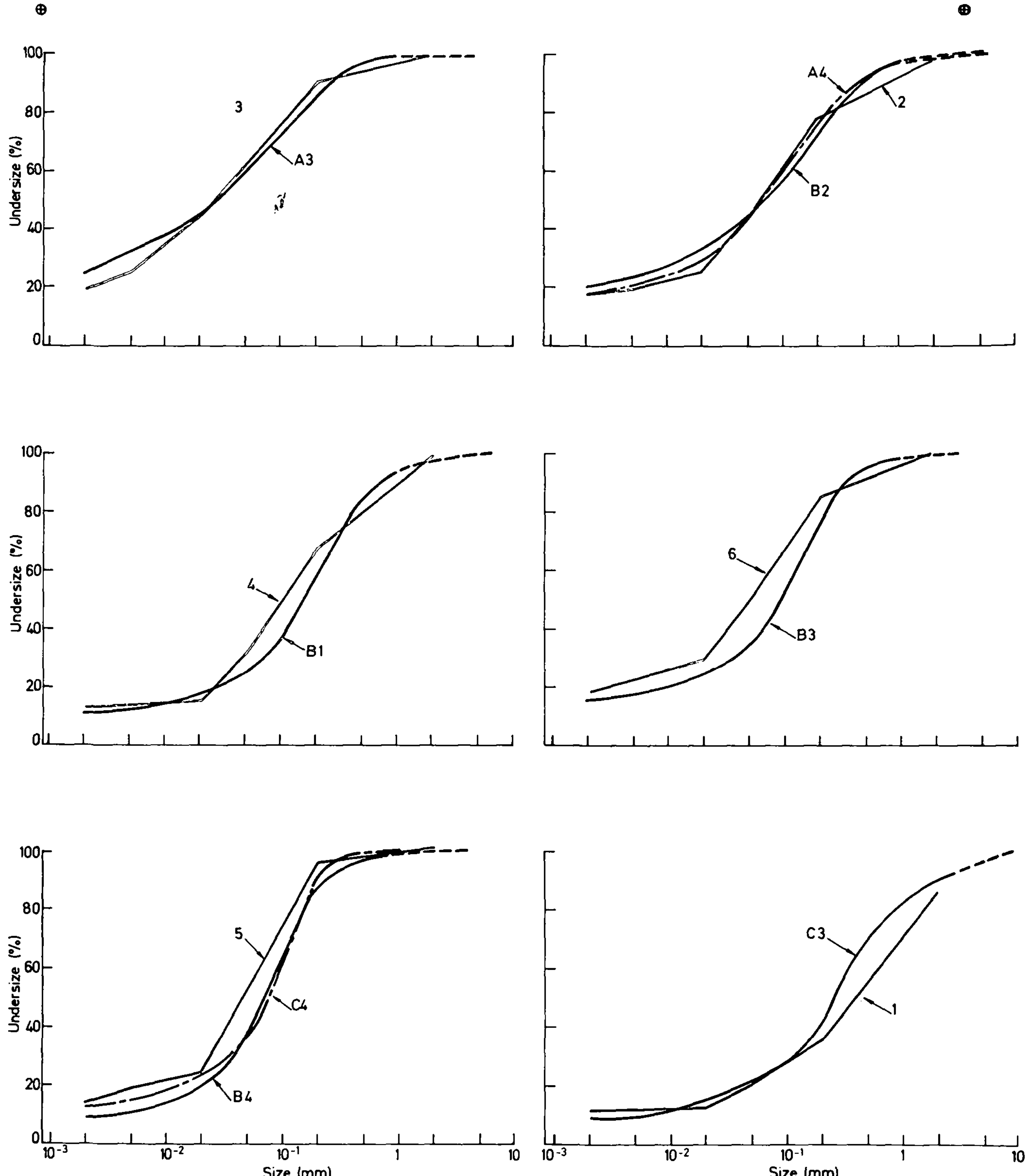


Fig. (b) Section through a polythene lined experimental hafir

Lunya Installations
(reproduced from reference 4)

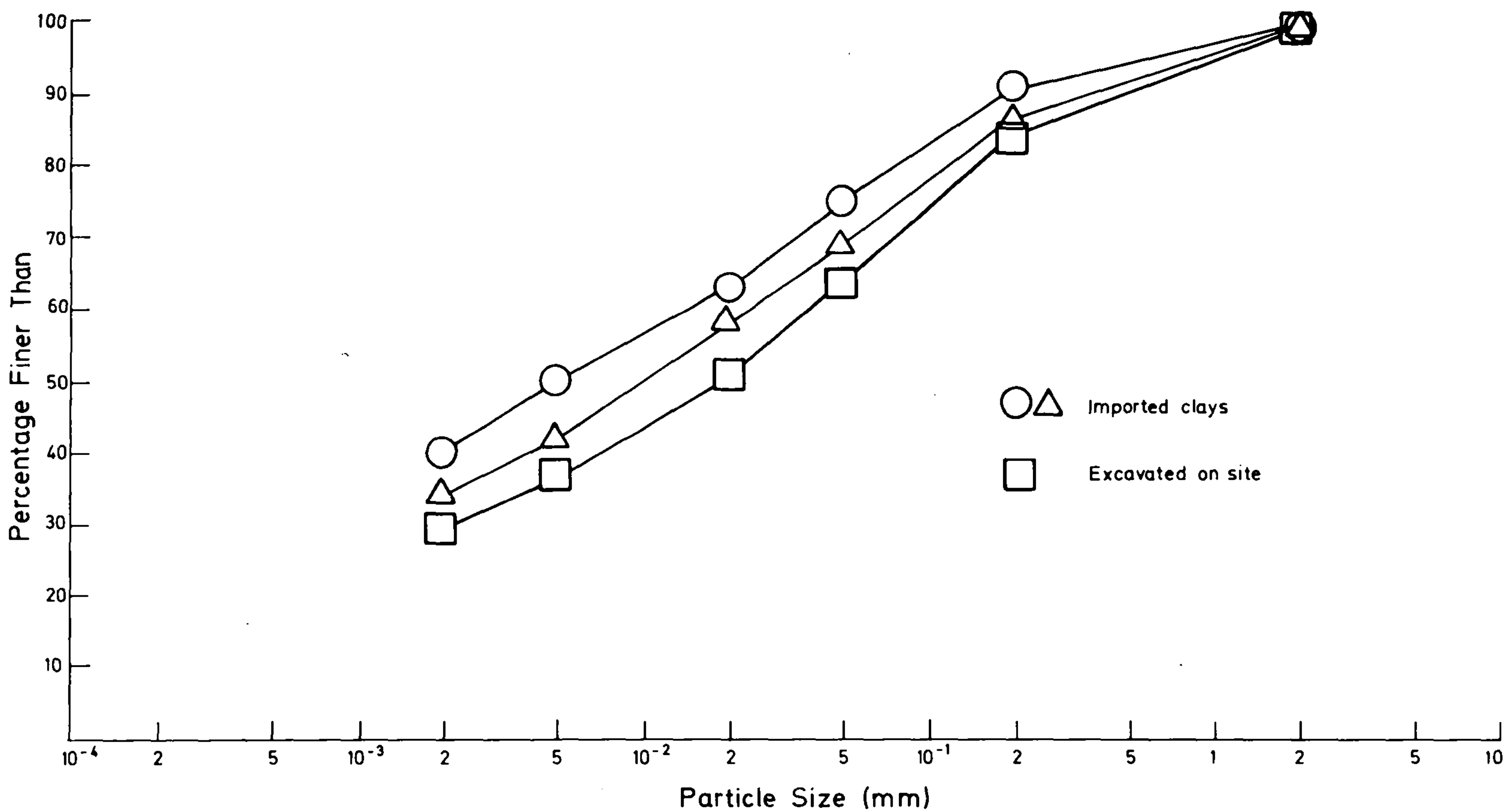
Fig.2



Samples 1 to 6 taken in 1969 - remaining samples taken in 1976

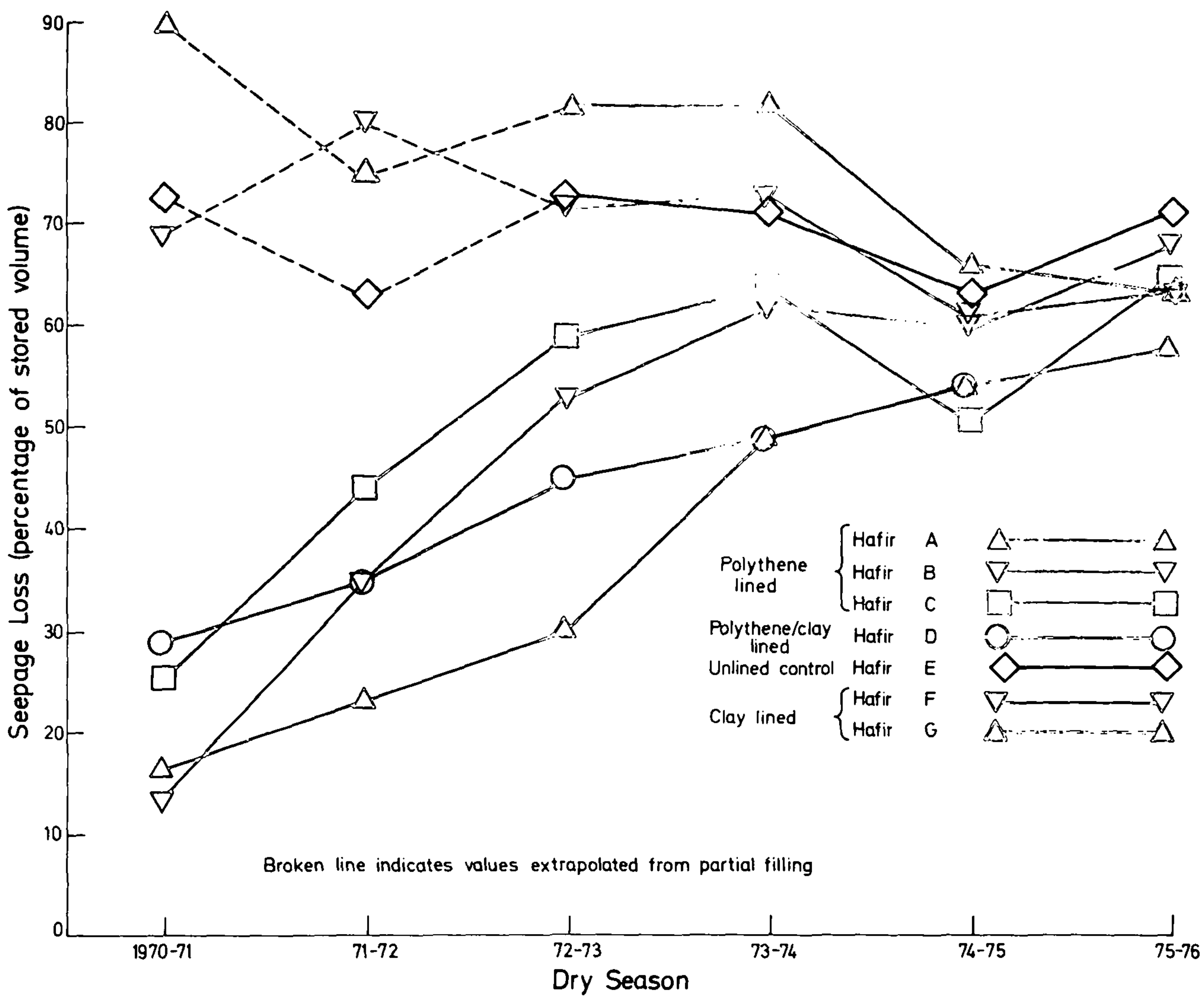
Summary of Particle Size Determinations of Lunya Sub-soils

Fig. 3



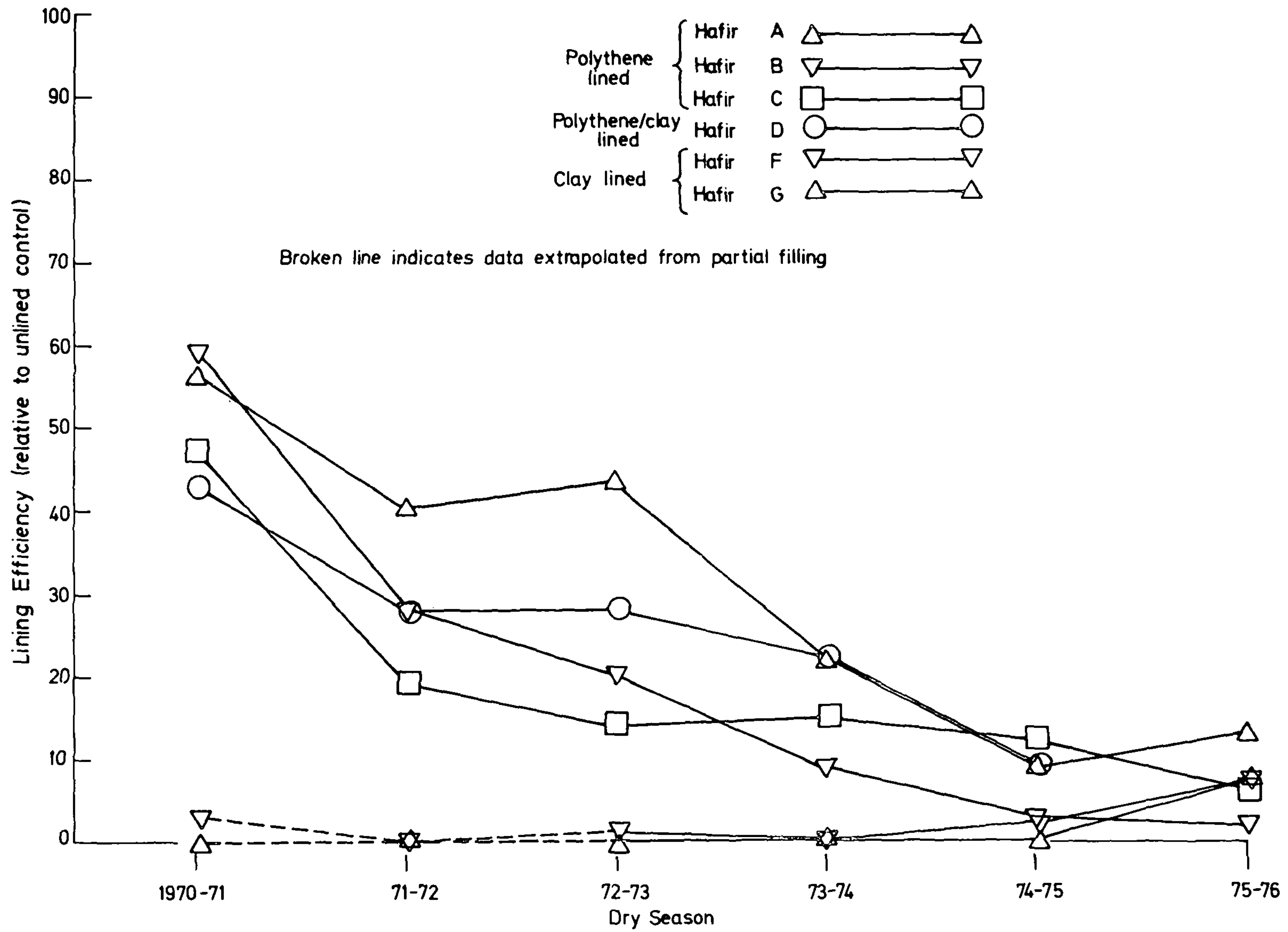
Particle Size Curves of Lining Clays in Lunya Hafira

Fig. 4



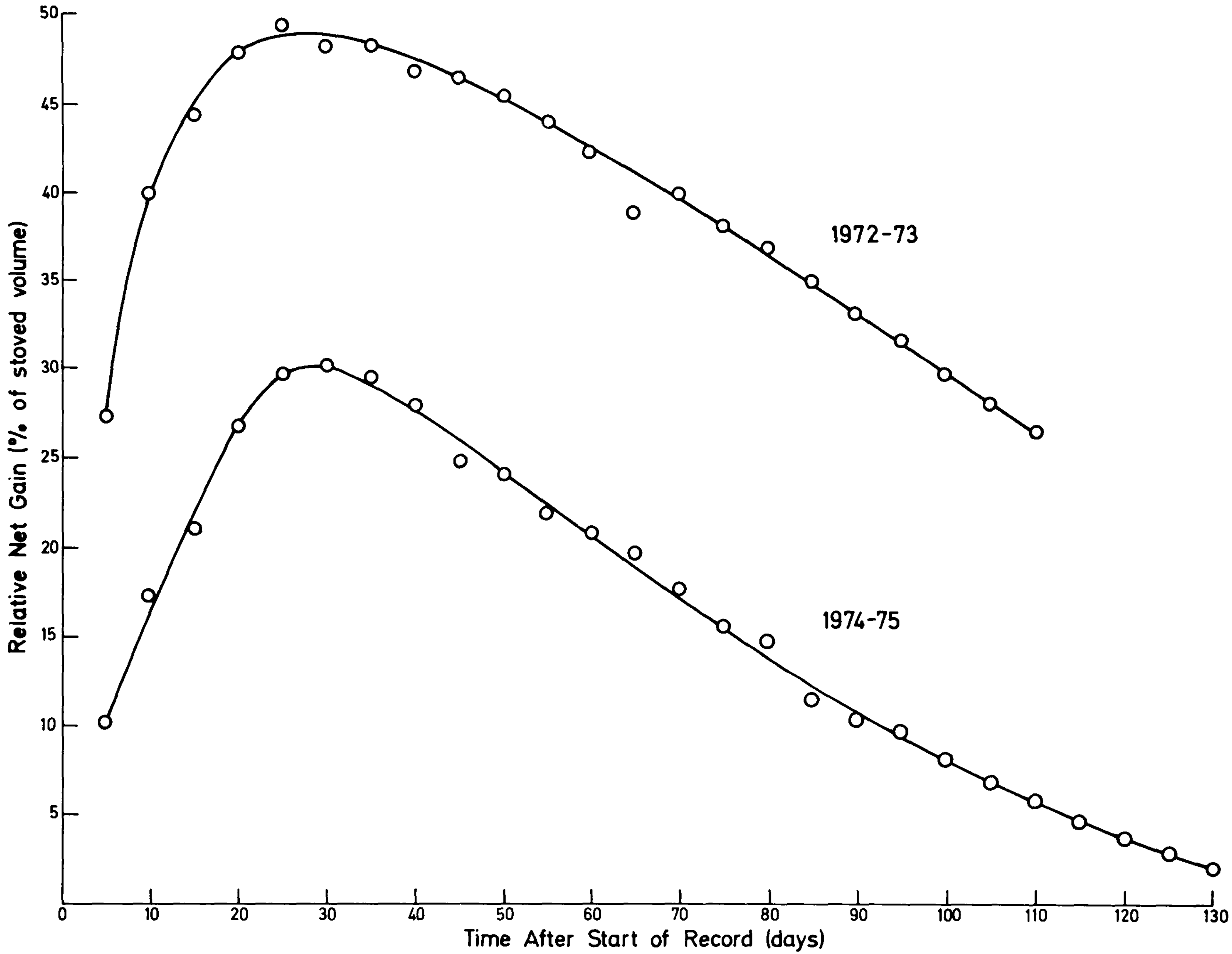
Comparison of Seepage Losses

Fig. 5



Comparison of Lining Efficiencies

Fig.6



Variation in Relative Net Gain During One Dry Season (Hafira A)

Fig.7

PLATES

PLATE 1 Meteorological site showing the two Class "A" evaporimeters and the standard screen

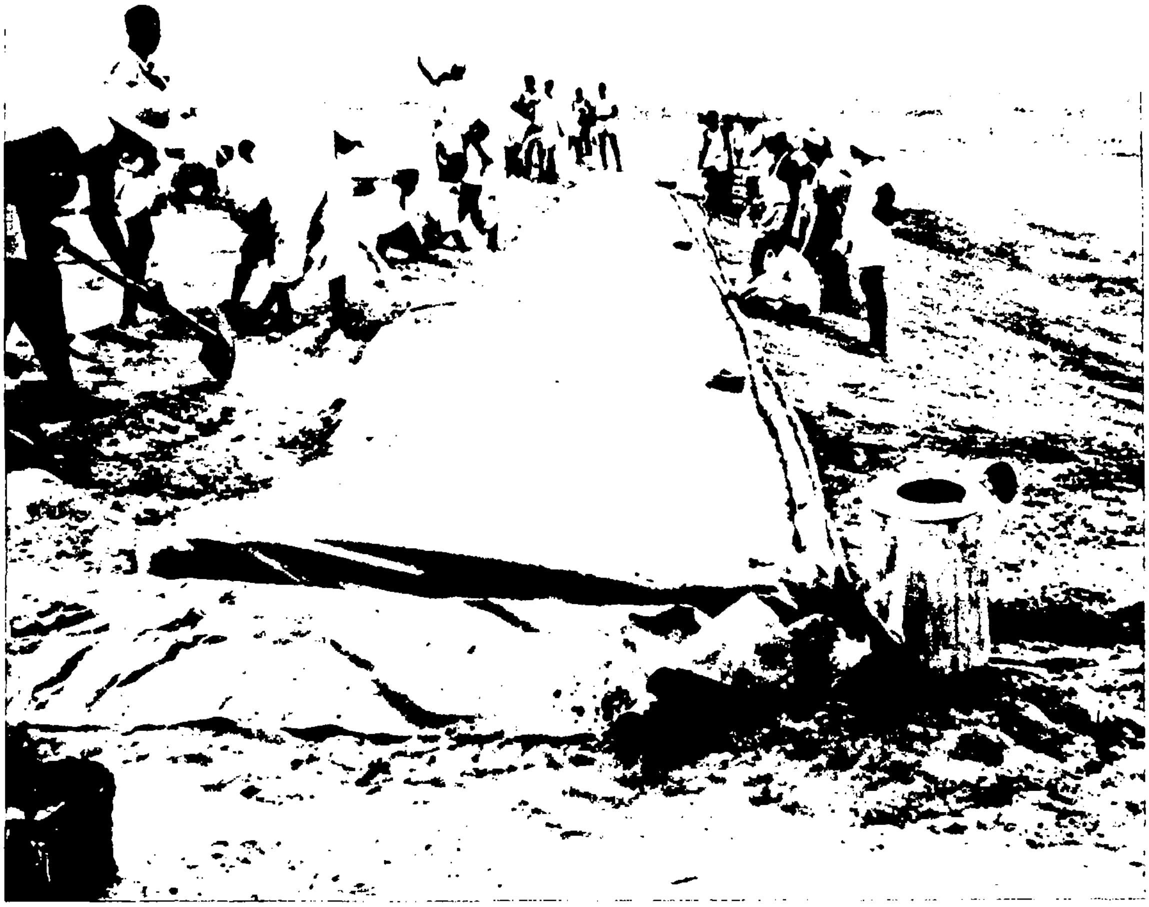


PLATE 2 Stages during construction of the hafira *Photo courtesy ICI*

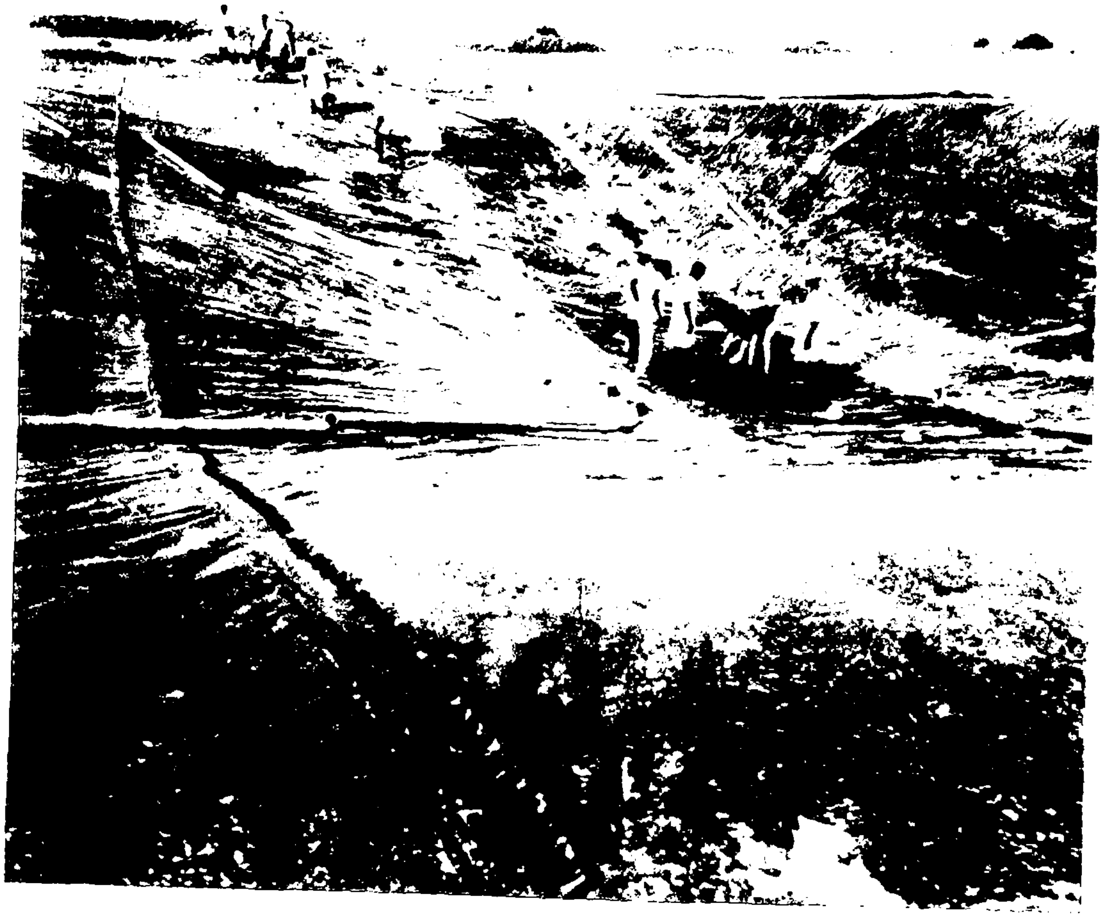


Photo courtesy ICI

PLATE 3 Removing backfill from hafir A to expose polythene membrane

PLATE 4 Earth slip in hafir A with lining exposed

PLATE 5 Root growth through membrane of hafir A

PLATE 6 Degraded adhesive jointing tape on hafir A

PLATE 7 Roots in insecticide slurry layer of hafir A

PLATE 8 Eastern quarter of hafir A showing jointing pattern of exposed polythene membrane

PLATE 9 Repaired joint on hafir A

PLATE 10 Western diagonal trench of hafir B

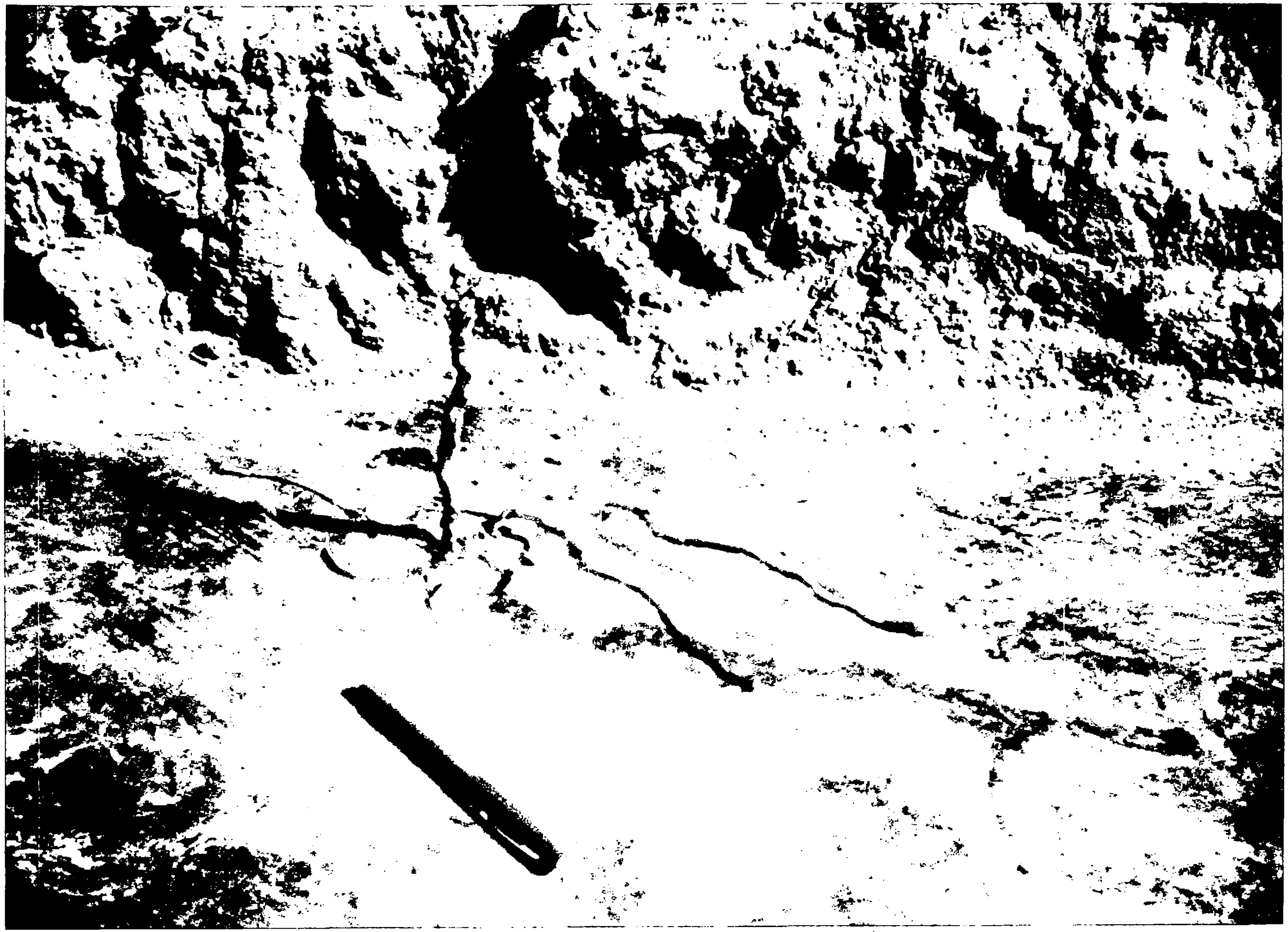


PLATE 11 Root growth through lining of hafir B

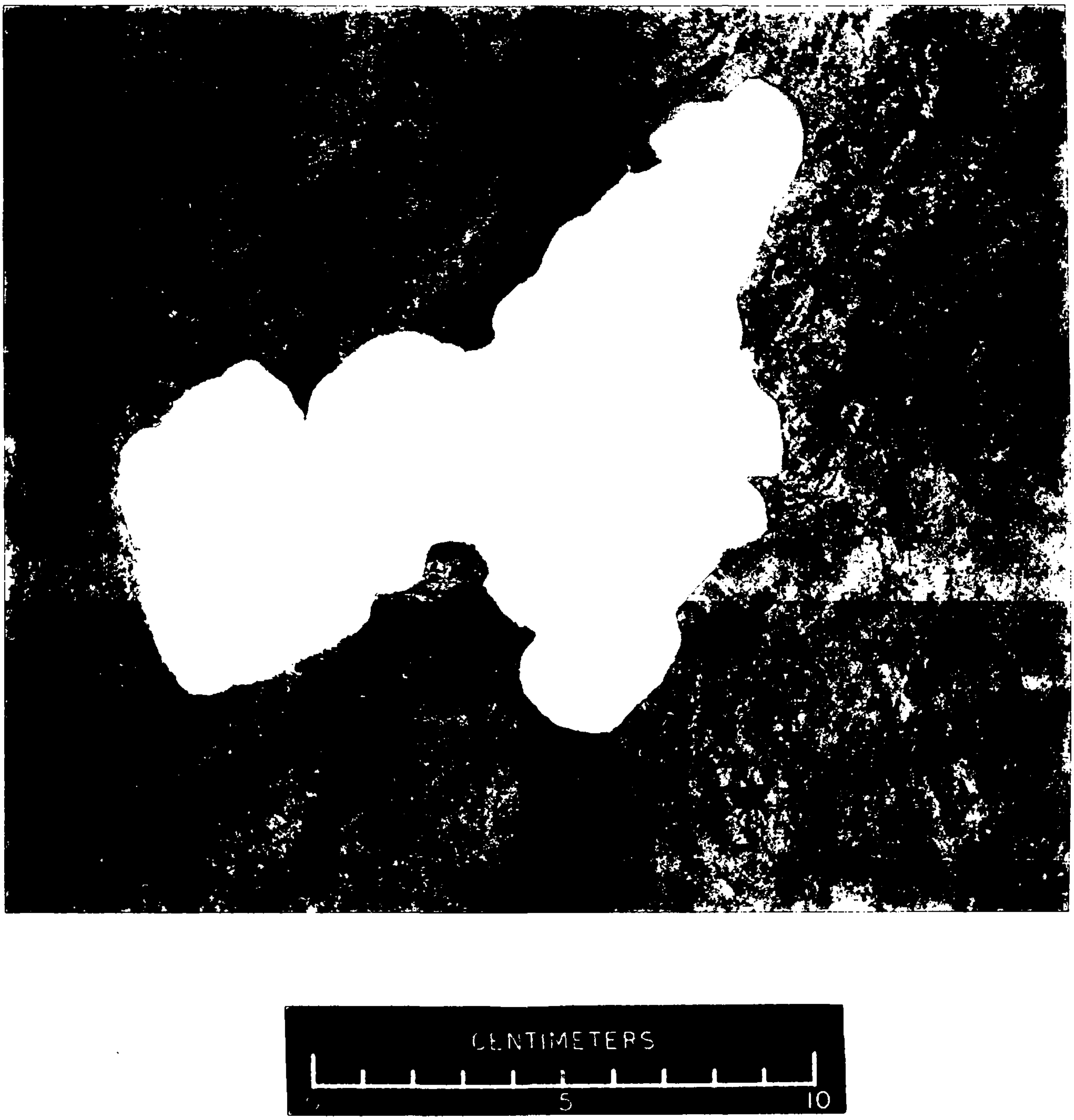


PLATE 12 Sample of lining membrane from hafir B

PLATE 13 Broken joint at top of eastern corner of hafir B

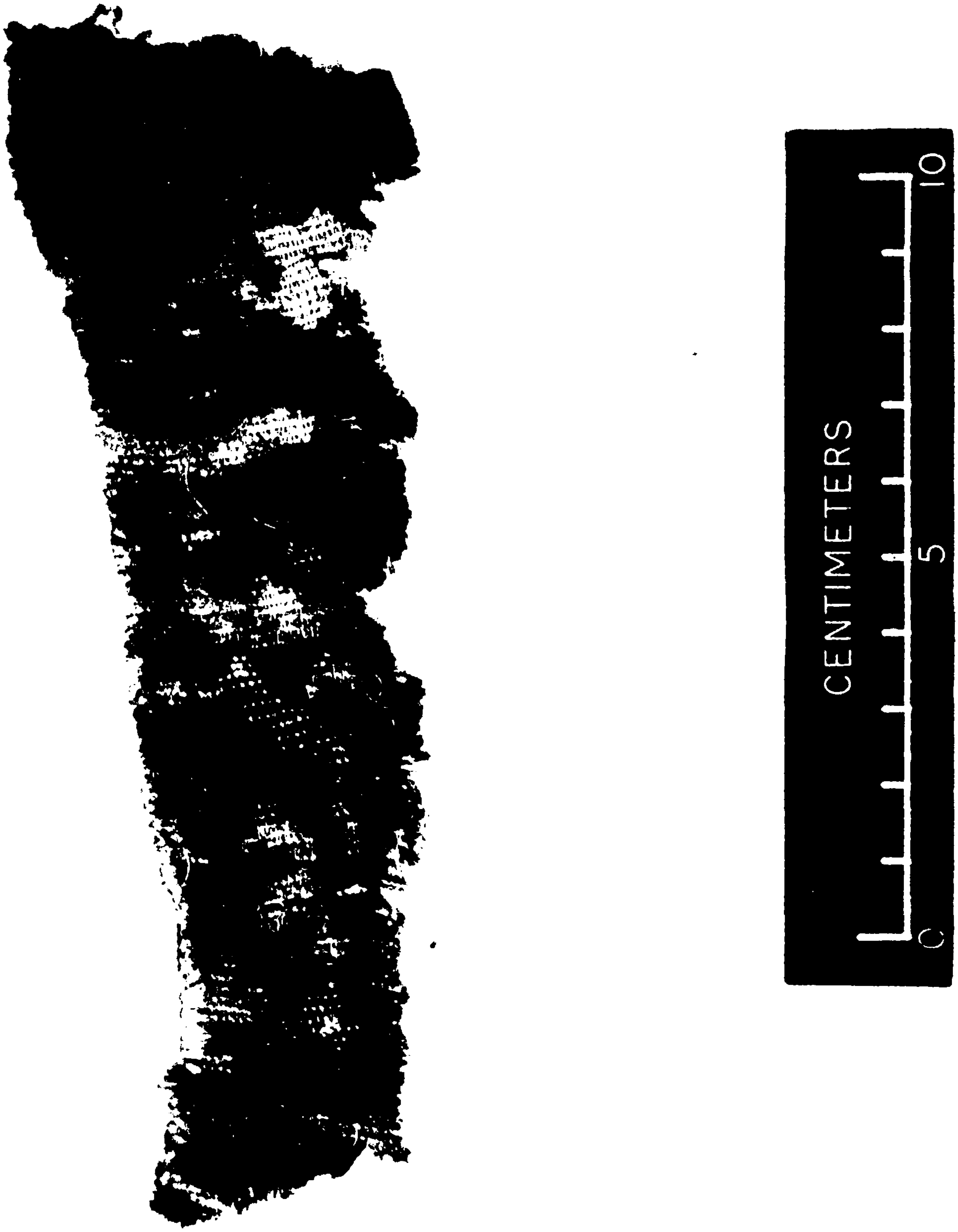


PLATE 14 Sample of mastic tape from hafir B

PLATE 15. Inlet/outlet pipe in hafir B

PLATE 16 Trench on hafir C from south-east

PLATE 17 Inspection trench on north-west face of hafir C

PLATE 18 Sample of lining membrane from hafir C

PLATE 19 North-east face of hafir D showing polythene uncovered by backfill erosion

PLATE 20 Sample of lining membrane from hafir D

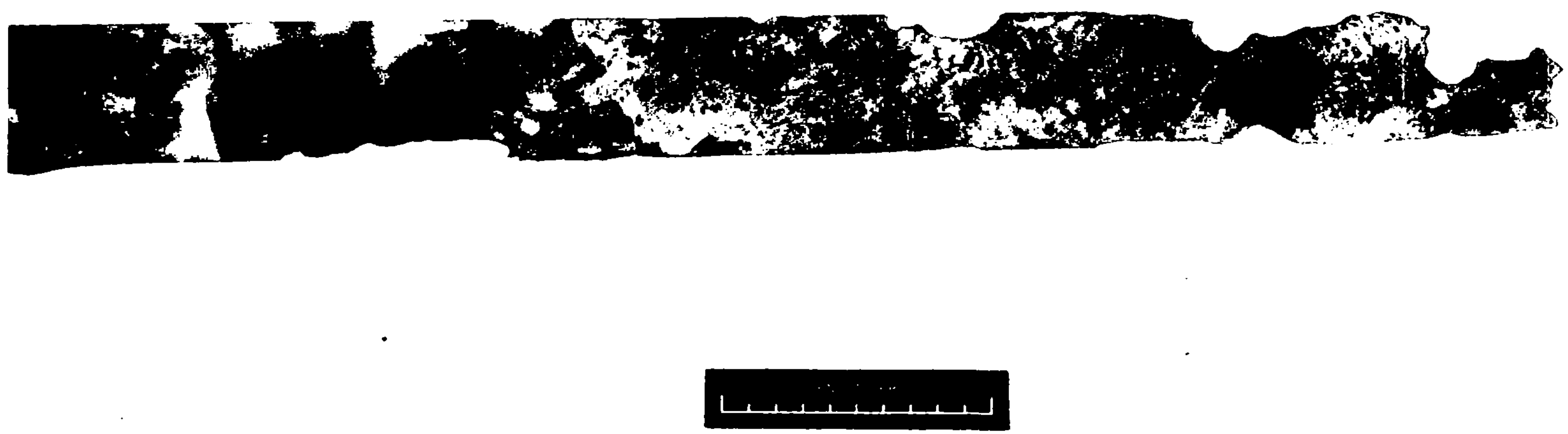


PLATE 21 Sample of adhesive tape from hafir D

PLATE 22 General view of hafir E from the eastern corner

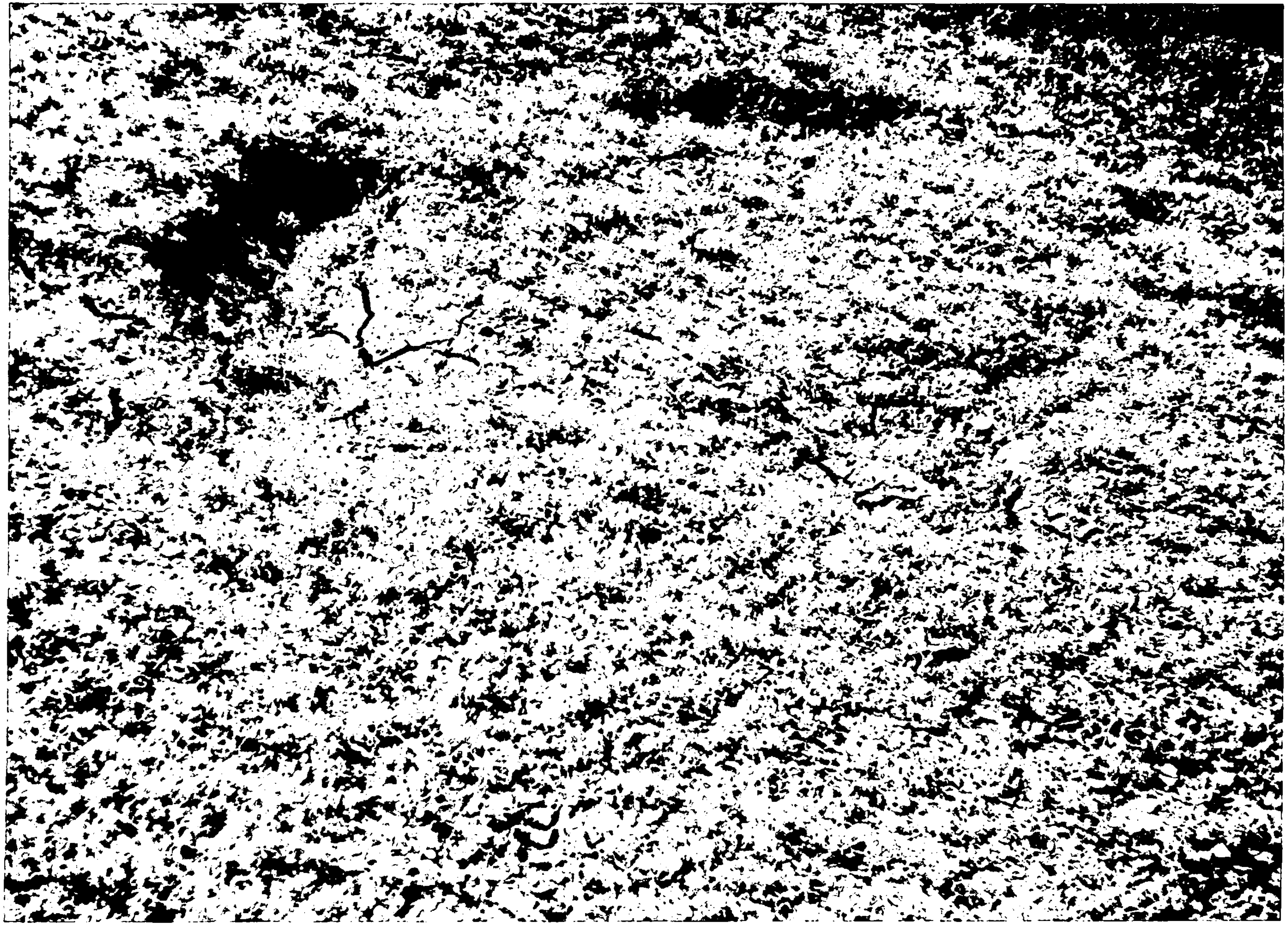


PLATE 23 Plant growth and surface soil cracking in hafir E

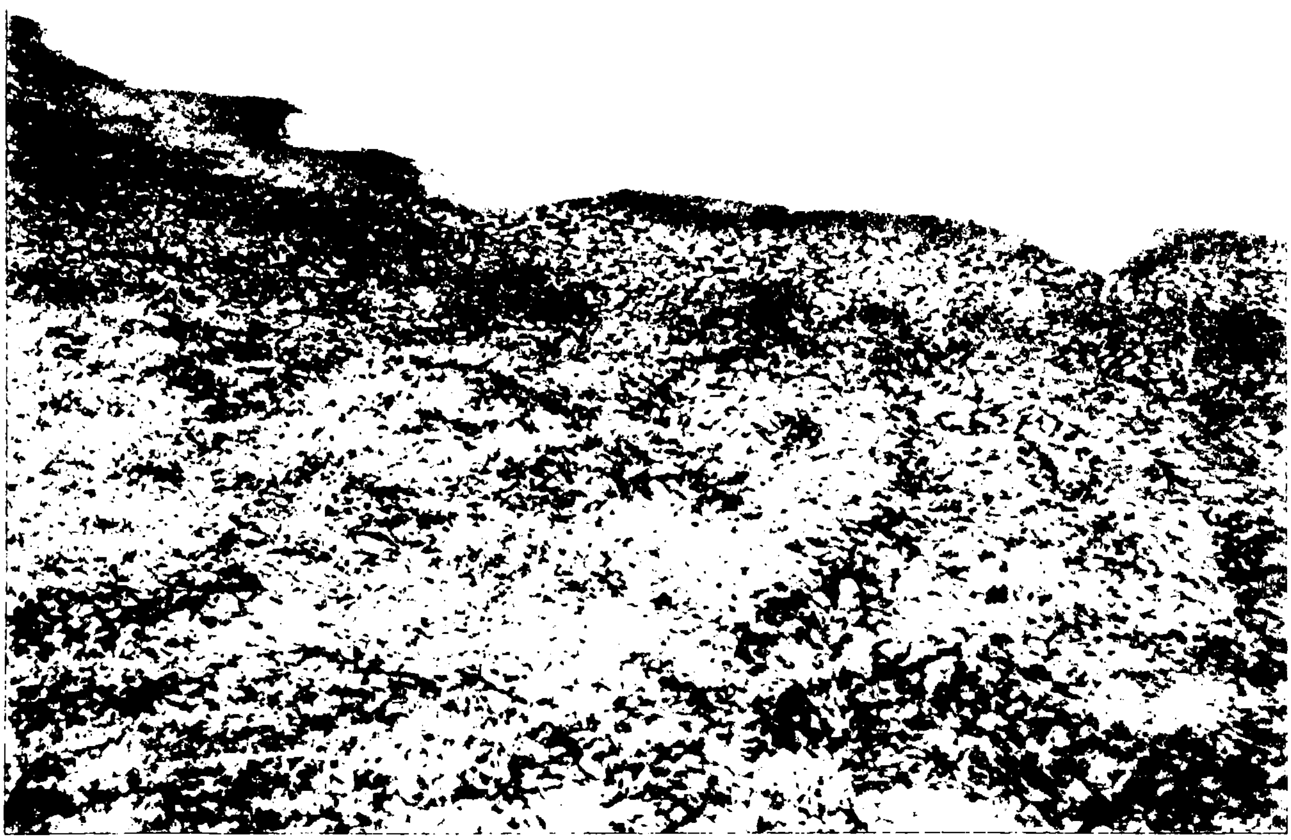


PLATE 24 Hafir F from the east