THE GEOMORPHOLOGY

OF THE

BROADMARSH - ELDERSLIE AREA

with special reference to
HILLSLOPE MORPHOLOGY

A thesis submitted as part of the
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Bachelor of Science with Honours

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To those people mentioned above, and to all those with whom I have had contact in the field, I proffer my thanks.

ABSTRACT.

The morphology of the Broadmarsh-Elderslie area is very largely controlled by lithology and structure — variations in topography, stream pattern, and valley and channel morphology are shown to be closely related to bedrock changes.

Hillslope morphology is examined in detail. Dolerite slopes decline by extending basal slopes with accumulated debris eroded from the summit sections. Differential protection by vegetation is held to be the main reason for the differences in form and rate of erosion on north- and south-facing slopes.

Alluvial terraces can be correlated only within individual segments of the valley, producing a 'ponded' effect.

When casually observed in the field, the channel of the Jordan River is a picture of disorder. To the contrary, an analysis of width-depth ratios reveals no significant variations in channel form.

Large valley meanders, extensive alluvial fans and aprons, and aeolian deposits provide evidence of marked variations in former climatic conditions.

INTRODUCTION.

The Broadmarsh - Elderslie area lies approximately 25 miles north-west of Hobart in the Jordan River valley. For the purposes of this study, the area under investigation is delimited on the west and east by the drainage divides of the Jordan River network, and extends from near Pontville in the south-east, upriver to within 3 miles of Kempton (Fig. 1). This area is readily accessible from the Midland Highway, which passes through Pontville and Kempton linking Hobart with Central and Northern Tasmania. The Elderslie Road joins the Midland Highway at Brighton and follows the valley upriver, passing through Broadmarsh and Elderslie.

All of this area falls within the 1;31,680 Kempton and Broadmarsh dyeline sheets (found in rear pocket) produced by the Lands and Surveys Department. The Australian Map Grid System in metres, has been used to refer to localities.

Only the geology of the area south of Broadmarsh has yet been published (McDougall, 1959b), although the area is currently under investigation by the Mines Department. Recent interest in the Jordan River by the Rivers and Water Supply Commission, investigating the feasibility of damming and regulation of streamflow for irrigation purposes, has resulted in additional geological information from two proposed dam sites within the study area. The soils in this area have been mapped by Dimmock (1957), and this map has provided a useful guide to the lithology of various locations where time did not permit close investigation.

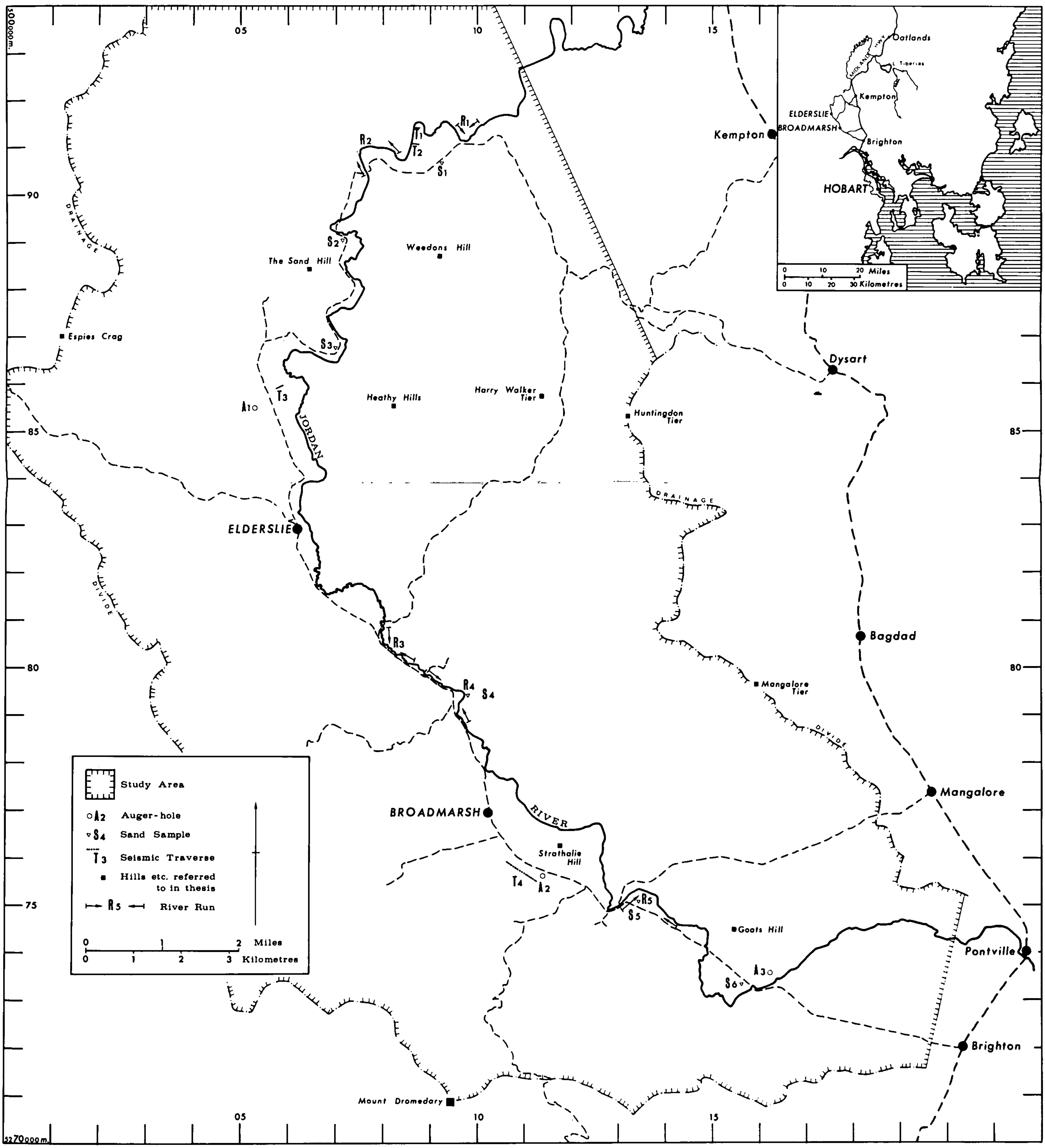
The aim of this study was to elucidate the variations in topography throughout the area. This investigation led to a closer examination of hillslopes. In addition, much attention was focussed on the channel and valley morphology of the Jordan River.

Approximately 15 weeks were spent in the field. A considerable amount of this time was spent collecting hill-slope data, levelling terraces and floodplains within the Jordan River valley, and measuring channel sections. Seismic traverses were carried out at several locations to determine the subsurface topography.

It was intended to complete the study of the area with analyses of sediment samples obtained principally from the river channel and from augering. However lack of time has prevented all but a few analyses to be made, so that descriptions of soils and alluvial deposits rely heavily on field observations.

FIGURE 1.

Location Map
of the
Broadmarsh-Elderslie Area



LOCATION MAP OF THE BROADMARSH–ELDERSLIE AREA

GEOLOGY.

Lithology.

Although the geology of only a small part of the area has been mapped, this proved of little inconvenience, since exposure in the area is good, particularly to the north between Espies Crag and Huntingdon Tier.

The Permian System is represented by sandstones, mudstones and limestones, and outcrops principally on the north-eastern flank of Mt. Dromedary. Permian strata are also found in the broad basin on the southern flank of Mangalore Tier. However due to their limited outcrop, only a cursory examination has been made of the topography developed on these formations.

The Triassic System consists of a series of sandstones, mudstones, shales and conglomerates and occurs over large areas, mainly to the north of Broadmarsh. McDougall (1959b) recognized two distinct rock associations in the Broadmarsh area - predominantly sandstone, and sandstone and shale - but because he found that the relationships of these associations to one another were not clearly defined, he mapped all the rocks of the Triassic System as one unit - the Knocklofty Formation. Bedding planes also are not always clearly defined, so that accurate dip measurements were difficult to obtain in many instances.

The difficulties noted by Hale (1962) in correlating the Triassic strata in Tasmania, are also apparent in the Broadmarsh - Elderslie area. The absence of any distinct beds for use as markers made even cross-valley correlation uncertain.

The Jurassic period is represented by extensive dolerite intrusions. South of Broadmarsh the dolerite bodies are principally dyke-like, so that long NW - SE trending ridges of dolerite now flank the river valley in this area. Leaman (1967a) found that the sedimentary rocks near Broadmarsh invariably show some evidence of metamorphism, indicating that dolerite once passed over the area as a nearly flat sheet, or that it underlies the area at shallow depth. Immediately upriver from Goats Hill the former seems almost certainly the case. Here the Jordan River has cut through dolerite which conformably overlies gently dipping Triassic sandstone, leaving a prominent sandstone ledge at the level of the contact on the south-western side of the valley. Presumably this ledge remains due to a resistant metamorphosed capping.

Near Kempton, Leaman (1967b) considered the dolerite intrusion

> to be a large sheet passing beneath the area with offshoots upward (through Triassic sandstone) in such a way that most of the

sedimentary outcrops present are inclusions or pieces remaining on the irregular roof.

A similar association occurs north of Elderslie - the northernmost extremity of Weedons Hill for example, is capped with Triassic sandstone conformably or near conformably overlying dolerite, and occurs adjacent to a dolerite hill at the same elevation.

During the Tertiary period, a basalt flow (The 'Brighton Basalts' of McDougall, 1959a) flowed down the pre-existing valley of the Jordan River. McDougall considered that this basalt flow displaced the Jordan River northwards near Pontville, and that the river has been migrating northwards ever since. Most certainly this is suggested by the steep undercut dolerite slopes formed here at the northern boundary of the valley. Two volcanic necks occur in the area - at 5142E, 52757N and 5136E, 52728N. Both these necks have been strongly eroded, almost to the general surrounding level.

Quaternary sediments occur along the Jordan River valley and some of the larger tributaries. The fluvial sediments will be discussed later.

Structure.

Faulting in the area south of Broadmarsh has produced a series of NNW striking normal faults forming the uplifted Mt. Dromedary block, and minor horsts to the east (McDougall, 1959b). This faulting was originally considered to be Lower Tertiary in age (Hills and Carey, 1949), however it now seems likely that it 'preceded, and probably closely followed' the dolerite intrusion (Solomon, 1962). Leaman (1967a) also found no evidence for post-dolerite movement in the Broadmarsh area, and considered the faulting to be pre-dolerite in age.

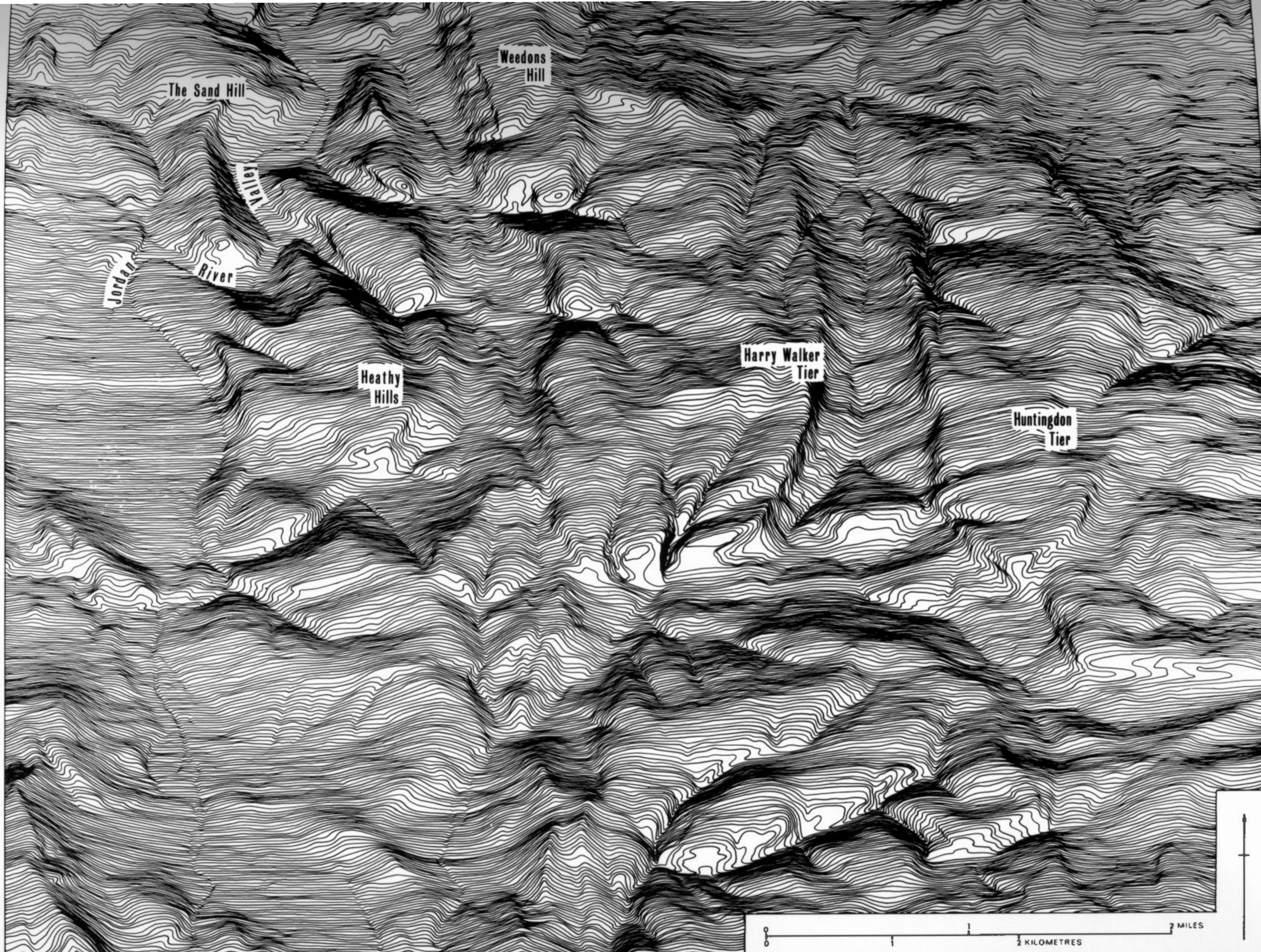
Between Heathy Hills and Weedons Hill is a large NNW trending valley in Triassic sandstone. The valley sides are straight and parallel, and are almost certainly the result of structural control. Running up the centre of this valley is a dolerite dyke at least 4 kilometres in length, which stands out as a linear ridge due to differential erosion. This dyke has undoubtedly exploited some major pre-existing weakness, namely one of the series of NNW striking faults.

Faulting may have played a significant role in the development of the Jordan River valley. This is suggested for example by the markedly straight dolerite scarp, some 2 kilometres in length, forming the abrupt south-western boundary of the floodplain midway between Broadmarsh and Elderslie.

To the north and east of Elderslie, large mesas of Triassic sandstone dominate the landscape (Fig. 2). Streams here have incised deeply along zones of weakness, producing narrow gorge-like valleys often over 100 metres deep, with characteristically cliffed margins. The regular arrangement of these mesas, again with predominant NW to NNW trending lineations (Fig. 3), most certainly suggests that faulting has played a large part in their evolution, although some valleys at least have been formed by stream incision along preferred joint directions (page 29).

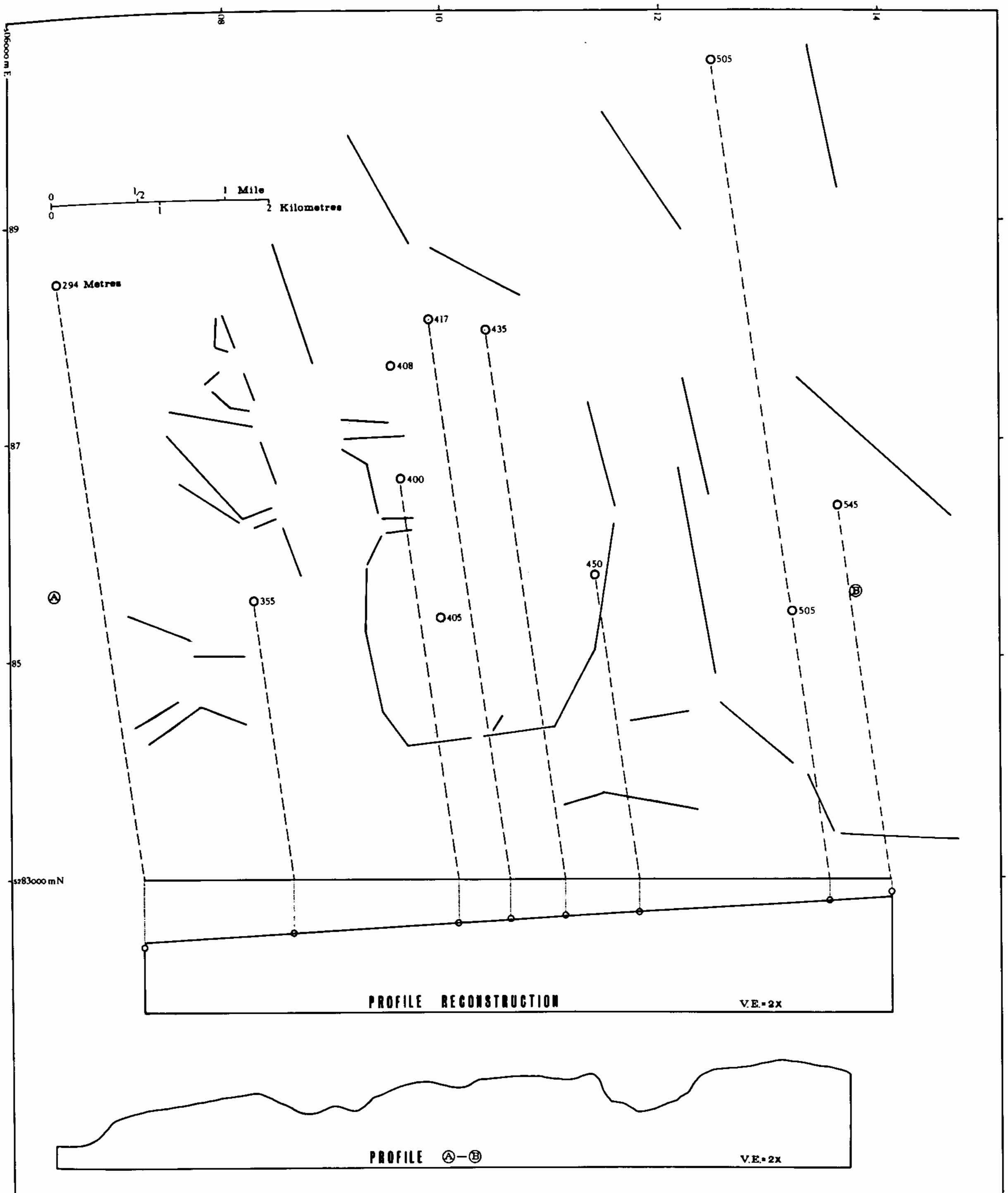
From Heathy Hills to Huntingdon Tier, concordant mesa summits form a broad gently sloping plateau (Plate 1). In Figure 3 the heights of selected summits within each mesa have been extrapolated along parallel lines, and are shown in cross-profile about a straight line. The remarkable alignment of these summit heights strongly suggests that this surface is structurally controlled. Although selection of summits in this analysis was largely subjective, those selected are all the highest and most prominent sandstone levels on each mesa, and undoubtedly represent the undissected remnants of a former surface. For comparison, a profile across the mesas has been included in Figure 3,

FIGURE 2



ORTHOGRAPHICAL RELIEF MAP OF THE SANDSTONE MESAS

FIGURE 3



LINEAR MESA BOUNDARIES & SUMMIT RELATION

PLATE 1.

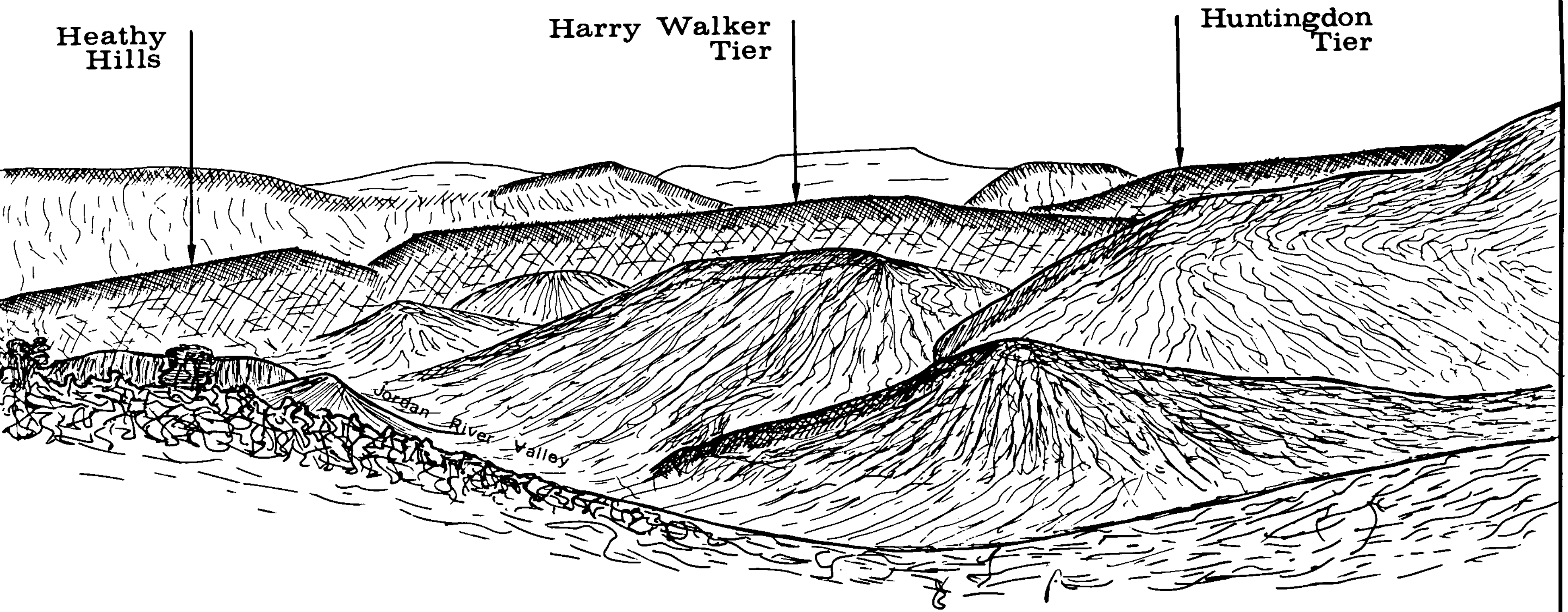
The sandstone mesas looking north-east.

and shows that no significant modification of this surface has occurred.

McDougall (1959b) found that the Triassic strata in the Dromedary area dip to the south-west, and enough satisfactory readings were made to establish this same trend for the Elderslie area. By plotting a close grid of spot heights, and considering variations in elevation between adjacent points as vectors, a vector sum for each mesa summit was produced. (This 'slope-vector' method determines the general trend of a sloping surface, and has the advantages of trend-surface analysis by virtue of its consistency, while allowing considerably more rapid calculation.) The vector sums from each mesa generally pointed WSW, close to the direction of dip of the beds, confirming the structural control of the mesa surface. On Huntingdon Tier and Harry Walker Tier the sandstone beds are dipping gently (2^{o} - 6^{o}), whereas dip-angles of up to 19^{o} (although generally at 8^{o}) were recorded at Heathy Hills. As expected, the steepening of the dip at Heathy Hills is reflected by the mesa surface - when viewed from Mt. Dromedary (Fig. 4), the increased slope is clearly demonstrated.

Further west across the valley of the Jordan River, the beds again resume more gentle dips, so that the

FIGURE 4



Landscape Sketch looking North from Mt. Dromedary steepening at Heathy Hills is most likely associated with some local disturbance, possibly the faulting in the valley on its eastern margin, mentioned previously.

Although it was not possible to relate the trend of the mesa surface with the dip of the Triassic strata other than in general terms, due to local variations and the difficulties in obtaining accurate dip measurements, the results of this investigation most certainly show that this surface is a dip-slope, formed from stripping along gently tilted bedding planes (Plate 2). The marked alignment of the mesa summits suggests that the sandstone was originally overlain by readily eroded sediments, possibly the same mudstones and shales which outcrop on the western side of the Jordan River valley opposite Heathy Hills at approximately the required level.

PLATE 2.

Sandstone dipslopes north of
Elderslie.

RELIEF.

Mt. Dromedary, at 989 metres (3245 ft.) above sea level, is the highest peak within the Broadmarsh - Eldorslie area. Extending north-west from Mt. Dromedary for 10 kilometres is a prominent flat-topped ridge at about 800 metres, forming the south-western drainage divide. The high ridge dominates the landscape of the area and represents a remnant monadnock of the St. Clair Surface defined by Davies (1959). Of the five surfaces postulated by Davies, this is the only clearly defined surface within the area, and presumably remains due to a thick resistant dolerite capping.

East of Broadmarsh, Mangalore Tier forms a prominent dolerite surface generally above 600 metres. A pronounced surface on dolerite at about 600 metres is again found at the far north-west boundary of the study area, and immediately to the south around Espies Crag this level is repeated on sandstone.

An analysis of summit frequencies showed no obvious accordant levels and so the area was divided into 500 metre squares, and spot heights within each square were selected by 'stratified systematic unaligned' sampling (Berry and Baker, 1968). It was hoped that by selecting points in this way, the need for selection of a more complete coverage of points would be avoided, however the resulting altitude-frequency graph showed very little significant peakedness, even at the 800 metre level. Consequently the area was further subdivided into 250 metre squares, and to facilitate more rapid calculation, this time spot elevations were taken from the centre of each square. The altitude frequency graph obtained from this increased number of points clearly accentuated the observed 600 and 800 metre levels. Apart from an expected high frequency in the 300 to 500 metre range - the general elevation of the mesas - the graph revealed several small peaks at the 740, 680 and 530 metre levels. These peaks reflect the stepped character of the landscape below Espies Crag and Mt. Dromedary. Near Espies Crag the sandstone is again dipping to the west and south-west, in the reverse direction to the general trend of the landsurface, and so continuous stripping of the sandstone along bedding planes, as in the 'mesa-area', has not so readily occurred; rather the sandstone beds have produced a stepped landscape in sympathy with the general trend of the land surface. Below the stepped levels, streams have developed very steep valley-heads, often with precipitous valley-head cliffs, and run between flat stepped spurs. One such spur at least (5040E, 52868N) has a pronounced backslope due to stripping along the tilted bedding-planes. The stepped benches below Mt. Dromedary are less pronounced. They are developed principally on Permian sediments, and again appear to be largely structurally controlled, or at least to have greatest affinity with particular rock-types.

COMPARATIVE MORPHOLOGY.

The smooth rounded summits and broad open valleys developed in dolerite areas, are readily distinguished from the deeply incised cliffed valleys and flat summits of the 'sandstone landscape' (Plates 3, 4, 5, 6).

To demonstrate the changes in topography, an isotangent slope map has been prepared (Fig. 5). Construction of isotangent lines as described by Strahler (1956), was intended expressly for areas which had been mapped with close contours, and so the isolines constructed from 10 metre contour intervals in this case can only be approximate. Also, working from a 1:31, 680 scale map, interpretation of contours becomes largely subjective. Nevertheless, this map does serve to distinguish the general variations of the landscape morphology, and is particularly appropriate for this study, since steep slopes are characterized by a marked convergence of isolines, so that the sandstone mesas are clearly delineated.

The pattern of isolines shown on the dolerite areas (generally south of 52800 metres N.) is by contrast open and irregular, reflecting the rounded and disoriented topography so typically developed.

Flat summit and basal areas are indicated on the slope map and again serve to emphasize the contrasting topography.

PLATE 3.

Dolerite and sandstone hills at the northern end of Weedons Hill. (The dolerite hill on the left has a smooth rounded summit in contrast with the flat-topped and cliffed summit developed on sandstone.)

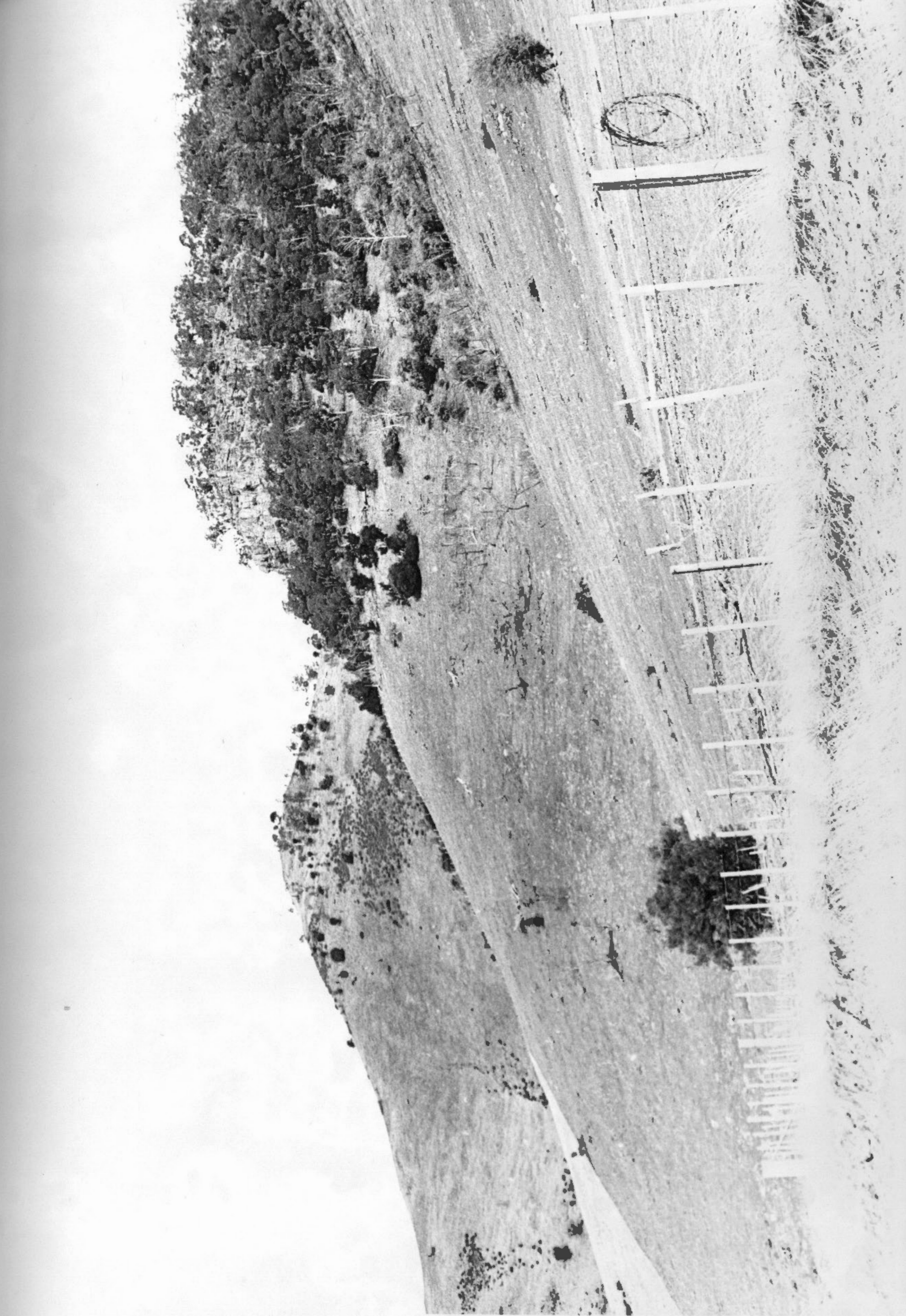


PLATE 4.

A typically rounded topography
of the dolerite areas.

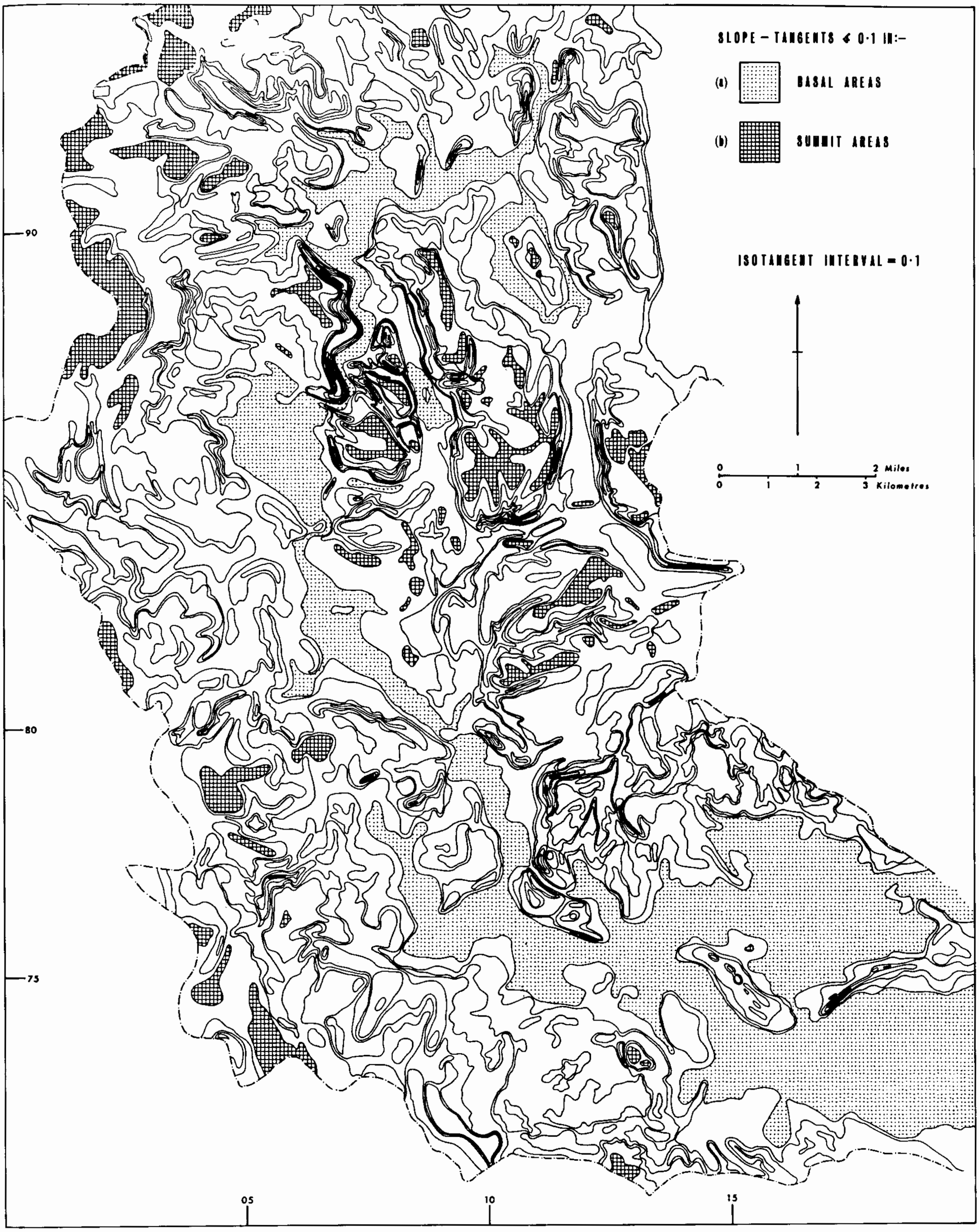
PLATE 5.

The cliffed and flat-floored
valley of the Jordan River in
the sandstone area.

PLATE 6.

The broad open valley below
Mangalore Tier, typical of
the non-sandstone areas.

FIGURE 5



ISOTANGENT SLOPE MAP

The southern portion of the study area is characterised by wide open valleys developed principally on the basalt surface, on Permian sediments below Mangalore Tier, and in the Jordan River valley (Plate 6), whereas to the north in the sandstone area, basal flats are confined almost exclusively to the now narrow floodplain of the Jordan River valley, and flat summit areas, on mesas and stepped benches below Espies Crag, are decidedly more prevalent.

Drainage Networks.

Of major concern in the study of drainage networks was the problem of defining exactly what stream lengths to measure - those marked on the Kempton and Broadmarsh dyeline sheets were not entirely satisfactory and in this analysis they have been supplemented from interpretation of aerial photographs.

Density: Drainage densities are generally given using drainage basins as the unit area, but as Lewin (1969) has observed, densities may vary from head to mouth within each valley, and valley networks may also influence the density values recorded by virtue of their variation in area. Consequently drainage densities were computed for each square mile, but since it was possible using such small areas almost to avoid valleys, thus giving abnormally low figures, the values of each four adjacent squares were averaged for use in the final analysis. Selected values are indicated (Fig. 6).

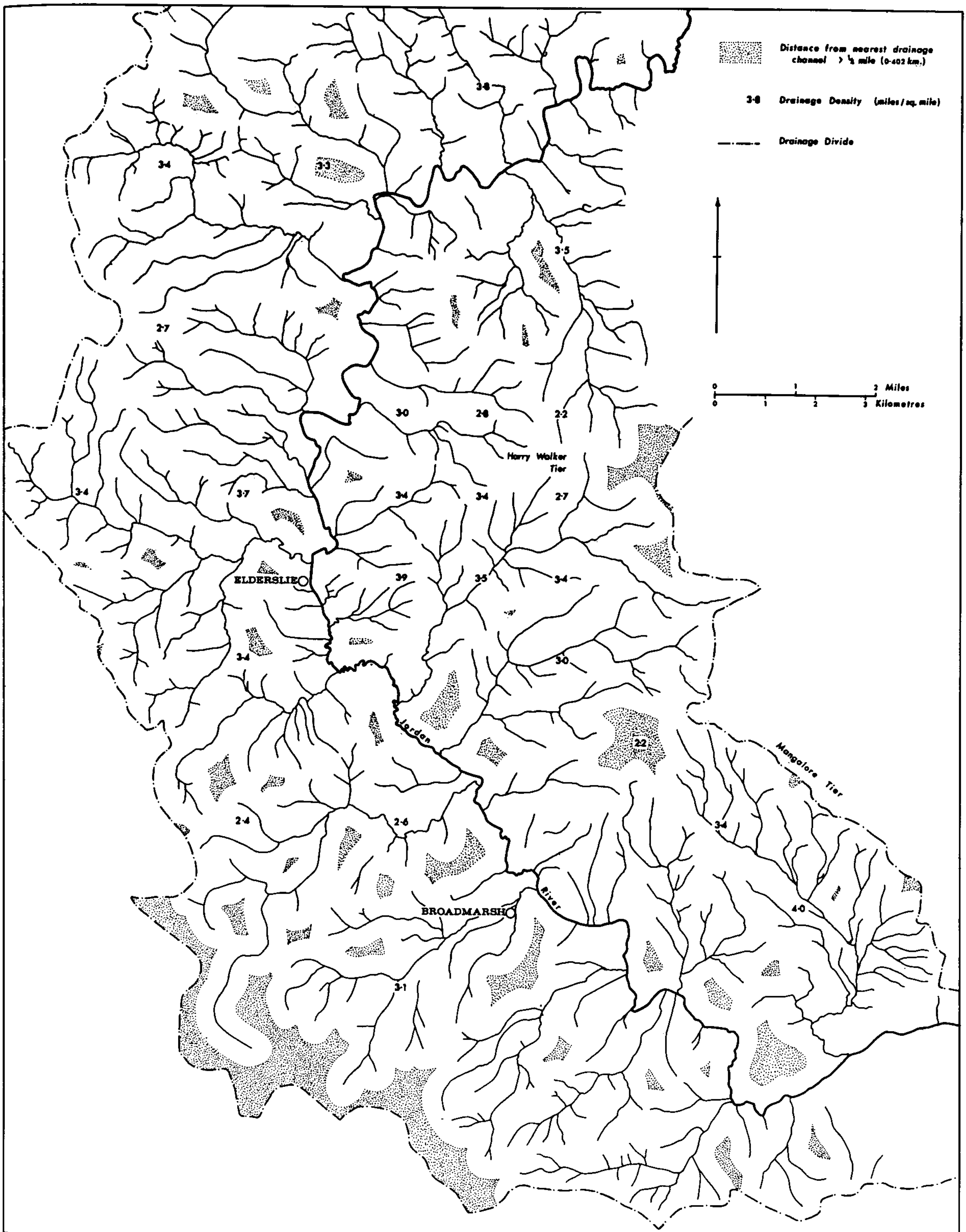
Apart from showing an increase in drainage density from the watersheds, the drainage densities recorded over the sandstone areas (generally north and east of Elderslie) are remarkably uniform (approx. 3.4 miles/square mile) whereas non-sandstone areas show a much greater variation (between 2.2 and 4.0 miles/square mile).

Areas in which valley axes are greater than ½ mile apart have also been indicated on Figure 6. These areas also reflect the variation in drainage densities, for the sandstone areas generally show a uniform drainage coverage, whereas in the non-sandstone areas around Broadmarsh, the distances between drainage channels are significantly greater.

Pattern: The sub-rectangular networks developed in the sandstone area east of Elderslie (Fig. 6) prompted a closer examination of stream patterns. In particular it was hoped to determine the differences in drainage pattern, if any, between the sandstone and dolerite areas.

For each 2-mile square, straight segments of the streams were stepped-off, and the orientation of each segment was allocated to one of 16 classes around the

FIGURE 6

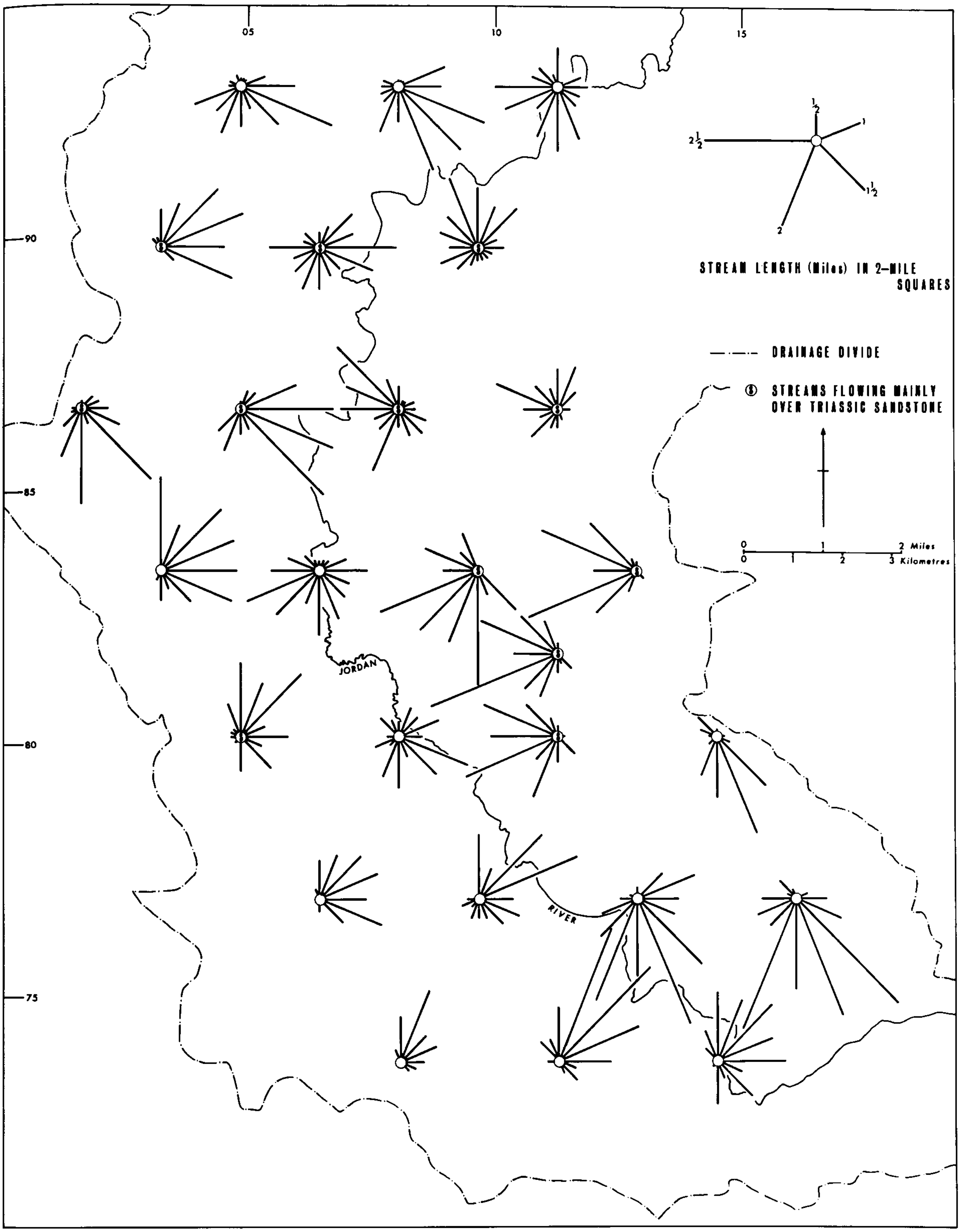


DRAINAGE NETWORKS

points of the compass and plotted on a rose diagram (Fig. 7). Roses which have been constructed principally from streams flowing on Triassic sandstone are indicated. In the non-sandstone areas, alignment of streams is most commonly in sympathy with the general slope-trend of the landsurface, whereas in the sandstone areas, orientation of the streams is generally more selective. In particular, in the 'mesa area' east of Elderslie, there is a marked preference for WSW and WNW alignment.

Joint directions were recorded from several locations within the mesa area, and in most cases there were prominent joint directions closely aligned with the nearby valleys. Of notable significance is the result of joint measurements recorded at the southern end of Harry Walker Tier (5103E, 52843N). Here three straight valleys intersect and flow off the Tier through a steep gorge. Some 64 joint directions were recorded from the cliffed edges of this gorge and the upstream valleys, and three joint-trends were repeatedly encountered - these three trends coincided _exactly_ with the directions of the three valleys. As suggested earlier, the large valleys separating the mesas may well be fault-controlled, but jointing most certainly has played a major role in the orientation of many of the smaller sandstone valleys, and in the

FIGURE 7



STREAM LENGTH AND DIRECTION

development of trellised drainage patterns.

Topology: The topology developed on the different rock-types also shows some variations. In particular, the networks formed on Triassic sandstone seem 'coarser' than in other areas.

The drainage networks were ordered following the scheme suggested by Strahler (1957), however using this system very little distinction between networks was apparent. In particular, some quite complex drainage networks had abnormally low orders. In recognizing this problem, Lewin (1969) observed that

> many valley patterns are of the pinnate type, with a large number of first - or second - order streams joining a trunk valley which is then not joined by valleys of higher order.
>
> This phenomenon points to certain problems in using the Strahler/Horton system of ordering. Pinnate systems are allocated a low order value in comparison with dendritic systems involving the same total length of valley and draining the same area.

Consequently, Lewin proposed an alternative system of stream-ordering in which all channel segments are considered equally. In this system, all outer tributaries are considered to be first-order, and where they join, second-order valleys are created as previously. However as soon as the point is reached above which there are 4 segments, a third-order valley is created; at the point above which 8 segments exist, a fourth-order valley is created, and so on.

However, although this system gave a slightly better distinction between the networks when applied to this study, again no significant differences were apparent. The Lewin system of ordering does give a better value describing the <u>size</u> of a drainage system, but gives no real indication of the <u>character</u> of the system, even when the various parameters used in the Strahler/Horton system are applied. So in order to reveal the differences in texture of the drainage patterns, both ordering techniques were discarded, and an analysis of stream lengths was made.

In this analysis, trunk streams were selected on the basis of the arrangement of confluences of tributary streams - where a tributary showed an obvious continuation past a confluence it was selected as the trunk system, so that the confluence became the lower limit for the more angular connecting stream, and where both tributaries showed no obvious continuation, the longest was selected as the trunk stream. In this way it was hoped that a greater range of stream lengths would be recorded, which might more readily reveal any differences present. The stream lengths were then allocated to one of 14 classes, so that each tributary is ordered on an ad valorem basis, and streams of vastly different lengths cannot have similar orders as in the Horton/Strahler system.

This system has a further advantage, in that by constructing a frequency distribution from a continuous variable, the data is readily available for conventional statistical techniques. Here only the mean and modes have been considered, but it seems likely that more adequate statistical parameters could well reveal quite small but consistent variations in topology.

For this analysis, 3 streams were selected from both the sandstone and non-sandstone areas (Fig. 8), and for comparison Table 1 lists the results of ordering techniques and the stream-length technique for each of these streams.

As suspected, the mean length of streams flowing over Triassic sandstone is greater than for those streams in non-sandstone areas, and again, modal values are significantly higher for the streams flowing on sandstone. The exception is stream No. 6 which gave an insufficient sample of stream lengths for an accurate analysis. Certainly however, on the more complex networks, this method does readily reveal slight topological differences,

FIGURE 8

&

TABLE 1

TABLE 1.

STREAM NUMBER (Fig. 8)	1	2	3	4	5	6
STRAHLER ORDER	4	3	3	3	3	2
LEWIN ORDER	7	6	5	6	6	4
MEAN LENGTH (Miles)	0.72	0.61	0.49	0.76	0.86	0.77
MODAL VALUES (Miles)	0.23 0.55	0.08 0.55	0.23	0.31 0.70	0.39 1.17	0.23

STREAMS FLOWING ON DOLERITE AND PERMIAN SEDIMENTS

STREAMS FLOWING ON TRIASSIC SANDSTONE

and although more tedious than previous ordering techniques, its use, at least in this study, is surely justified.

Because the number of streams measured here is too small to allow any positive assessment of the effect of varying lithology, a further 8 streams were measured. The same differences resulted, confirming that the drainage texture developed in the sandstone area is significantly coarser. Generally, thicker layers of soil are found on dolerite than on Triassic sandstone, and underground seepage of water may be more significant in the dolerite areas, so that as noted previously, the watersheds are wider in the dolerite areas and channelling does not occur high up on the slopes, and first-order tributaries are generally short. On the other hand, increased runoff on the sandstone may have caused earlier channelling, extending first-order streams and reducing the watershed area.

Sandstone Caves.

Unique to the sandstone areas is the development of caves in the valley-side cliffs. The caves have characteristically pitted honey-combed roofs with fluted walls where cross-bedding structures have been etched out. The floors are covered with fine sand derived from breakdown of the sandstone. Flat iron-rich joint faces often remain due to their increased resistance to weathering. They vary in size and shape and appear to have no preference for particular horizons, although often the floors slope with the direction of dip of the sandstone beds (e.g. by the roadside at 5066E, 52867N), suggesting that percolation of groundwater along preferred bedding planes may be largely responsible for their initiation.

As Goede (1964, unpub. Hons. thesis) has observed in the Buckland Basin, cave development occurs on both sheltered and exposed positions. Goede has suggested that these caves are formed by chemical weathering by hydration of salts contained in the sandstone cement. McIntosh Reid (1922) found that salts have been redeposited on the floors from solutions percolating through the sandstones. Goede and the writer found no redeposition of salts on the floors of the caves visited, however one resident of the Elderslie area claims to have found 'high quality pickling salt' in one cave in the vicinity of 5105E, 52835N.

HILLSLOPE ANALYSIS.

The striking contrast between dolerite and sandstone hillslopes in the Broadmarsh - Eldersslie area prompted their close examination. This investigation has led to a deeper analysis of their form and development.

Method.

The site for each slope was selected where contours are rectilinear, since as Pitty (1966) has suggested, on sections where contours are convex or concave, slope wash may become more diffused and more concentrated respectively. In this way also, slopes on the axes of spurs were avoided, so that each slope selected was the result of modification in one direction only, and was not effected by the back-to-back wasting often associated with ridge-end slopes.

Following the scheme outlined by Pitty (1969), the inclination of successive unit lengths of the hillslope from the summit to the base were recorded. This method of hillslope measurement was particularly favoured since it requires no field assistance, unlike precise surveying and other levelling techniques. Where obstructions such as trees were encountered along the line of slope measurements, readings were taken to the side by moving along the slope-contours, and the section line was resumed when the obstruction had been passed. Where possible, outcrops have been similarly avoided, so that the resulting slope measurements reflect essentially the angle of rest of loose material on the slope.

Initially, the 'inclined board' technique (Strahler, 1950) was adopted using a 10 ft. collapsable rod. This rod was placed on the slope surface and the inclination of the rod was recorded using an abney level. However this method not only proved most time-consuming, but where vegetation was dense, it was often difficult to obtain an accurate measurement of the ground surface. In such situations, at best, the top of the vegetation could be measured. A slope pantometer (Pitty, 1968) proved similarly inadequate. Subsequently a new device was constructed which facilitated more rapid and easier progress, and largely eliminated the problem posed by vegetation. (A description and diagram of this new device is included in appendix A.) Since this device measures the slope in units of 5 feet, successive pairs of readings were adjusted for consistency with the earlier slope measurements.

In measuring the hillslopes, one problem was repeatedly encountered - that of determining the lower limit of each slope. Some slopes merged so gradually onto the valley floor that it was impossible to satisfactorily delimit the basal section. However at several sites it was observed that basal slopes maintained angles of up to 9 degrees for large distances out onto the valley floor, and for consistency, all angles less than 9 degrees in the basal section have been discarded in this study. This has an advantage in that low angles recorded from the summit areas become clearly defined in the analysis.

For the purposes of this study, it is assumed that each rock-type is homogeneous and uniform within the area. In some localities the dolerite is more strongly shattered than elsewhere, and this shattering no doubt facilitates more rapid weathering and downslope movement of debris. However in most cases strong shattering appeared to be very localized, and it was assumed that where it occurs the slopes are not significantly effected as a whole. Variations in lithology between the 'sandstone' slopes is however a more serious problem, due to the wide variations within the Triassic System. It is hoped that this problem has been largely overcome by selecting slope sites in nearby areas. Seven of the sandstone slopes come from the main valley and offshoot valleys between Heathy Hills and Weedons Hill. Even within such a localized area, correlation of beds is difficult, but the regular relation of mesa summits as noted previously, and the regular occurrence of quartz sandstone on the exposed cliffs at the summit of these selected slopes, suggests that approximately similar lithologies occur.

The aim of this study was to elucidate the differences in form between slopes developed on sandstone and on dolerite and if possible, to determine the mode of formation and factors influencing the development of these slopes. Consequently, to investigate the effect of aspect on slope development, the orientation of each slope (from the summit in the direction of the slope section) was also recorded. In particular, to give any significant results, as large a sample as possible was necessary, and as time was limited, 31 slopes were selected from dolerite areas (Slope Nos. 1 - 31) from which it was hoped that slope morphology could be analysed in depth, whereas only 9 slopes have been selected from sandstone areas for comparison (Slope Nos.32 - 40).

For each set of hillslope data, slope-angle frequency distributions were constructed. Following the recommendations of Pitty (1969), slope-angle classes of 2 degrees were used, with class intervals running from $-\frac{1}{4}$ degrees to $1\frac{3}{4}$ degrees, $1\frac{3}{4}$ degrees to $3\frac{3}{4}$ degrees, $3\frac{3}{4}$ degrees to $5\frac{3}{4}$ degrees, and so on. A class interval of 2 degrees is particularly desirable because the range of error of each reading using the abney level in the earlier results is almost a half degree.

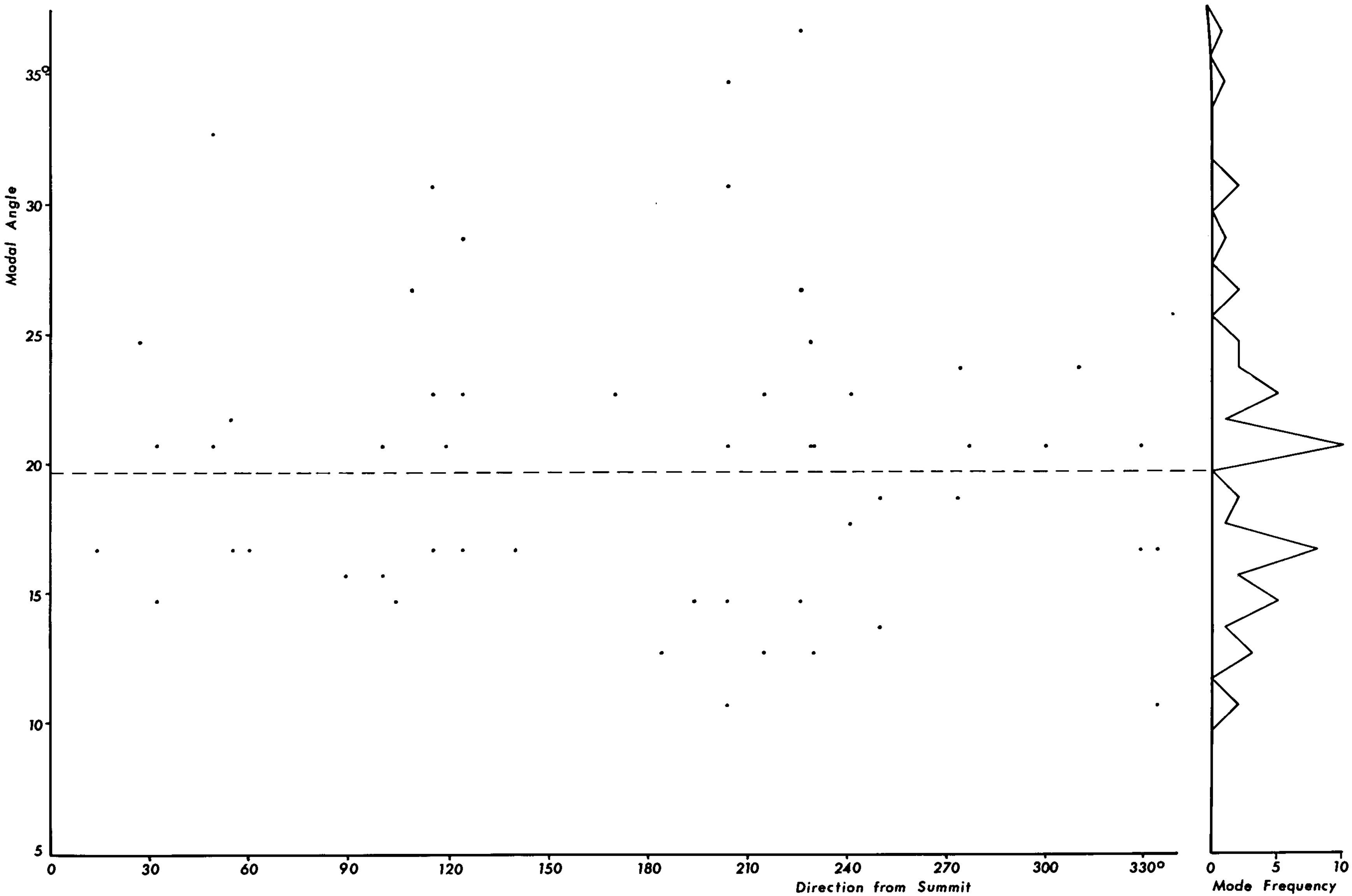
Comparison of Slopes.

Modal angles obtained from the frequency distributions of each dolerite slope have been plotted against the respective slope directions (from the summit), and the recurrence frequency of each modal value has been determined (Fig. 9). A marked division of modal values is apparent, with a strong preference for angles around 20.75 degrees and 16.75 degrees.

Since the selection of dolerite slopes was made only on the basis of rectilinearity of contours, no preference for selection was given with regard to the form of the hill-slope. Consequently, the various hillslopes measured include a wide variety of form - some are markedly undercut and steep, whereas others have gently graded basal sections. In view of this apparent dissimilarity of form, it is significant that such a division of modal values and marked preference for selected angles should occur.

To further investigate the similarities of slope-form, an attempt was made to describe each slope parametrically. Percentiles were calculated from the frequency distributions, and following the suggestions of Pitty (1970),

FIGURE 9


Modal Angle
35°
30
25
20
15
10
5
0
30
60
90
120
150
180
210
240
270
300
330°
Direction from Summit
0
5
10
Mode Frequency

for each slope the parameters of dispersion,

$$D1 = \frac{P_{75} - P_{25}}{2} \quad \text{and} \quad D2 = \frac{P_{90} - P_{10}}{2}$$

skewness, $$Sk = \frac{P_{90} + P_{10} - 2\ P_{50}}{P_{90} - P_{10}}$$

and kurtosis, $$K = 10 \times (0.263 - \frac{P_{75} - P_{25}}{2 \times (P_{90} - P_{10})})$$

were calculated.

Since it was apparent that steepness* of the slope had real significance , in particular with respect to undercutting of the base, a parameter to describe steepness was also needed. The main objection to using the mean as a parameter for steepness is that it is readily influenced by 'straggler' values. Even by employing an arbitrary lower limit of inclination for the basal section (9^{o}), variations in gradation to this limit and especially summit values can greatly effect the mean. However, it was observed that nearly all slopes maintained a predominant

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* For the purposes of this study, the term 'steepness' has been coined to refer to the degree of inclination of the predominant (generally midslope) section of the slope.

midslope facet, and it was assumed that the median Md = P_{50} would occur somewhere within this section, giving a close approximation of steepness.

Since the above five parameters give no distinction for example between slopes with short steep summits and gentle midslopes, and gentle slopes with short steep undercut basal sections, a further parameter describing the summit portion of the slope was necessary. One parameter, which evaluated the number of readings less than the median value in the upper section, with respect to the total number of readings less than the median value was considered, but it was found that midslope values had significant effect. Consequently the parameter $U = \bar{x} - \bar{x}_{25}$ was selected, where $\bar{x}$ is the mean slope-angle, and $\bar{x}_{25}$ is the mean of the upper 25 per cent of the slope-angle distribution.

For each parameter, the average and standard deviation was calculated, and standardized results (see for example Sokal and Sneath, 1963) were tabulated to give equal weight to each parameter (Tables are included in Appendix A). A program was written for the Elliott 503 Computer (also in Appendix A) to compare individual slopes on the basis of these 6 standardized parameters. This program determines dissimilarity between slopes by computing the distances between slopes when plotted in a 6-dimensional hyperspace, so that similar slope forms are plotted much closer to one another than dissimilar ones (See for example Sokal, 1966).

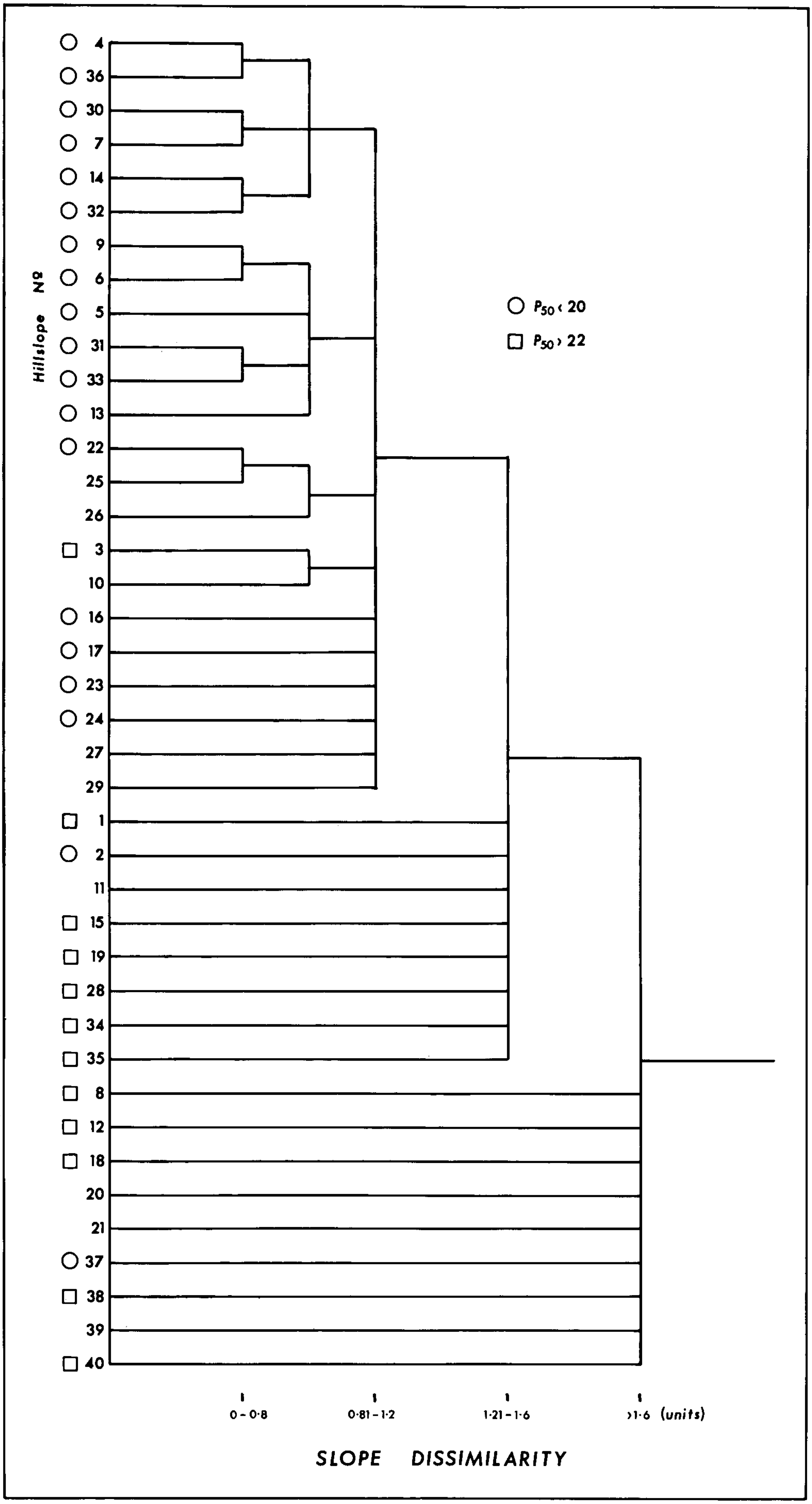
From the results of the program, arbitrary limits of 0.8 units, 1.2 units, and 1.6 units were selected for similarity groupings, and an ordered phenogram was constructed (Fig. 10).

The dolerite slopes (Nos. 1 - 31) have been numbered in order with respect to direction from the summit, and as might be expected from such a wide variety of slope situations, any effect that aspect may have on slope development is by no means clear. However slopes with median values (steepness) less than 20 degrees and greater than 22 degrees are indicated, and it is clearly apparent that greatest similarity occurs between the less steeper slopes.

The average steepness for the dolerite slopes within each similarity grouping is 17.5 degrees, 17.9 degrees, 22.5 degrees and 24.2 degrees with respect to increasing dissimilarity, further indicating that similarity increases with decreasing steepness.

Since only few sandstone slopes were measured it would be hazardous to assume that the same relationship occurs

FIGURE 10



Hillslope Nº
4
36
30
7
14
32
9
6
5
31
33
13
22
25
26
3
10
16
17
23
24
27
29
1
2
11
15
19
28
34
35
8
12
18
20
21
37
38
39
40
$P_{50} < 20$
$P_{50} > 22$
0 – 0·8
0·81 – 1·2
1·21 – 1·6
>1·6 (units)
SLOPE DISSIMILARITY

on both rock-types, however slopes 32 and 33 are singled out for comment: These two slopes were specifically selected since they have abnormally gentle slopes and are not cliffed at the summit - it is significant that with median values of 18.3 and 15.4 respectively they should occur in the greatest similarity grouping, whereas slopes 34 and 35 for example, with median values of 29.9 and 28.0, occur in the greatest dissimilarity grouping.

Many slopes showed a strong bimodality in their frequency distributions. This was particularly so on most of the longer slopes where invariably a steep boulder - strewn upper slope and a more gentle soil-covered basal slope were found. Slope 19 on the south-western side of Goats Hill clearly illustrates bimodality (Plate 7). The basal section of this slope lies at an inclination of approximately 16 degrees and meets the steeper upper section at a sharp angle. Clearly the basal slope has been built up and extended at the expense of the upper slope, and it seems likely that the low angle uni-modal slopes which occur represent the final stages of this process.

To test this possibility cumulative sum charts (cusums) were drawn for each slope which showed no basal undercutting. These charts are constructed by summing the

PLATE 7.

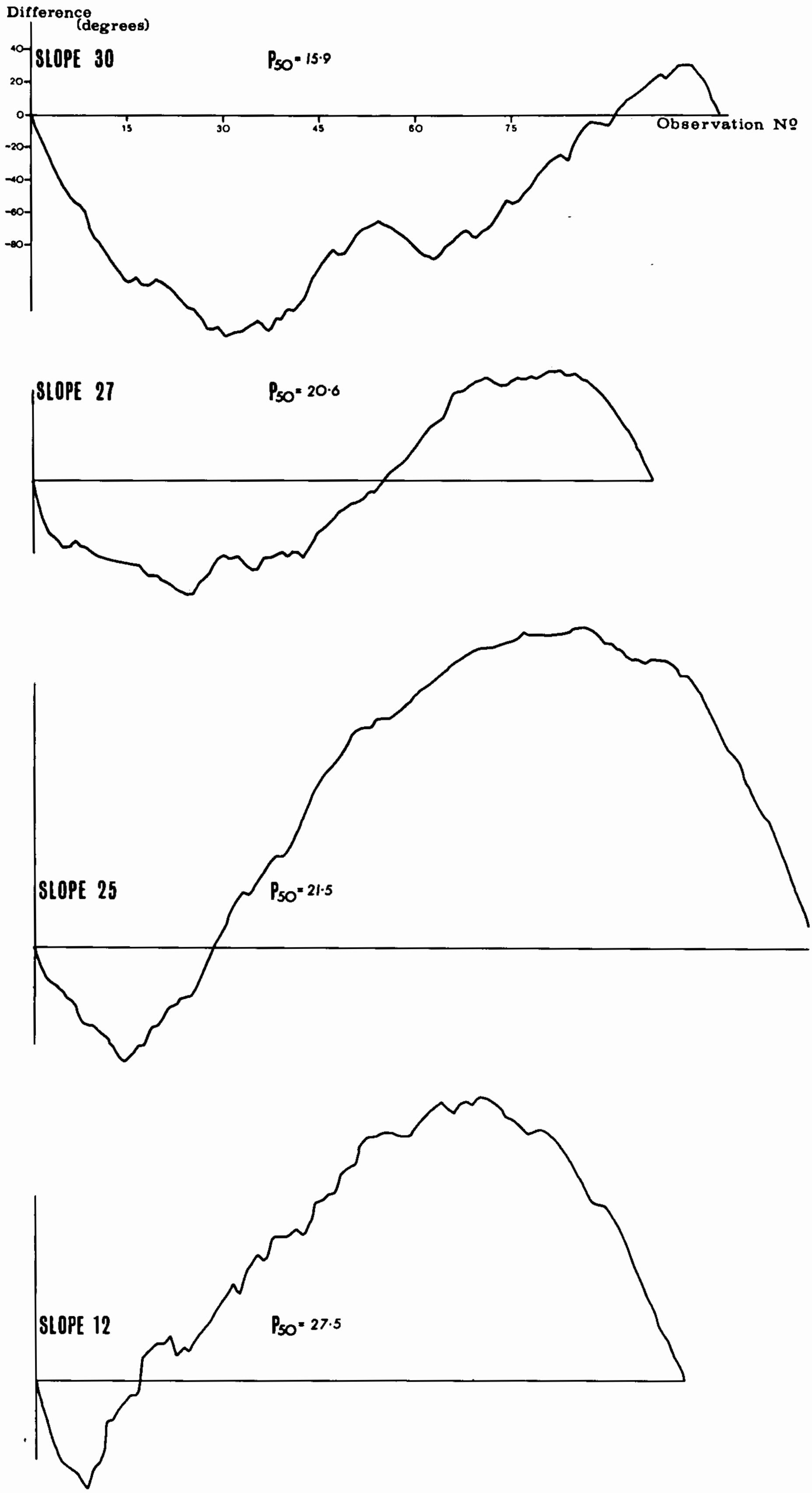
Goats Hill looking north-west.

differences between each slope angle and the mean value for the entire profile (see Pitty, 1969), and are particularly useful as they readily reveal even minor changes in slope. On such charts, linear sections represent constant facets of the slope profile, and downwarps and upwarps represent convex and concave sections of the slope profile respectively. Since slopes with similar median values (steepness) consistently produced similar cusums, only the cusums for slopes 30, 27, 25 and 12 are illustrated (Fig. 11). These charts clearly show that as steepness increases the convex (upwarped) summit section is diminished to the advantage of a constant mid-slope and basal concavity .

The basal slopes consistently have inclinations of approximately 16 degrees which may reflect the stable angle of rest of the slope debris. Hence the increased similarity of form observed with decreasing steepness most likely reflects the stage of development of these 'repose slopes' (Strahler, 1950).

Whereas the significance of the frequent occurrence of angles at approximately 16.75 degrees (noted earlier) is satisfactorily elucidated, the reason for the preference for slope angles near 20.75 degrees is by no means clear. Although only a cursory examination was made of the sub-surface, it was observed that coarse debris containing

FIGURE 11



SLOPE CUSUMS

platy dolerite fragments up to 10 cms. in length occurred on most of the midslope sections. Below this a transition into finer fragments generally occurs, until finally the basal slopes have a uniform soil cover. The observed angles of approximately 21 degrees may well reflect the angle of rest of this coarser debris.

The results of this analysis support the conclusions derived by Strahler (1950) that slopes tend to decline until they form a continuous 'repose slope', so that beyond this semi-stable state, significant slope development occurs only after the reduction of base-level and steepening of the basal slope.

The Contribution of Aspect.

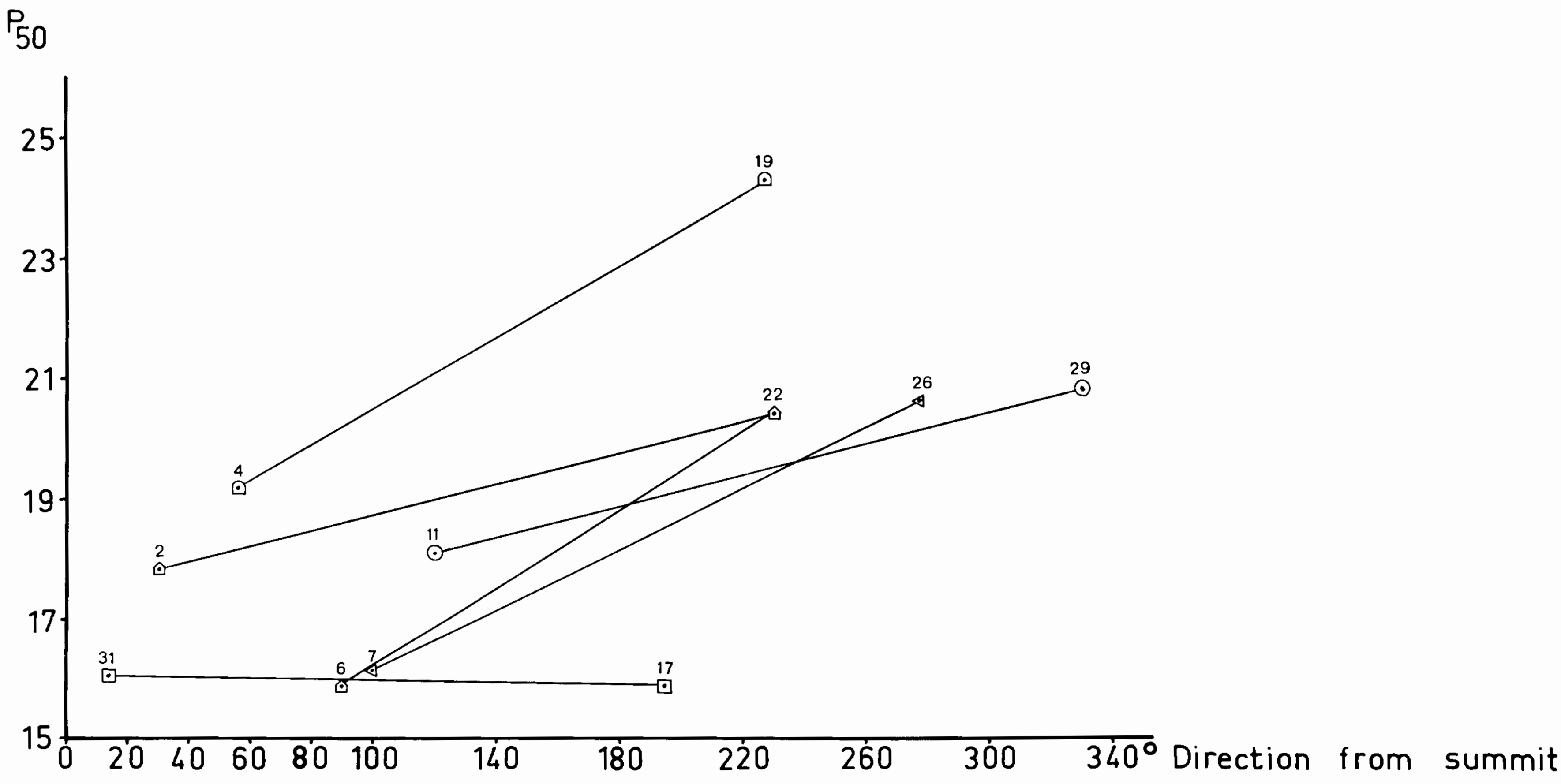
Several hills in the Broadmarsh area appear asymmetrical, and initially it was hoped to investigate the effect of directional exposure in slope development (N.B. The pronounced asymmetry shown on Plate 7 is misleading since the north-east facing slope is not shown in orthogonal profile). However as noted previously, the readily accessible dolerite hills in the Broadmarsh area occur principally in NW-SE trending ridges, and since slopes on the axes of ridges were not acceptable for this study, very few satisfactory slopes facing north-west and south-east were available.

It was apparent that the effects of undercutting by streams was a dominant factor in slope development, locally destroying or at least masking any effects which aspect might have. Hence it was considered more profitable to compare pairs of slopes in close location which show no apparent undercutting by streams. For this purpose, opposite hillslopes having gently graded basal sections were selected, and it is assumed that equal conditions other than aspect have prevailed on these slopes. In plotting these pairs (Fig. 12) the median slope value (P_{50}) has been used since the 2 degree class interval allows no fine distinction of modal values. The median values for each pair have been linked to show that with one exception, slopes facing south and west are steeper than north- and east-facing slopes.

On three pairs of slopes flanking E-W trending valleys, the south-facing slopes appeared to be markedly undercut by streams, and were much steeper than the opposite north-facing slopes which had gently graded basal sections. Inspection of the area from aerial photographs has revealed that in a large number of similar situations, the south-facing slope is noticeably steeper than its north-facing counterpart.

In assessing the cause of asymmetry of valleys, Ollier

FIGURE 12



RELATION of SELECTED SLOPE-PAIRS

and Thomasson (1957) have noted that a major difficulty occurs with the interpretation of the effects of different rates of erosion. In particular, they have questioned whether intense erosion causes a slope to steepen or decline, for unless this is known, the contribution of a suspected process towards development of asymmetry must always be uncertain. However the analysis of the dolerite slopes in this area most certainly suggests that slopes decline by extending the basal section with accumulated debris eroded from the higher slopes, and it seems likely that an increased rate of erosion would only hasten this process. Hence the lateral stream displacement and asymmetry developed in these valleys is the result of either:

1) greater erosion on the north-facing slopes,

2) basal undercutting and steepening of the south-facing slopes,

or 3) a combination of both.

Invariably the south-facing slopes have a thick grass cover and retain quite moist soil even during extended dry periods, whereas the north-facing slopes are considerably drier with a thinner soil layer and a comparatively sparse grass cover. As suspected, on these latter slopes, down-slope movement of material is everywhere apparent — small accumulations of debris are commonly found banked-up behind clumps of grass and other obstructions.

Changes in vegetation across the valley are also reflected by the tree cover. The three pairs of slopes studied are covered with 'dry sclerophyll' forest (Jackson, 1965) which is noticeably thicker on the steeper slopes. In all three cases, on the north-facing slopes, eucalypts are largely replaced by Casuarina which are with few exceptions confined to this side of the valley. The variation in tree cover may reflect more permanent and significant differences in available moisture across the valley.

It would seem then, that rather than the stream having undercut the south-facing slope causing this slope to steepen, either material from the readily eroded north-facing slope has progressively filled the valley forcing the stream over to the northern side, or this slope has been reduced more rapidly and the stream has merely maintained its original position by removing material derived primarily from the north-facing slope. Certainly it appears that the effect of aspect is to maintain a thick retaining vegetation on the south-facing slopes, increasing surface resistivity and infiltration capacity through the thicker soil layer, i.e. as Walker (1948) has observed on slopes in Western Wyoming, differential protection by vegetation is a significant factor in slope development.

The dolerite slopes near 5108E, 52902N are of especial interest. Here the hillsides are strewn with small dolerite tors (Plate 8). These tors have apparently developed in two stages, by differential subsurface weathering and development of corestones and rounded blocks, followed by differential erosion (Plate 9). Unlike the tors described by Linton (1955) for example, which have developed in this manner, the tors found here do not retain the rounded edges formed by subsurface spheroidal weathering, and become markedly jagged in appearance, suggesting that exposure at the surface is followed by some form of mechanical weathering.

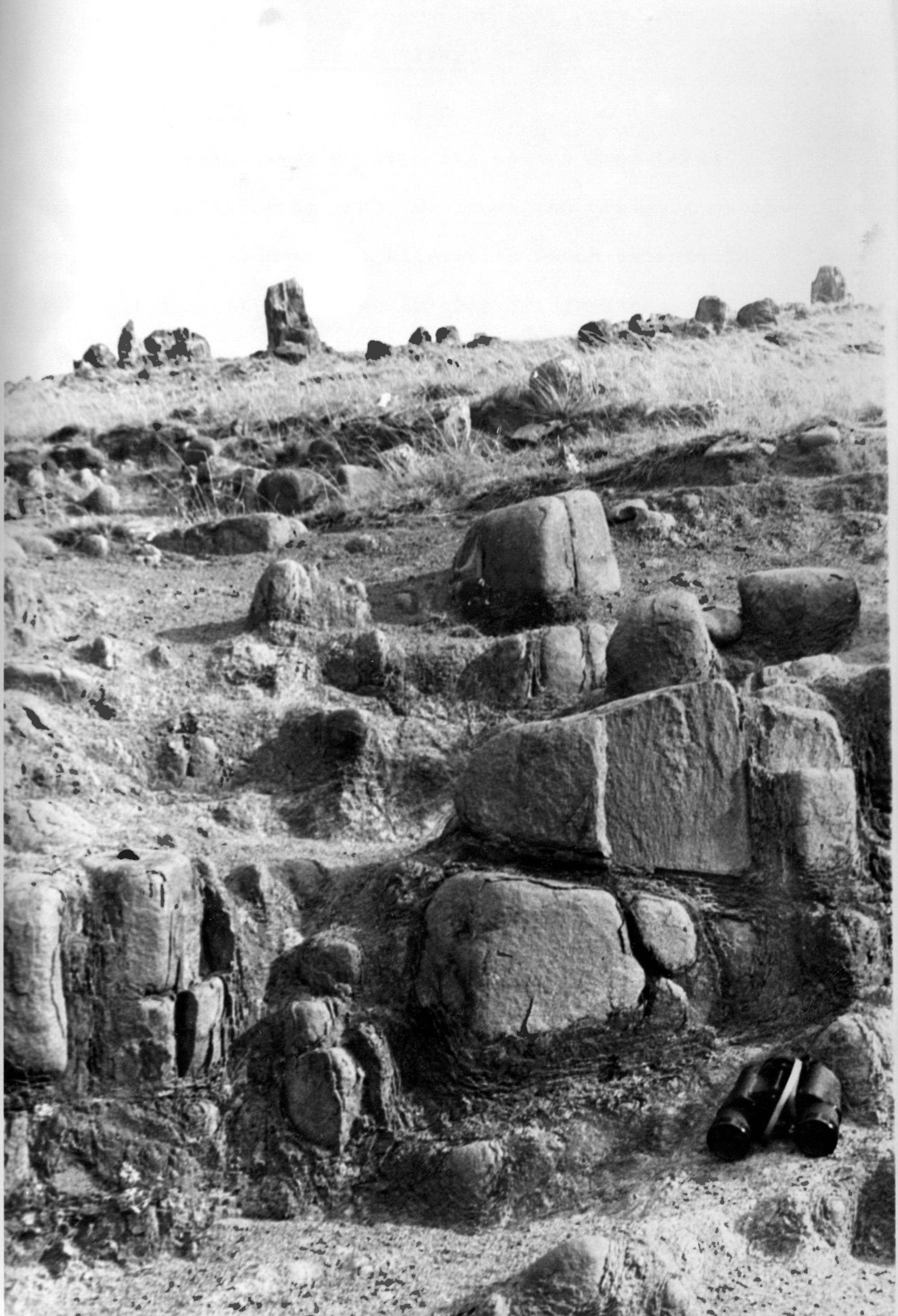
The real significance of these tors lies in the fact that on several dolerite hills in this area, the tors are found only on the north- and east-facing slopes. They are particularly well developed near the upper midslope section and become progressively infrequent and smaller towards the summit. Although these slopes are completely cleared of vegetation, and evidence of recent erosion is present, the surface weathering of the tors suggests that they originated much earlier, as the result of long standing variations in directional exposure. Their development cannot be attributed to increased subsurface chemical weathering, for it has been shown that in fact the south-facing slopes retain more moisture in the soil, so they are most likely the result of increased rates of erosion, due presumably to differential protection by the natural vegetation.

PLATE 8.

The dolerite tors.

PLATE 9.

The development of the tors.



THE JORDAN RIVER.

Jordan Catchment.

The Jordan River derives its waters from Lakes Dulverton and Tiberias near Oatlands, and drains a catchment of about 1300 square kilometres which extends 58 kilometres south to its mouth near Bridgewater.

The Jordan River is of especial interest to the geomorphologist by virtue of the river capture which has occurred near its headwaters. Capture of the upper part of the Jordan River by the Coal River was first recognized by Nye and Blake (1938) who considered that by headward extension of the Coal River northwards, the headwaters of the west-flowing Jordan River near Lake Tiberias were diverted, so that the present course of the Coal River describes a sharp right-angled bend in this area. It is doubtful however whether the loss of this section of drainage would have significantly effected the total discharge of the Jordan River. Certainly, under present climatic conditions, most of the source region receives little more than 20 inches of rainfall annually so that the outlet from Lake Tiberias for example, occupied by the Jordan River, is dry for much of the year (Leaman, 1967c).

Valley Morphology.

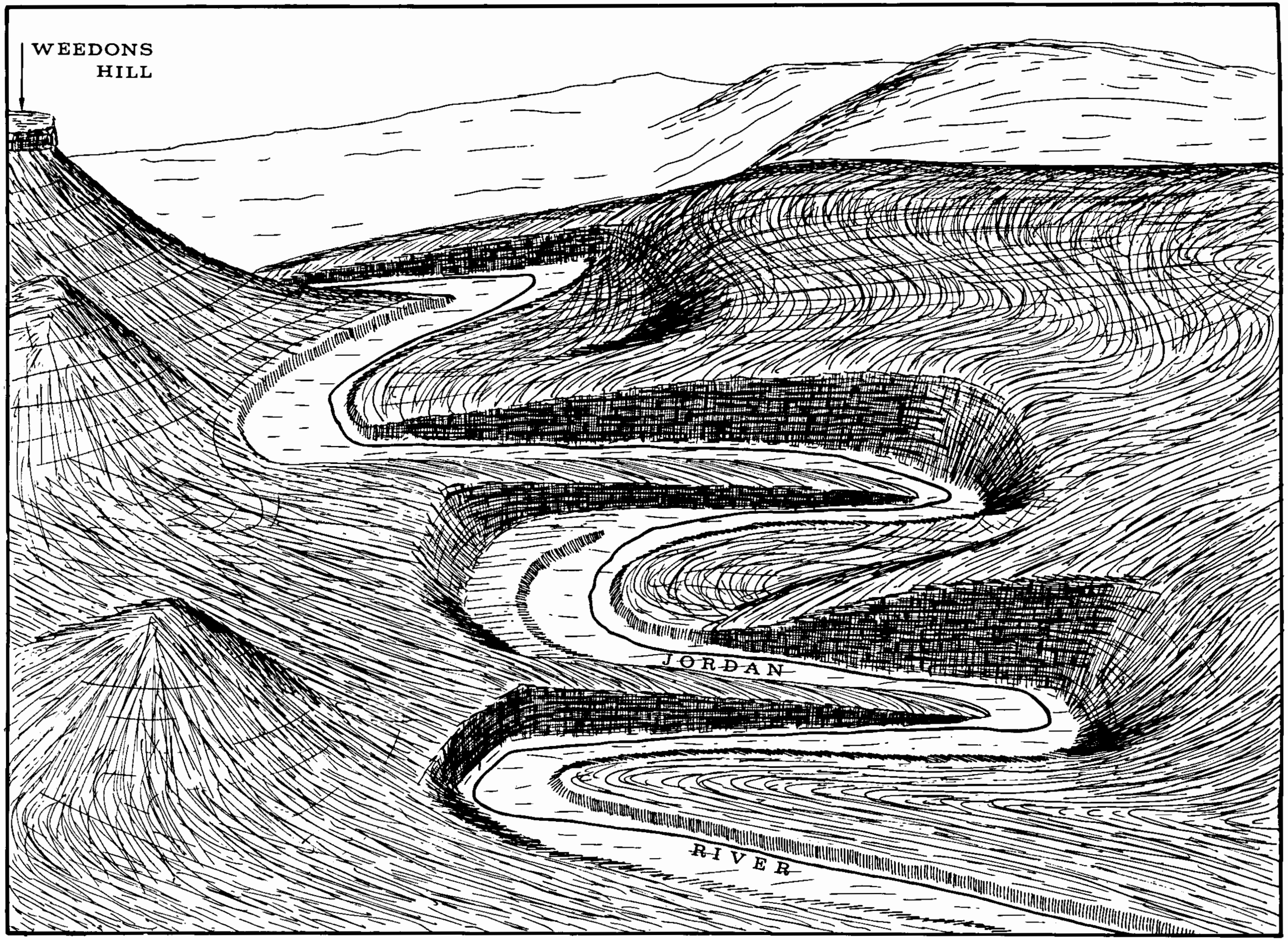
Within the Broadmarsh - Elderslie area, the valley of the Jordan River undergoes marked changes which appear to be largely related to variations in lithology and structure.

North of Weedons Hill the valley runs approximately south-west in the direction of dip of the Triassic strata, and has developed a unique morphology in consequence. The river here winds through a series of interlocking spurs. These spurs are cuesta-like in cross-section, with pronounced cliffs on the upstream side, sloping behind gently along the dip of the sandstone beds (Fig. 13, Plate 10).

Seismic traverses (using a 'Terra-Scout' Refraction Seismograph) were carried out across the floodplain between two of these spurs (T1 and T2; see Fig. 1) and indicated that an approximate subsurface continuation of these dip-slopes occurs. The seismic surveys also revealed a shallow channel beneath the floodplain, and it seems certain that the incised river meanders are so markedly ingrown because the dip of the strata has facilitated lateral incision rather than vertical incision and intrenchment. Consequently the channel has been displaced downdip, so that invariably the river now flows beneath the cliffs.

After passing through the 'cuesta-spurs' the river turns south and flows through a deep meandering sandstone

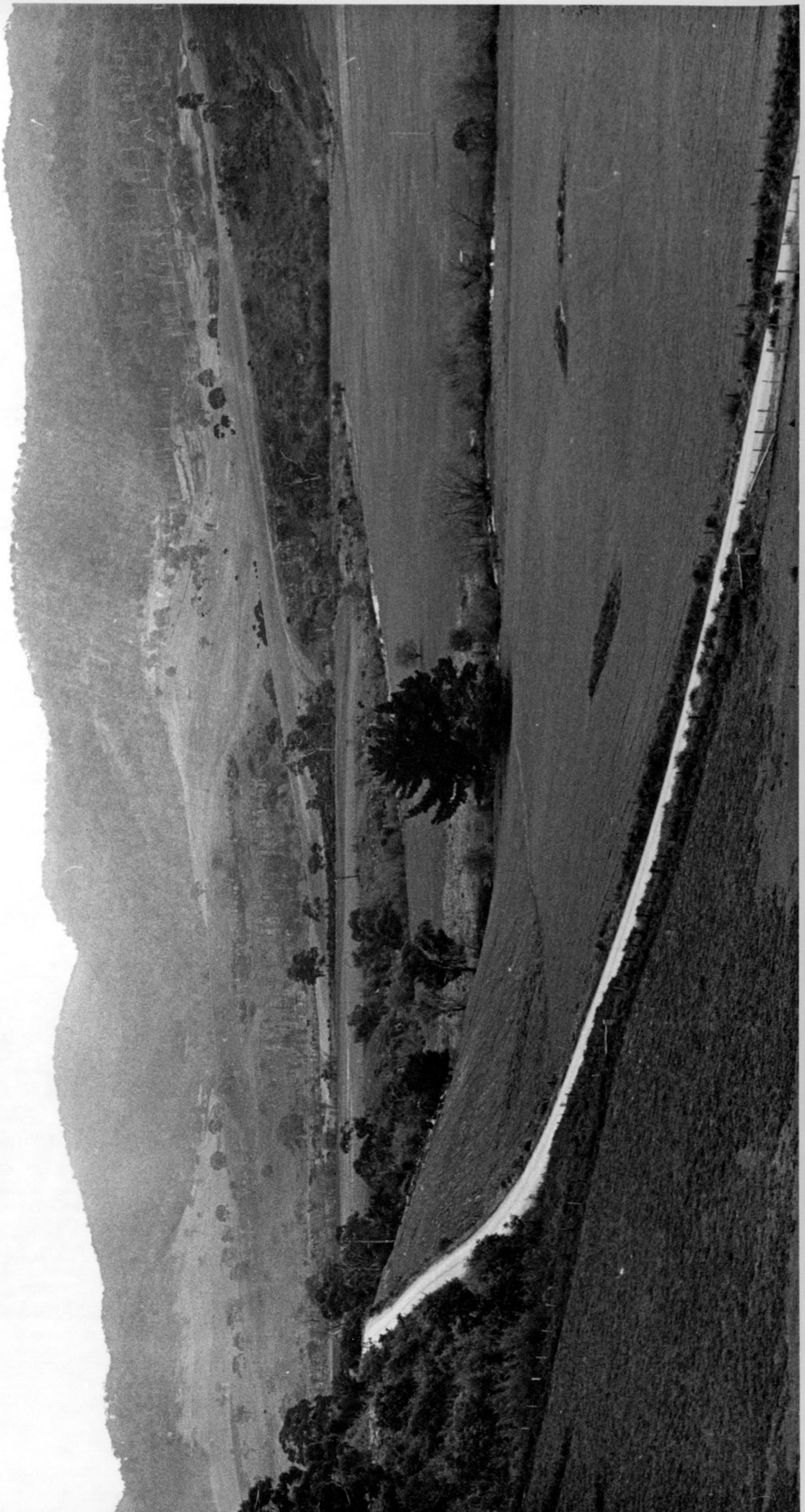
FIGURE 13



THE CUESTA-SPURS LOOKING DOWNRIVER

PLATE 10.

The cuesta-spurs looking north-west.



gorge. The uniform valley meanders described here are certainly too large to have been formed by the present river and are undoubtedly related to periods of higher discharge (discussed later). The valley here is flat-bottomed with steep and often cliffed sides (Plate 5), and it seems likely that the absence of cuesta-spurs, so typical of the valley less than 2 kilometres upstream, is the result of the change in trend of the valley with respect to the direction of dip of the Triassic strata. It might be expected that a pronounced asymmetry of the valley would develop as the river progressively favoured the western side, migrating laterally with the dip of the beds. Indeed, several valley spurs are oversteepened on this side, but no significant asymmetry is present, so that the valley meanders here have a characteristically intrenched form.

At the end of the gorge, the valley opens out into a broad floodplain, and from here downstream to Broadmarsh the valley is typically wide and open. It is significant that throughout most of its course past Elderslie to Broadmarsh, the valley is bounded on at least one side by dolerite hills. For a considerable distance past Elderslie at least, dolerite and sandstone hills occur on opposite sides of the valley, suggesting that the course of the valley has been largely influenced by structural weaknesses. Most certainly this is substantiated by the straight south-western valley wall below Elderslie, mentioned previously.

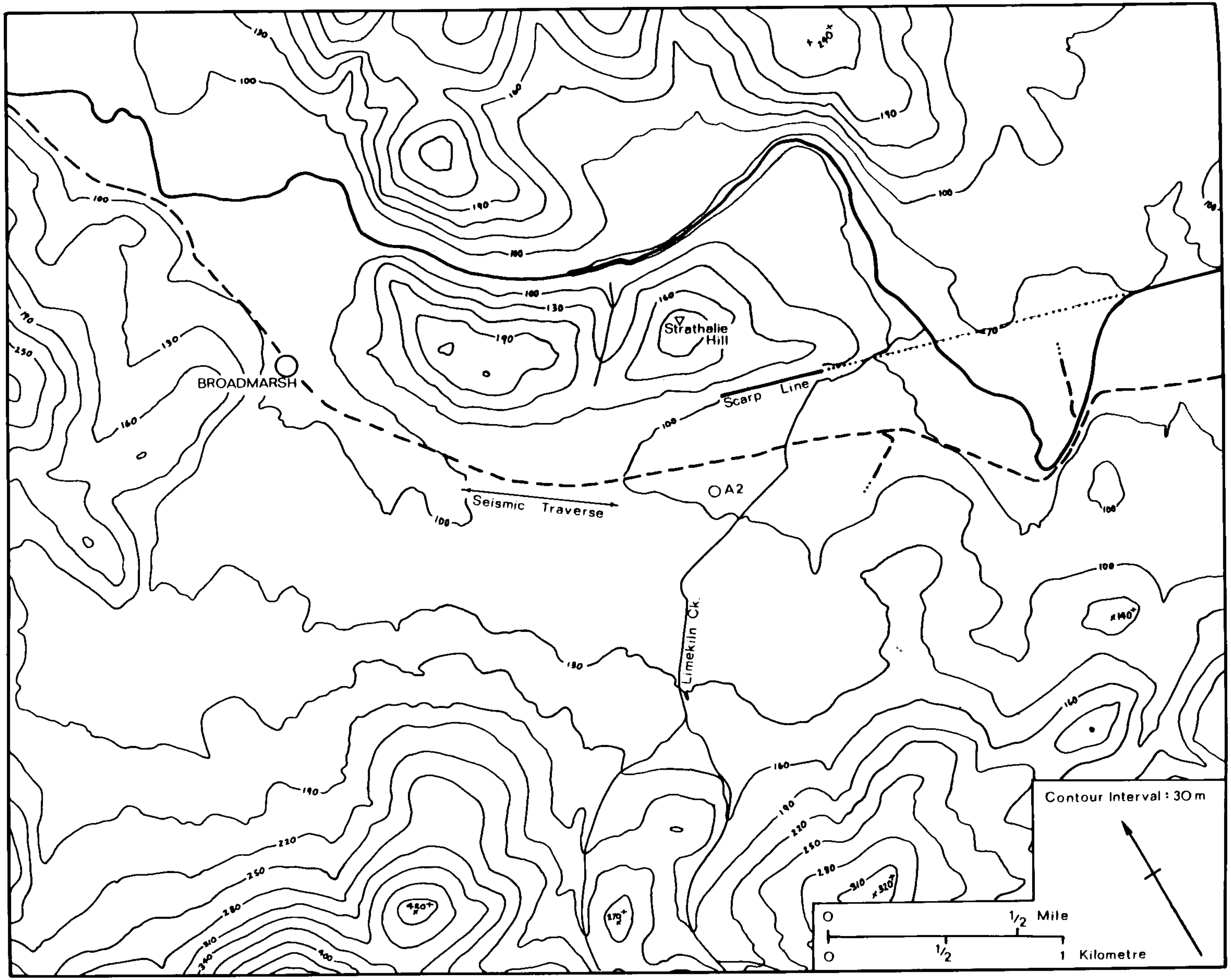
After the river has emerged from the long curved dolerite gorge behind Strathalie Hill (see below) the valley again opens out into a series of broad floodplains. A notable feature of the lower valley here is the reappearance of undercut sandstone cliffs where the river has cut through dolerite into the underlying Triassic strata.

The Strathalie Anomaly.

Near Broadmarsh the Jordan River enters a steep-sided dolerite gorge and follows a broad curving course, swinging gradually to the east behind Strathalie Hill. On the south-western side of Strathalie Hill is a wide open valley in Triassic sediments (McDougall, 1959b) which extends from Broadmarsh south-east until it meets the Jordan valley emerging from the dolerite gorge (Fig. 14).

Most certainly the softer Triassic sediments would have been more favourable for valley development, and McDougall has suggested that the river was originally superimposed on the dolerite. He found that the semi-circular course of the river follows a concentric pattern of cooling joints and considered that the broad Triassic

FIGURE 14



BROADMARSH
Strathalie Hill
Scarp Line
Seismic Traverse
A2
Limekiln Ck.
Contour Interval : 30 m
0 1/2 Mile
0 1/2 1 Kilometre

valley was originally covered by a continuous dolerite sheet, so that rather than presenting a more unfavourable location for valley development as the present surficial geology indicates, the joint weaknesses may well have presented the most favourable site.

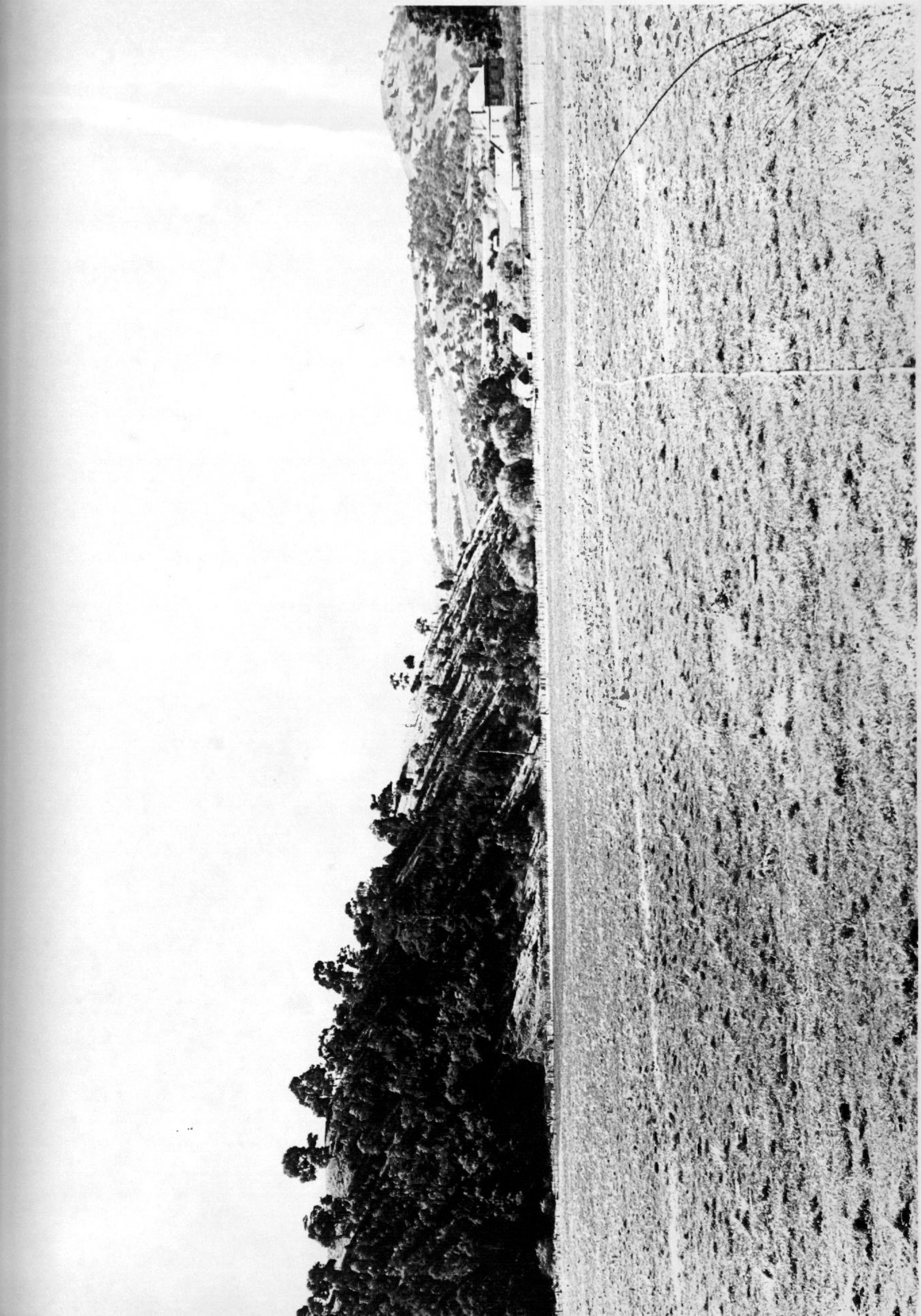
McDougall considered that this dolerite sheet has since been eroded off by 'small creeks' and that once the dolerite was removed, more rapid lowering of the less cohesive Triassic rocks ensued. Unless the dolerite covering was very thin, it is difficult to envisage such a complete denudation of this area. If this was the case greater reduction of surrounding areas might also be expected.

In short, whereas superimposition and joint control appear from available evidence to be the most satisfactory explanations for the dolerite gorge, the presence of the valley through Broadmarsh requires further examination. In particular, several unique morphological features in this area appeared to offer most profitable consideration.

The south-eastern end of Strathalie Hill is bounded by a particularly steep straight slope (Plate 11). This slope was selected as a suitable site for hillslope analysis, and it is significant that slope No. 18 measured here gave

PLATE 11.

The scarp slope at the southern end of Strathalie Hill (looking east).



much steeper values than were recorded on any of the other dolerite slopes — inclinations of up to 40^{o} (generally 36^{o}) were recorded on loose scree slopes along this section. Limekiln Creek is deflected by this slope and flows along the foot of the hill to join the Jordan River. However the present Limekiln Creek is certainly too small to have caused any significant undercutting, and it seems likely that this slope is a structural feature. This is suggested by the remarkably straight slope-face, and further substantiated by a long straight stretch of the Jordan River further downstream — this section of the river channel is in perfect alignment with the scree slope (Fig. 14).

Along the south-western side of Strathalie Hill forming a continuation of the scree slope is

> ...a sliver of much shattered and strongly metamorphosed Ferntree Mudstone (Permian) up to 200 yards wide and 1 mile long (McDougall, 1959b).

McDougall interpreted this as being due to dragging-up of the Permian beds along the dolerite contact by forcible intrusion. However this would undoubtedly lead to marked disturbance of the bedding planes, but the long horizontal zones of reeds (where presumably preferred seepage occurs) along the slope here suggests that in fact very little disturbance of the Permian strata has taken place. Indeed, based on this evidence, the possibility of faulting seems the most likely, and this has been confirmed by Leaman (1967a) who considered that the Strathalie Hill block was upthrown relative to the Triassic valley. Although Leaman considered the faulting to be pre-dolerite in age, the very steep slope present suggests that either more recent fault movement has occurred, or that the slope is a recently formed fault-line scarp.

The scarp ends with a pronounced break of slope at the flat valley floor. The material here consists of stratified sands and clays which have apparently been deposited here by sheet-wash. The deposits are quite deep — an auger hole (A_2) showed a depth of at least 15 feet. Undercutting by Limekiln Creek may be partly responsible for over-steepening of the scree slope, but the thick deposits present suggest that the stream has normally been aggrading. If significant undercutting had taken place it might be expected that gullying of this unconsolidated material should also have occurred.

A deeply incised valley in the centre of Strathalie Hill also poses a problem. The present 'stream' here is most certainly underfit in relation to the size of this valley. Even after very heavy rainfall, little or no streamflow occurs. The dolerite outcropping on the sides of this valley shows no evidence of any weaknesses which may have been readily exploited by a small stream, so it seems most likely that the catchment area for this valley was at one time very much larger and that following the loss of much of this catchment, the valley has now become dry.

If recent faulting has occurred, it seems reasonable to suppose that a continuation of this valley occurs past the fault-line, so that the downfaulted block should retain evidence of the continuation of this valley, which was presumably linked with one of the streams flowing out of the higher areas to the south-east. Large sheet-floods could then have covered much of the downfaulted block with alluvium, burying the continuation of the dry valley. Certainly the existence of a buried channel would undoubtedly support the contention of recent fault movement.

Seismic traverses were made across the valley floor over the expected path of the buried channel. These traverses showed only an undulating subsurface topography varying between 15 and 20 feet below the surface. Wave velocities of 7000 to 9000 ft./sec. suggest that the bed-rock is sandstone and not dolerite as might be expected had the valley been downfaulted. Hence the problem of the underfit valley remains unsolved. Nevertheless a structural origin as against an erosional origin is more readily envisaged for the Triassic valley.

Alluvial Morphology.

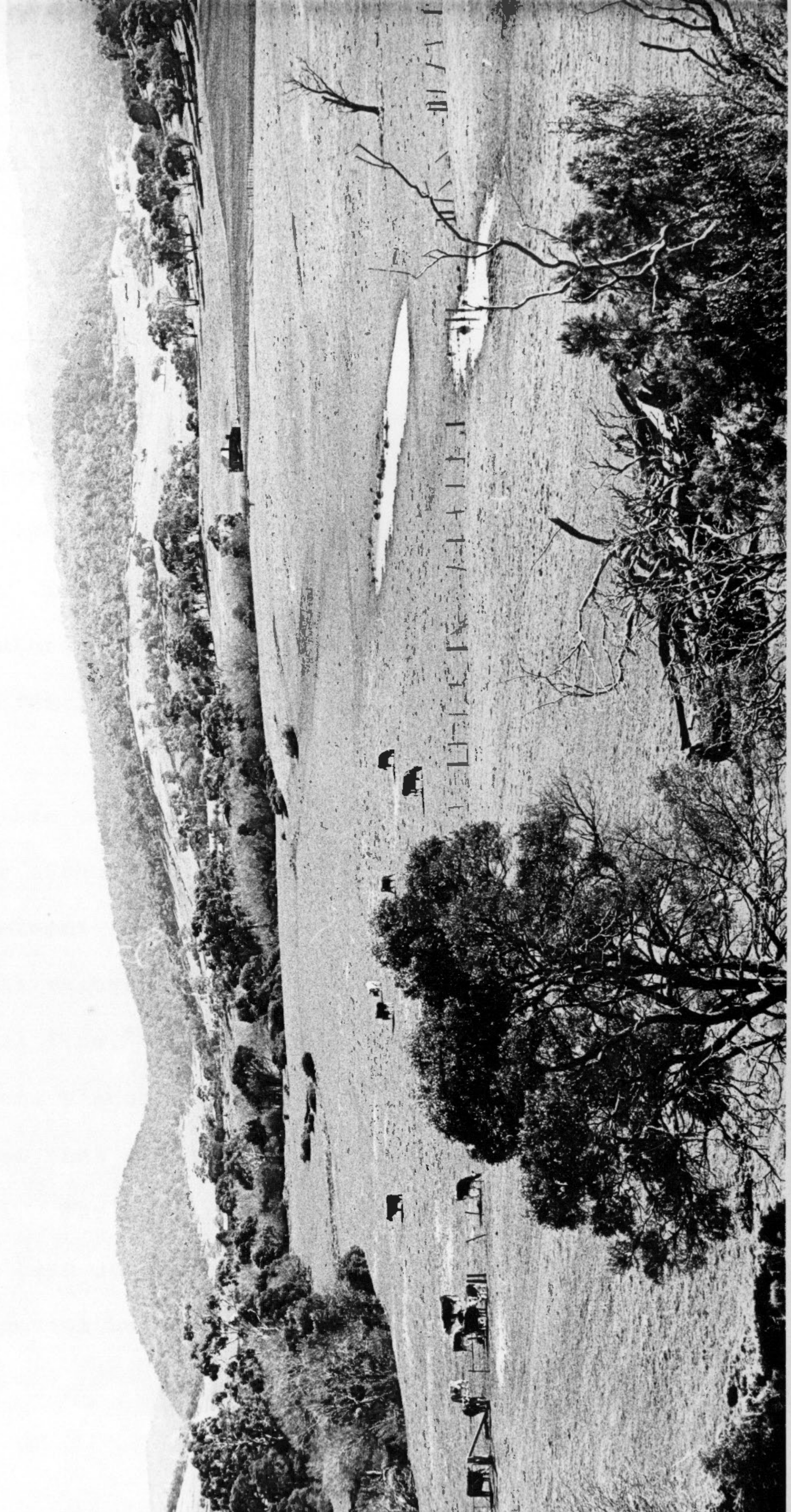
River Terraces: Terraces at various levels occur in the downstream sections of the Jordan River valley (Plate 12), and have been surveyed at various locations.

Between Strathalie Hill and Goats Hill the highest terrace occurs at about 30 feet above river level. This surface is by no means clearly defined and grades rapidly uphill into colluvium, but pebbles obtained from excavations at this level near Goats Hill consisted of comparatively fresh rounded dolerite quartzite pebbles up to 6 cms. in diameter, undoubtedly of fluvial origin, which were readily distinguished from the more weathered and angular dolerite debris found further upslope.

Overlying sandstone on the river bank near here (5162E, 52733N) is at least 8 feet of well consolidated material consisting of rounded dolerite cobbles up to 20 cms. in diameter, set in a clayey matrix. This material is repeated for example at 5131E, 52750N between 28 and 35 feet above river level on the higher terrace. It appears to have been dumped in large quantities and later partially removed, for in this latter locality, the cobbly alluvium occurs at the downstream end of a prominent sandstone cliff — the top of this cliff has been planed off by the river forming a continuous sloping surface across both the sandstone and the cobbly alluvium. The occurrence of this

PLATE 12.

Alluvial terraces upstream
from Goats Hill.
(Lower terrace at 7 ft., higher
terrace at 26 ft. grading into
colluvium.)

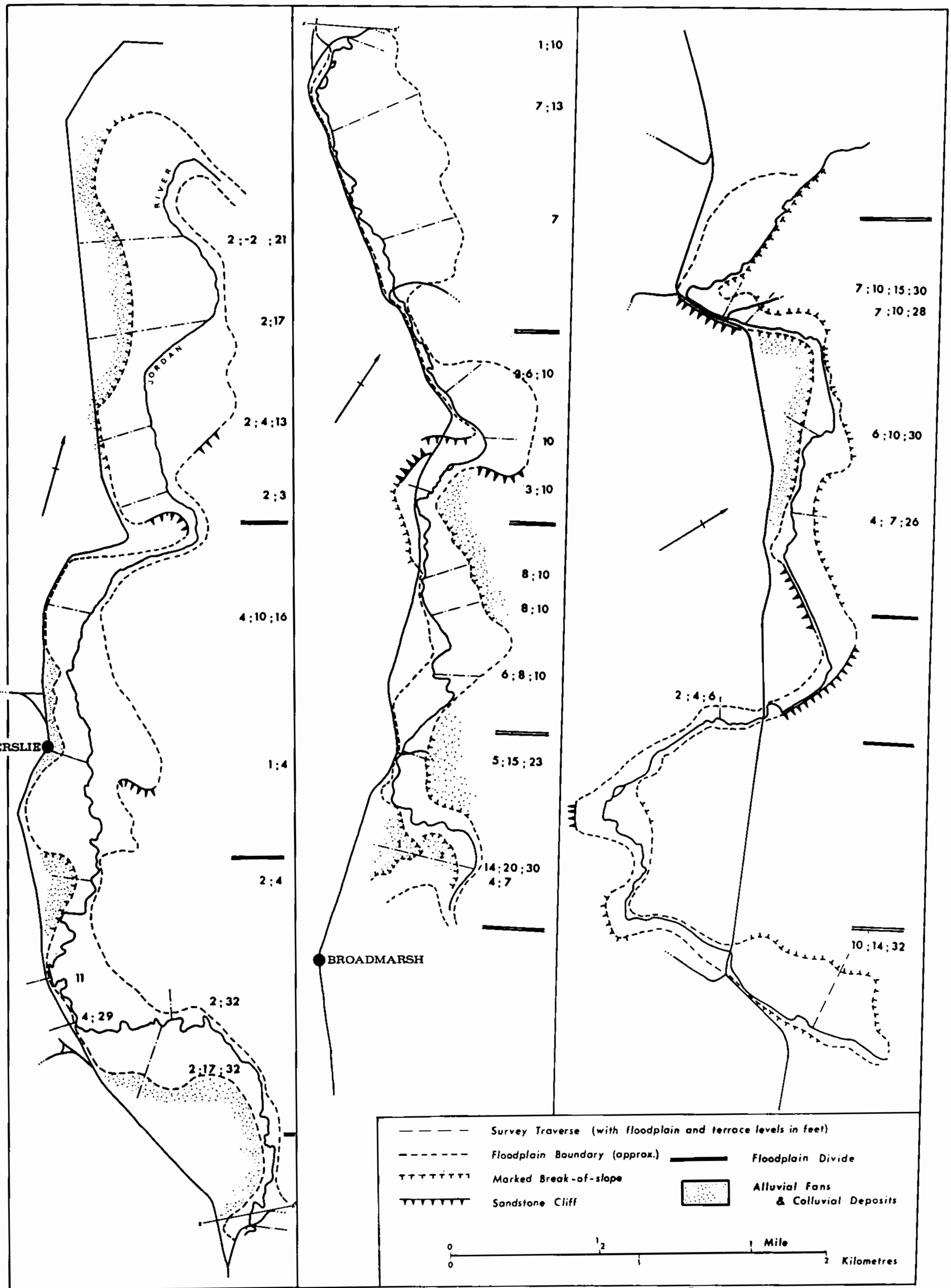


material at the highest terrace level most certainly supports the evidence of the valley meanders further upstream, namely that a prior-stream of much greater magnitude than the present existed, for this material is far larger than the bedload transported by the present river (page 88).

It soon became apparent that no general correspondence of the lower terrace levels existed, however a marked accordance of levels appeared within individual sections of the valley. The river valley is divided into regular segments by natural barriers, and within each segment a unique set of levels emerged which suggested a 'ponding' effect.

To test this possibility, further surveys were made to give a more adequate sample of terrace levels from each segment. Prominent levels from each survey are given in figure 15. All values given are with respect to river level at normal flow. Before the terraces were surveyed, marker pegs were placed at regular intervals along the river's edge so that adjustments could be made to variations in river level. The boundaries of the floodplains and terraces have been determined from aerial photographs and the valley segments have been divided at constrictions in valley width.

FIGURE 15



TRANSVERSE PROFILE LOCATIONS ALONG THE JORDAN RIVER

As suspected, within each segment a unique sequence of floodplain and terrace levels can be recognized. These levels may not always be uniform with respect to present river level, but generally their relative elevations are markedly similar. For example, within the segment below Broadmarsh, three surveys have terrace levels at approximately 7, 10 and 30 feet above river level, whereas a fourth survey has levels at 4, 7, and 26 feet. Apparently the four surveys have only the 7-foot level in common, but in each case the terrace levels occur at uniform intervals of approximately 3 and 20 feet.

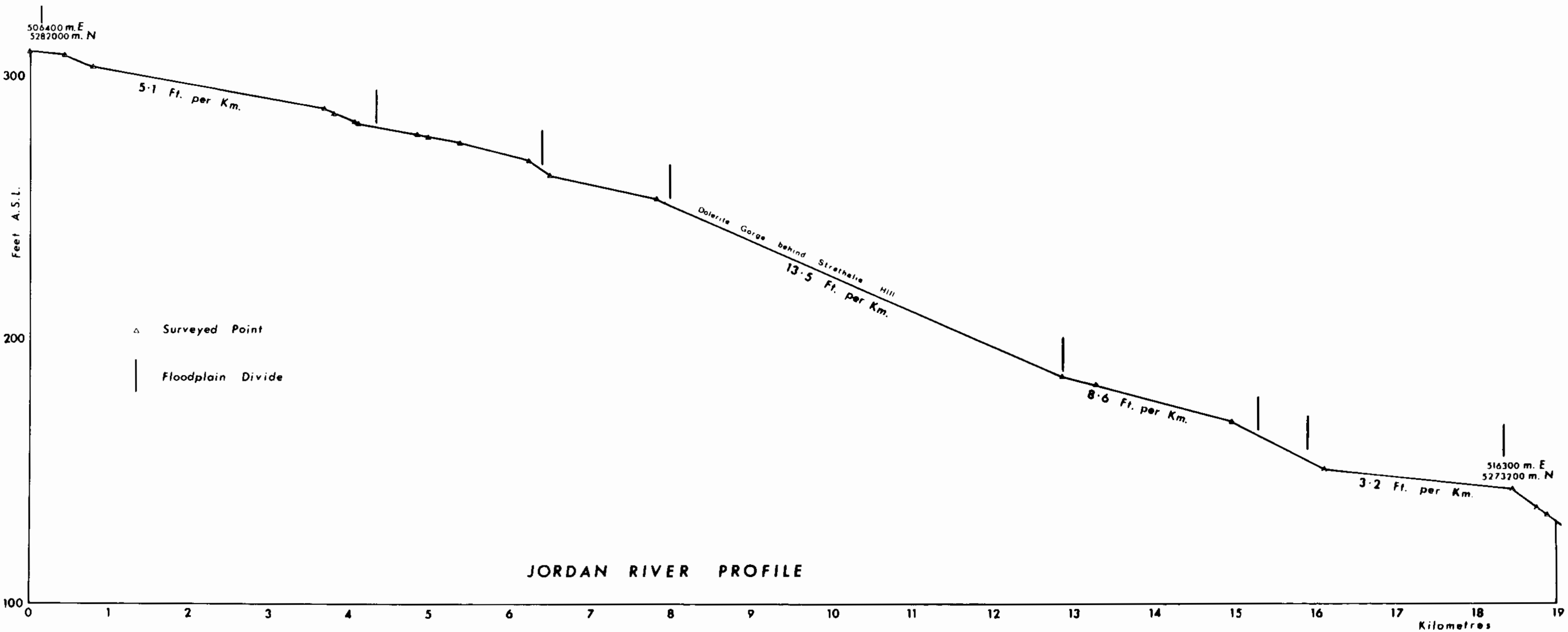
One terrace level at 11 feet just south of Elderslie on the western side of the valley does not agree with the levels obtained elsewhere within that segment. However it was found that this 'terrace' was in fact an alluvial fan containing angular dolerite and sandstone debris built up at the mouth of a small valley which enters the Jordan River valley at this point. A disparity also occurs in the level of the 'higher terrace' within the segment north of Elderslie. Again however this surface was found to be a large alluvial apron formed from material deposited by streams debouching onto the floodplain.

At several points traverses were run from the recently surveyed Elderslie Road down to the river's edge, and a longitudinal profile of the Jordan River has been prepared

(Fig. 16). Unfortunately the road survey did not extend upriver beyond Elderslie, so that only a portion of the profile is presented. The distance between the road and the river at some locations prevented a more adequate number of heights to be determined, but so far as can be judged from the surveyed points available, the distinction of the floodplains on the basis of morphological barriers is closely coincident with steepening of the river profile. On some floodplains the river describes a very sinuous course, so lesser gradients on the floodplains are to be expected, however even when meanders are ignored and general downstream trends of the river are measured, the effect is the same. Hence the 'ponding' effect suggested from a consideration of the terrace levels is further reflected by the stepped longitudinal profile of the river.

Natural Levees: Natural levees were observed at a few locations. Near Broadmarsh they are poorly developed, rising little more than a foot above the level of the floodplain and extending only 10 feet or less from the river bank. In some cases these may well be 'plowshare' levees (Wolman and Leopold, 1957), formed by trapping sediment in the margin of uncleared land beside the river. However upriver natural levees become a significant feature of the

FIGURE 16



JORDAN RIVER PROFILE

floodplain morphology, so that during periods of high flow as in March of this year, the river breaks its banks and causes considerable flooding. Water is retained by these levees at the side of the valley long after the flood has receded. At the northern end of the floodplain north of Elderslie the floodplain slopes away from the river down onto a markedly low-lying surface 2 feet below the level of the river. This 'levee' extends from the river for over 300 metres and it seems unlikely that it has been formed solely by overbank deposition during periods of high flow, for more localized accumulation of material would be expected. More likely it has been formed by some mechanism associated with lateral shifting of the channel.

<u>Other Alluvial Landforms</u>: A marked feature of the Jordan River valley from Elderslie to Broadmarsh is the encroachment of large alluvial fans and colluvial deposits onto the present floodplain. A notable example occurs on the western side of the valley north of Elderslie. Here alluvial fans coalesce to form a continuous gently-sloping apron some 2 kilometers wide, which extends out from the hills onto the floodplain.

Debouching onto this apron are several streams from the Espies Crag area. As mentioned previously, these streams have cliffed valley heads with very steep scree deposits sloping toward the headwater gullies. No doubt these scree deposits have created a plentiful supply of material, so that lower downstream the valleys become choked and flat-floored, grading out gently onto the alluvial apron. Presumably this surface originally extended down onto the river floodplain, but the river has now extended its flood-plain and has cut into this surface creating a sharp break of slope up onto the higher surface (Plate 13). The alluvial apron lies 21 feet above the floodplain at the northern end and slopes down gradually to merge with the floodplain at the southern end, suggesting that the dominant source of material was from the northern valleys.

An auger hole (A_1) reached 12 feet without striking bedrock, passing through layered sands and clays. Continuous with this alluvial surface at the northern end of the valley is a partially buried pebbly conglomerate containing a large proportion of extremely coarse white quartz grains. This conglomerate can be traced westward into the foothills and the abundance of similar quartz sand grains within the deposits near here attests that the deposit has a significant colluvial component.

A short seismic traverse (T3) was made across the floodplain at the edge of the higher alluvial surface. Although very wet conditions hampered readings, it seems

PLATE 13.

The floodplain and alluvial
apron north of Elderslie.

likely that approximately 18 feet of floodplain alluvium is present. That very large quantities of material have choked the valley in this area is also suggested by the abnormally sharp break of slope from the flat river floodplain up into dolerite hills at the southern end. Much of the supply of material to this area seems certain to have come down the river valley. Just before the Jordan River leaves the meandering sandstone gorge to enter this floodplain, long narrow sandy deposits are found up to 26 feet above river level, no doubt as a result of incompetence of the river due to unusually large volumes of material supplied to this area.

Further downstream, more obviously fan-shaped deposits occur as well as other sheetwash aprons (e.g. at 5135E, 52752N). Davies (1967) has described alluvial fans which have formed on the north bank of the Derwent River at the mouths of streams flowing south-east off Mt. Dromedary. Mt. Dromedary is mantled with solifluction material, and Davies has observed that the valleys of the tributaries joining the Derwent from here contain abundant material derived from this source. A cursory examination of the valleys in the Broadmarsh area confirms Davies' observations. Only one valley was adequately investigated, and it appeared from this however that the valley alluvium becomes progressively finer in the lower reaches, where it consists predominantly of clays.

CHANNEL MORPHOLOGY.

Within the study area, the present channel of the Jordan River undergoes marked changes. In order to investigate these variations in channel morphology, a reconnaissance was made along selected sections of the river by boat.

Method.

At various sites along each section, cross-profiles of the channel and banks, and bankfull level were measured. At each site, sediment samples were taken from the banks and where possible from the channel bottom, and pertinent observations along the course of the river were recorded. Sites for the measurement of transverse profiles were selected only on the basis of ease of access (in many cases, dense vegetation made measurement impossible), so that on each reconnaissance, measurements were taken from a wide variety of channel conditions. Indeed, where possible, significant changes in the channel were specifically recorded for the following analysis.

A most obvious difficulty in this study was the actual identification of bankfull stage. Where the river channel is bounded abruptly by extensive flat surfaces, the lowest surface was assumed to be the present floodplain, and bankfull level was clearly determined. However at several sites, recognition of the present-day floodplain was made difficult by the presence of narrow flats and benches below the level of more clearly defined floodplains. Woodyer (1968) considered that

> In view of the possibility of very recent incision of former flood-plains at some sites (in New South Wales), it can be expected that the present active floodplain may be represented at some sites by a relatively inconspicuous, narrow depositional bench occurring below the apparent (former) flood-plain, while at other sites the present floodplain may correspond with the apparent floodplain.

Although no implication of recent incision along the Jordan River is intended, these lower benches cannot be ignored, and so for consistency at least, the level of these benches has been interpreted as bankfull level.

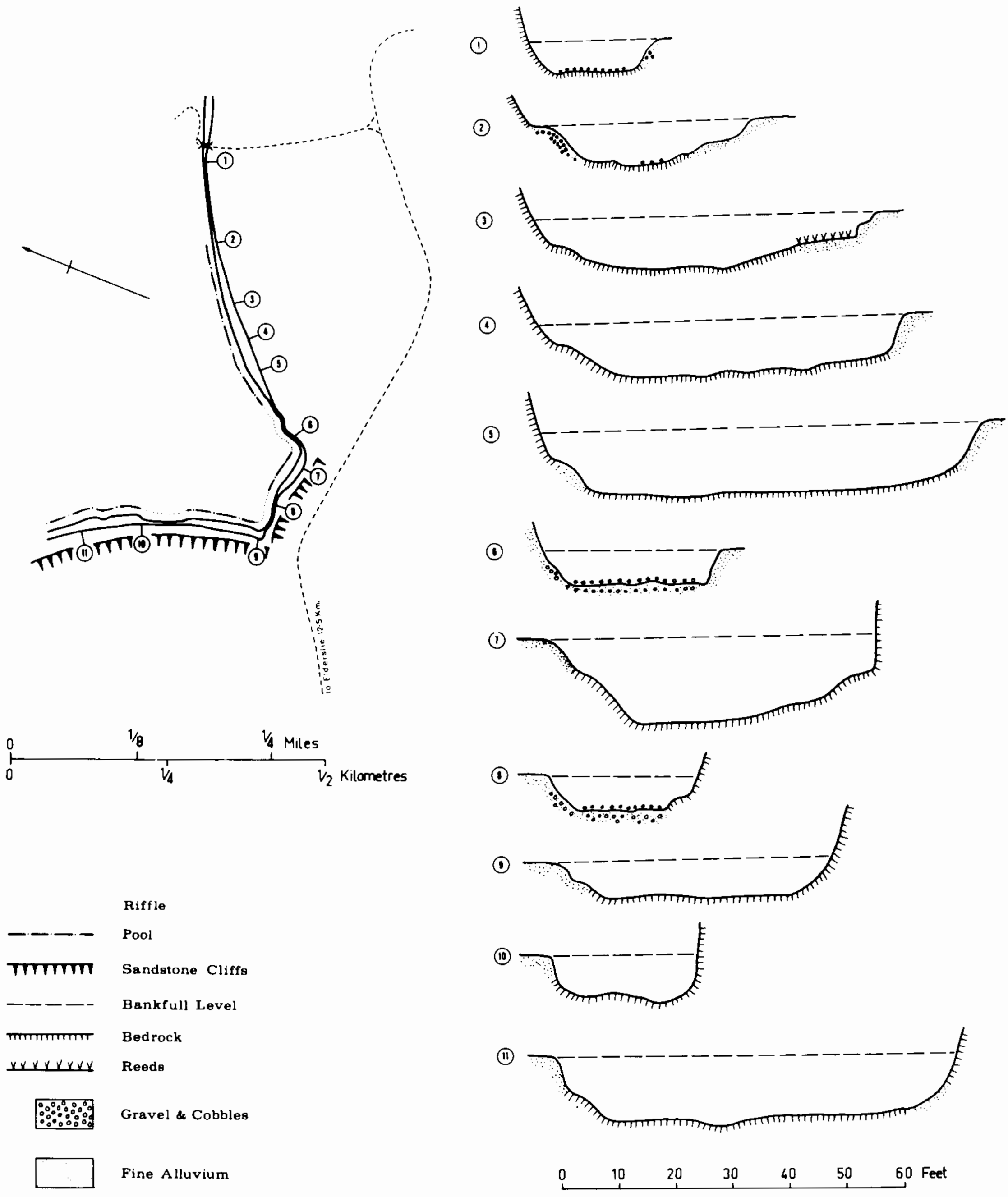
Because of the difficult and time-consuming nature of this study, it was not possible to survey the entire course of the river, so only five short sections were selected. North of Weedons Hill the Jordan River flows round the 'cuesta-spurs' along distinctly straight reaches, whereas the course of the river becomes much more sinuous for example within the broad floodplains below Elderslie, and selection of suitable sections for study was made chiefly to include these variations. The studied sections have been termed Runs (1 to 5) for the purposes of this discussion and their location is indicated on Figure 1. Figures 17 to 21 show the channel profiles and their location for each run.

Channel Variations.

Runs 1 and 2 flow almost exclusively on sandstone bedrock. The channel bottom is often quite flat and site 9 (Fig. 17) for example, at a sharp bend where the river is deflected by a sandstone cliff, shows no asymmetry as might be expected. It seems certain that the form of the channel here is very largely controlled by the Triassic strata, so that the river bed now rests on the sandstone bedding planes. Sites 15 to 17 (Fig. 18) occur along a particularly straight section of the channel. Forming the northern bank along this reach is a smooth sandstone face, presumably a joint-surface. Undoubtedly the course of the river and the channel morphology is largely structurally controlled along runs 1 and 2.

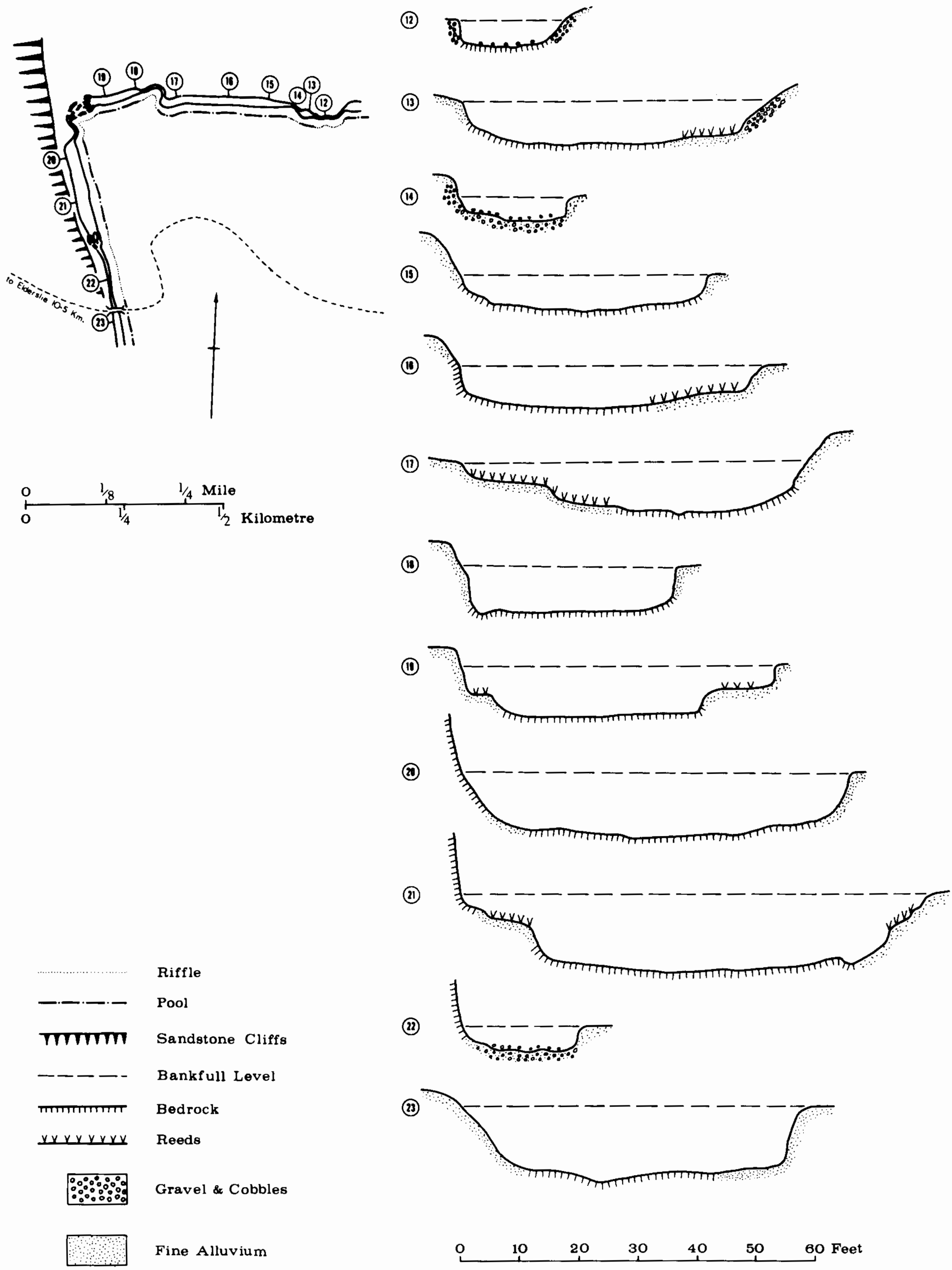
A marked feature of the channel along these two runs was the striking contrast between 'pools' and 'riffles'. In this study distinction between pools and riffles has been made on the basis of surface water flow - where the surface flow was very slow to nil, that section was

FIGURE 17



RUN 1: CHANNEL PROFILE LOCATIONS

FIGURE 18



RUN 2: CHANNEL PROFILE LOCATIONS

designated as a 'pool', and 'riffles' have been defined where surface flow is rapid. The pools invariably occur along straight sections of the channel and are characteristically 'beaded', increasing gradually in depth and width downstream, achieving greatest proportions in the longest pools. Sites 2 to 5 (Fig. 17) are a fine illustration of this beading effect. Site 2 at the upstream end of the pool has a bankfull width of only 36 feet and a maximum bankfull depth of 7.6 feet, and through sites 3 and 4 these dimensions increase regularly until at site 5 the river has a bankfull width of 76 feet and a maximum bankfull depth of 12 feet (See Appendix B).

At riffles the channel is noticeably smaller and invariably cobbly and sandy banks and bedloads are present. Even downriver in runs 4 and 5 riffles were always associated with cobbly bank material, suggesting that the bedload is largely locally derived. Nowhere throughout the five runs was a pool associated with cobbly bank material, and it appears that very little downriver transport of this material occurs. At the end of each riffle section the stream rapidly widens and flows over bedrock again between banks of fine alluvium.

Leopold, Wolman and Miller (1964) found that

> A straight or nonmeandering channel characteristically has an undulating bed and alternates

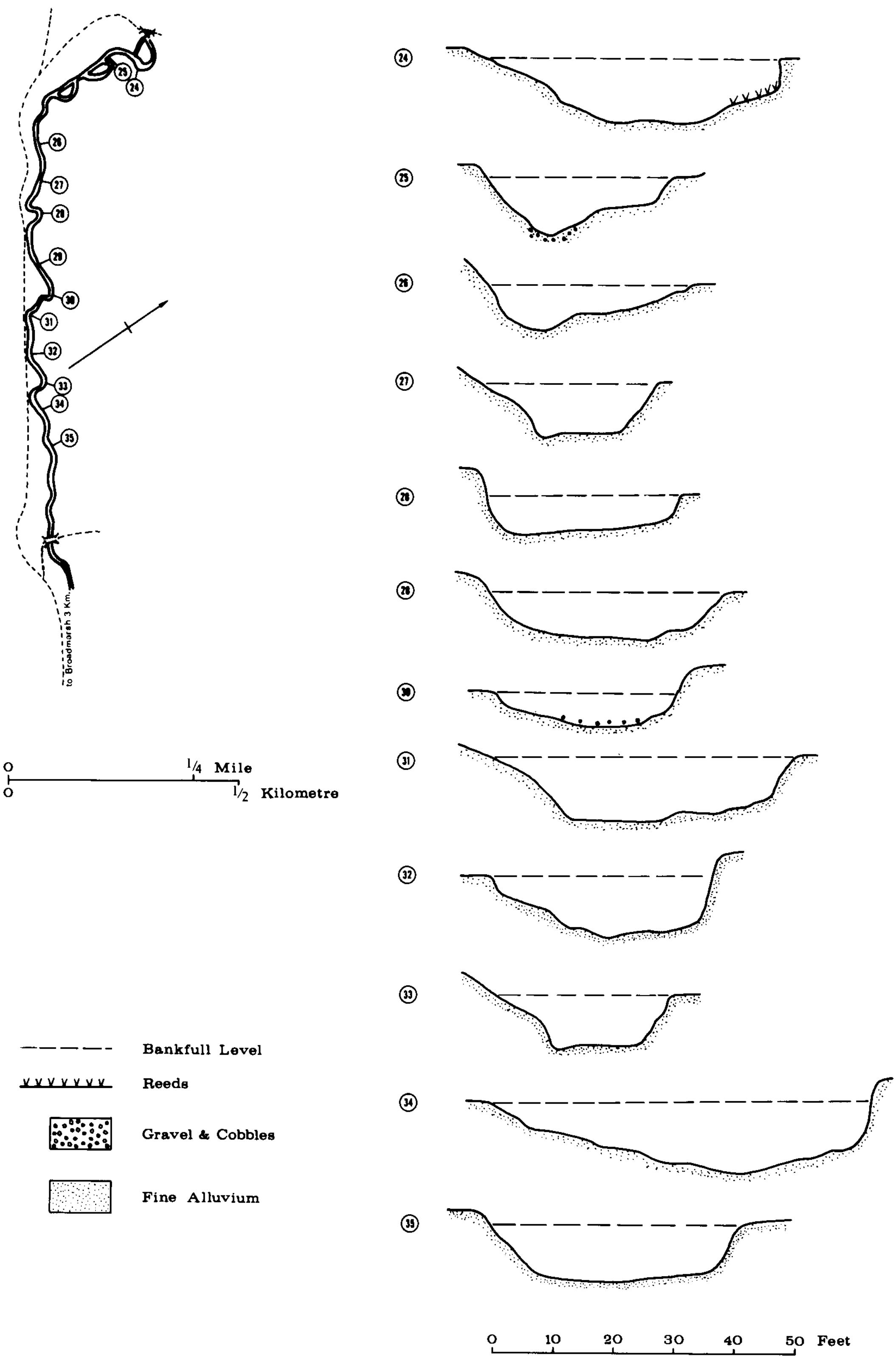
along its length between deeps and shallows, spaced more or less regularly at a repeating distance equal to 5 to 7 widths.

This is certainly not the case for this section of the Jordan River channel, where a far larger spacing is found. Leopold, Wolman and Miller attribute the regular spacing of pools and riffles to a 'mechanism associated with some form of wave phenomenon', but the spacing observed here appears to be entirely dependent on the local occurrence of cobbly alluvium. Perhaps a regular spacing of 5 to 7 widths is achieved only when the stream has sufficient energy to effectively distribute its bed-load.

By contrast with the straight pool-and-riffle character of Runs 1 and 2, Run 3 (Fig. 19) meanders regularly between banks of fine alluvium. Along this run, the cross-profiles are far more uniform in size and develop greater asymmetry. Pools and riffles have not been distinguished in Run 3, although frequently deepening occurs at bends where the concave bank has been eroded. With regard to the surface flow of water however, no distinction is apparent .

Certainly the beading effect noted in Runs 1 and 2 appears to be an alternate expression of meandering for

FIGURE 19



RUN 3: CHANNEL PROFILE LOCATIONS

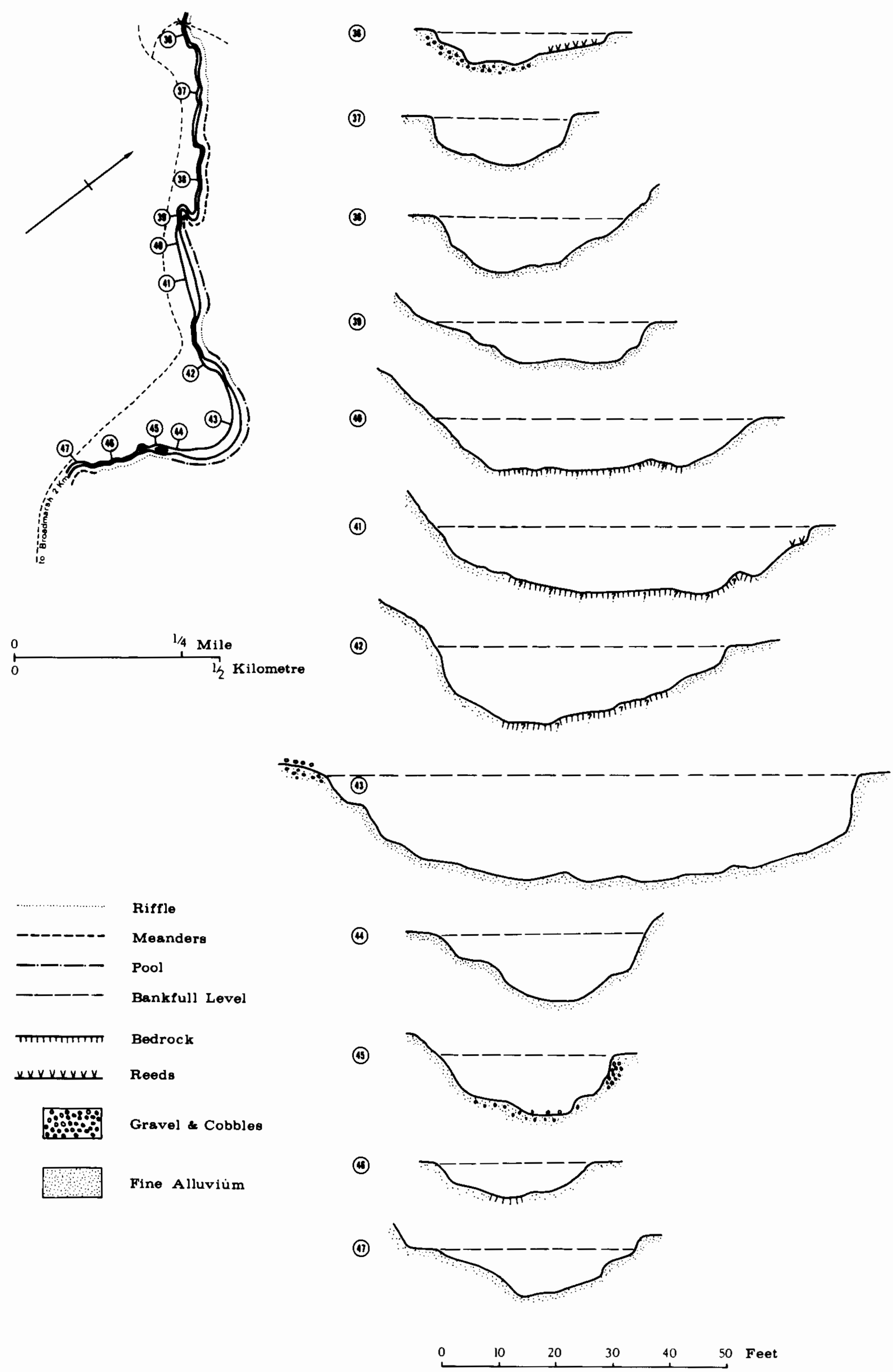
straight channels. Downstream in runs 4 and 5 (Figs. 20, 21) where straight reaches again occur, the cross-sections again vary markedly in size along beaded pools.

At various sites submerged, reed-covered benches were found. These benches are presumably built up with material that has been trapped by the reeds, and give the impression that the present channel is becoming narrower. At very few locations was active undercutting and widening of the channel observed, whereas development of 'reed-benches' is comparatively frequent. Their occurrence causes some concern for it may be supposed that some of the raised benches which have been interpreted as present flood-plain levels may well be simply raised reed-benches. However, with few exceptions, these reed benches slope away from the banks and are not as extensive or level as the 'flood plain' benches.

Width - Depth Relation.

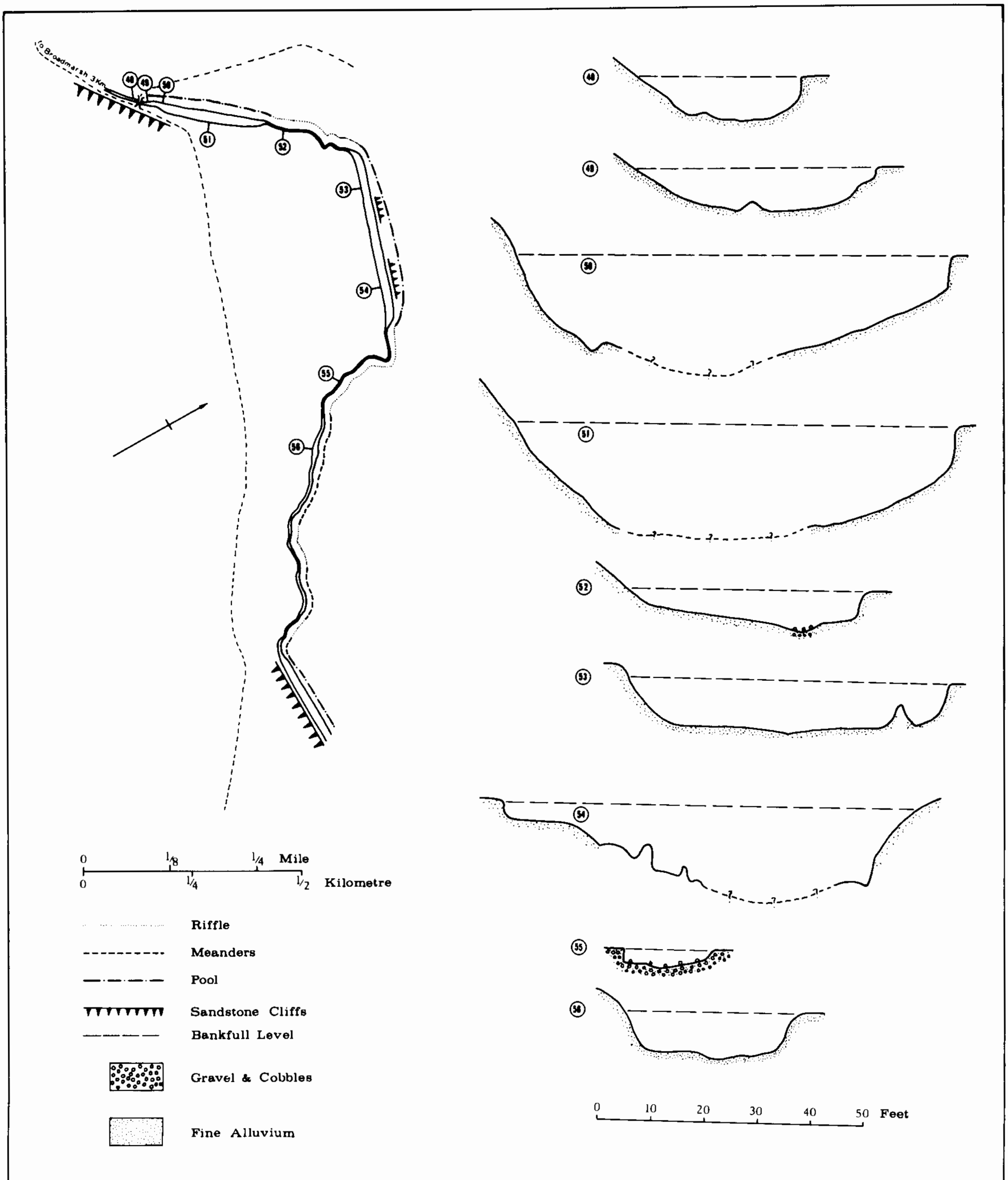
For each site maximum bankfull depth has been plotted against bankfull width, and a regression line has been fitted by the method of least squares (Fig. 22). (2 sites from run 5 have not been included in this analysis, since their maximum depth is unknown.) A linear relation has been assumed since the range of data is insufficient to warrant the investigation of more complex relations, and

FIGURE 20



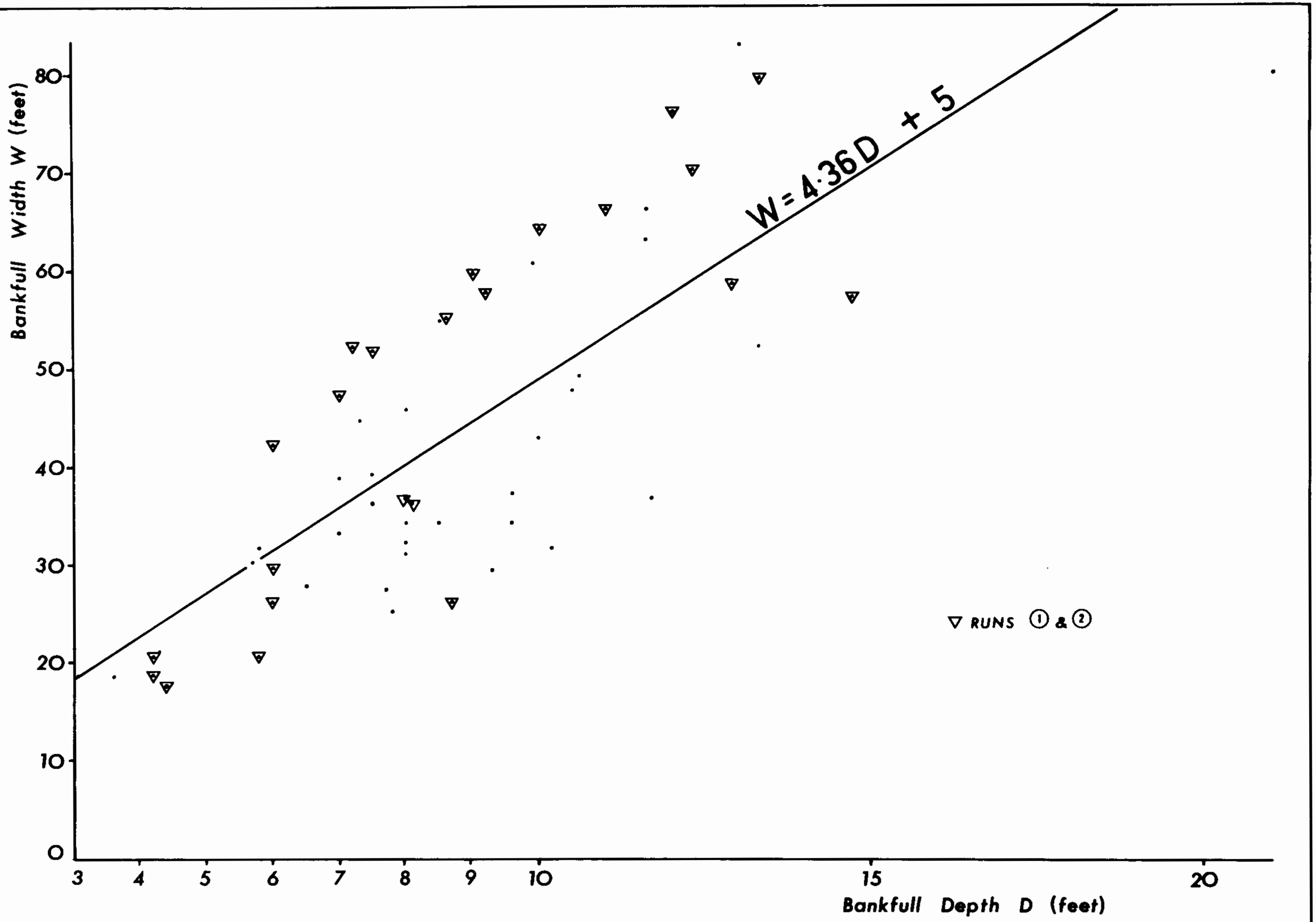
RUN 4: CHANNEL PROFILE LOCATIONS

FIGURE 21



RUN 5: CHANNEL PROFILE LOCATIONS

FIGURE 22



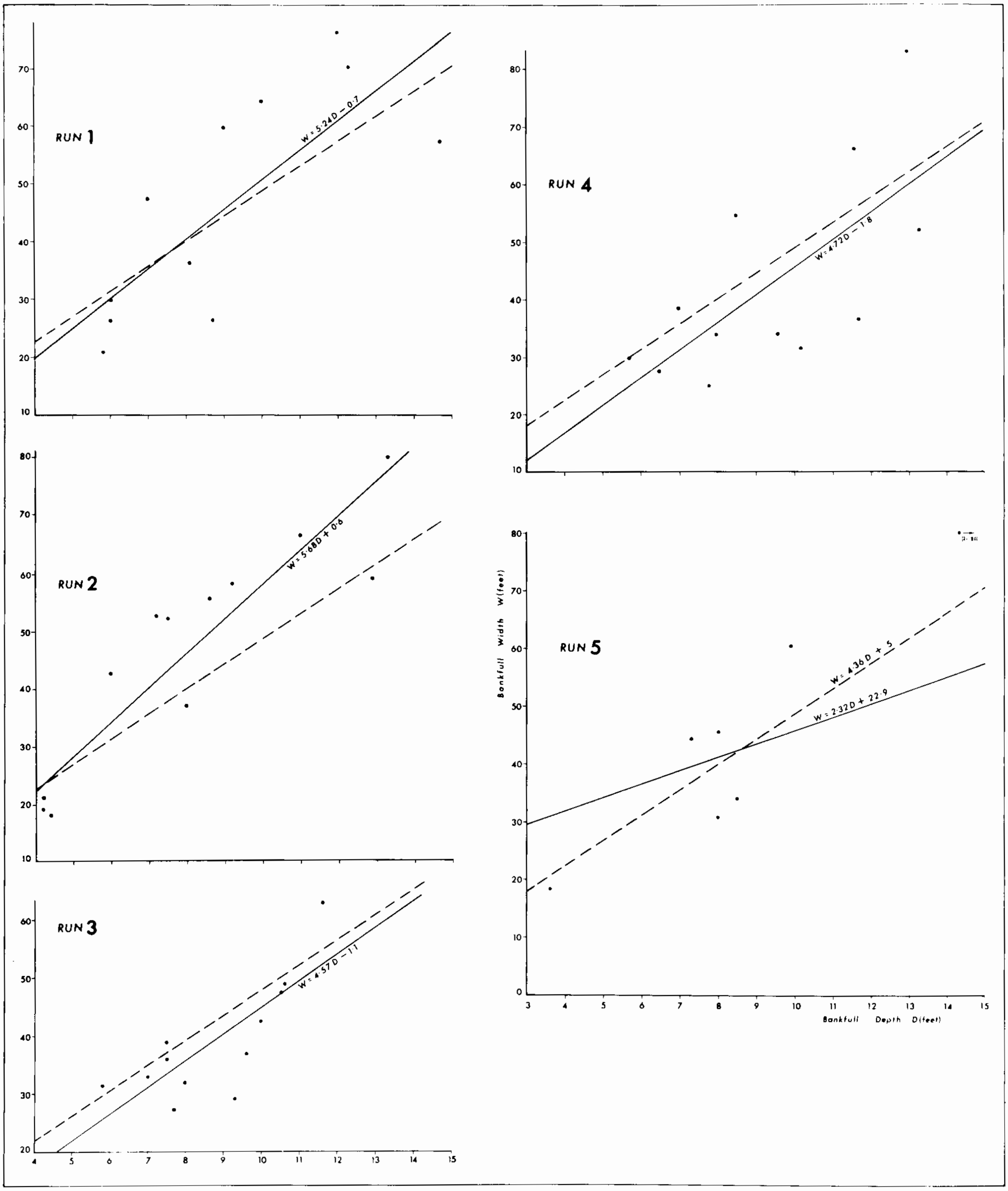
WIDTH—DEPTH RELATION of RUNS 1 to 5

the regression equation obtained is valid only within this range.

An overall correlation coefficient (Pearson product-moment) of + 0.77 for the 5 runs confirms that a marked relation exists between maximum bankfull depth and bankfull width. It is significant that measurements from runs 1 and 2 tend to plot above the regression line. As noted earlier, along these sections the river flows on bedrock, and consequently the channel is shallower than in other runs where the bed is more readily scoured.

Because specific conditions along runs 1 and 2 have caused an obvious departure from the overall relation, it seems likely that the regression equation $W = 4.36D + 5$ is only a very rough approximation of the true width-depth relationship. Consequently, regression lines have been calculated separately for each run to investigate the changes occasioned by variations in channel conditions (Fig. 23). In particular, in view of the relative uniformity of run 3, and the absence of structural control on this run, it seemed likely that a more accurate relation would be derived from this section of the channel. On each graph, the position of the overall relation has been indicated so that the differences of each run can be compared.

FIGURE 23



RUN 1
W = 5·24D − 0·7
RUN 2
W = 5·68D + 0·6
RUN 3
W = 4·57D − 1·1
RUN 4
W = 4·72D − 1·8
RUN 5
W = 4·36D + 5
W = 2·32D + 22·9
Bankfull Width W(feet)
Bankfull Depth D(feet)

Along runs 3 and 4 the channel has depths generally up to 1 foot greater than the overall relation, which has presumably been significantly influenced by the shallow channel in runs 1 and 2. It is significant that the regression line from run 4 agrees well with that obtained from run 3 for although run 4 contains pool-and-riffle sections, there are large stretches which have been designated as 'meander-reaches'.

Run 5 shows a marked increase in depth. Although a regression line based on so few points is uncertain, it was noticed that straight sections of channel here invariably had silty bedloads. Sites 53 and 54 occur along the straight section of channel which aligns with the scarp line of Strathalie Hill mentioned previously. Low sandstone joint faces and massive dolerite walls form the northern bank of this reach, and as suspected, it seems certain that the course of the channel is in fact largely controlled by structure. Most likely greater depths occur in these pools in comparison with the pools along runs 1 and 2, because of the more readily scoured bed, and it seems highly probable that depth of pools and the degree of beading is very closely related to the resistance of the bed to erosion.

Correlation coefficients also reflect the changes in channel morphology. The extremely high correlation figure of +0.908 for run 2 reflects the high degree of uniformity occasioned by the sandstone beds. Run 4 however has a comparatively low correlation of +0.681, and this no doubt is the result of variations between meandering and pool-and-riffle sections.

Since run 3 so obviously differed from the other runs by virtue of its meandering course and uniform cross-sections, it was decided to ascertain whether in fact the channel along this run was significantly different.

For each cross-section the ratio $W/_D$ was calculated for comparison. Since the cross-sections were not selected randomly and an insufficient sample was taken to determine the population distribution, non-parametric statistics have been applied. In this analysis, run 3 has been compared with runs 1 and 2, using the Kruskal-Wallis H test (see for example Downie and Heath, 1959). This test determines whether independent samples are from the same or different populations, and is particularly useful in this analysis as it is a powerful indicator of significance even when the samples are relatively small. A value of $H = 2.5116$ gave rejection of the null-hypothesis only at the 13% level, and this was again confirmed using the Mann-

Whitney U test. Hence there are more than 13 chances in 100 that the differences observed between Run 3 and Runs 1 and 2 could have occurred by random sampling from the same population, so that whereas changing controls on the course of the river produce apparent differences in channel morphology, no significant differences occur between the beaded and meandering sections.

Hence as Wolman (1955) observed (at Brandywine Creek, Pennsylvania)

> Although possibly a dominant factor at a cross section, the resistant bed is not the sole factor determining the shape of the channel. That this is true is indicated by the fact that the channel is not inordinately wide where it passes over the resistant bed material.

Wolman also found that

> This 'constructive' as opposed to 'erosive' aspect of channel formation is illustrated by the narrow benches built adjacent to the bedrock walls.....

The reed benches found along the Jordan River most certainly support Wolman's observations — these benches are developed almost exclusively within the 'bedrock Runs' (principally Run 2, Fig. 18).

Thus Wolman concluded

> There is an infinite variety of factors which may modify the results or interrupt the processes.... ...of a self-formed channel. Nevertheless, it is probable that these chance irregularities simply obscure but do not suspend the governing principles.

Wolman compared the width-depth relation obtained for Brandywine Creek with those derived by Lacey (1939) for canals in India, and with river data presented by Leopold and Maddock (1953). The rivers and canals compared have 'vastly different topographic, lithologic, and climatic environments', yet all lines showed a close parallelism. Within the range D = 4 to D = 20 ft. the regression line obtained in this analysis conforms to this same trend.

> This agreement indicates that the processes which determine the shapes of natural alluvial channels are much the same regardless of their geographic location (Wolman,1955).

CALCULATION OF FORMER DISCHARGE.

The valley meanders intrenched in sandstone north of Elderslie are most certainly related to a prior stream of much higher discharge than the present Jordan River. The uniformity of these meanders permits accurate measurement of wavelength and sinuosity and an attempt has been made to calculate the former discharge.

Leopold and Maddock (1953) related width and discharge of streams by the formula:

$$w = aQ^b$$

where w = water surface width, Q = discharge and a and b are constants. Hence if w, W, q and Q are the widths and discharges of the former and present Jordan River respectively, then $w = aq^b$ and $W = aQ^b$ so that $Q/q = (W/w)^{1/b}$.........(1).

Certainly north of Weedons Hill in the 'cuesta-spur' area, the meanders are largely ingrown, so that any estimate of valley width as the width of the prior stream must be used with reservation. However the narrowest section of the valley in the 'meander-gorge' (350 feet approx.) has been used for the purposes of this discussion. The results of Run 3 of the channel survey provide reasonable estimates of the dimensions of the present Jordan River, since here the stream is meandering freely within alluvium and is not effected by structural controls as in other sections. To obtain a reliable estimate of width the values for Run 3 have been averaged, giving $w = 38.9$ feet.

Dury (1960) found that 'an average value of 0.5 for b (eqn. 1) seems well substantiated by much hydrological research'. Hence from equation 1,

$$Q/q = (W/w)^2 = (350/38.9)^2 = 80.95$$

This would indicate that the bankfull discharge of the prior Jordan was over eighty times greater than that of the present river. However Dury (1965) showed that meander wavelength is a better criterion of bankfull discharge than is the meander-belt width, and he presented a relationship between meander wavelength (l) and bankfull discharge (Q_b) as follows:

$$l = 30 Q_b^{0.5},$$

$$\text{from which } Q/q = (L/l)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where q, Q, l and L are the discharges and wavelengths of the former and present Jordan respectively.

Meander wavelengths of the present river are variable, but measurements from Run 3 and from other sections of the river which appear to be freely meandering, suggest a value for l of 300 ft. A value for L of 3800 ft. has been obtained from the valley meanders. Hence, from equation 2,

$$Q/q = (3800/300)^2 = 160$$

Such a high figure is extremely difficult to envisage, and Dury (1965) has observed that in all calculations based on this formula, the observed wavelength ratios L/l are unusually high with corresponding extreme discharge ratios. Schumm (1968) observed that

> Dury's (1965) relationship $l = 30\ Q_b^{0.5}$ is highly significant, but considerable scatter of the data about this regression line is evident. In fact, within the limits of scatter, a tenfold variation in meander wavelength can occur for a given bank-full discharge.

Schumm found that a plot of calculated bankfull discharge against meander wavelength for some United States rivers fell near or below Dury's regression line when the silt-clay content of the channel was high. However low silt-clay channels generally plotted well above the regression line. It appeared therefore that the type of sediment load moved through these channels, as expressed by the silt-clay content of the channels, has a major influence on meander wavelength. With data obtained from rivers in the Great Plains of America and the Riverine Plain area of Australia, Schumm found a regression line of the form

$$l = 438\ \frac{Q_b^{0.43}}{M^{0.47}} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

where l and Q_b are as before and M = channel silt-clay (%).

Unfortunately, both areas mentioned above are semi-arid and so Schumm's relationship cannot be applied to humid areas with certainty, but for the purposes of this discussion it is assumed that this relationship holds.

Schumm (1963) found that sinuosity (P) is related to M as follows:

$$P = 0.94\ M^{0.25} \qquad \text{.........................(4)}$$

The sinuosity of the valley meanders can be readily calculated - in this case P = 1.26. Hence from equation 4,

$$M = \left(\frac{1.26}{0.94}\right)^{1/0.25}$$

$$= 3.2281$$

and by substitution in equation 3

$$L = 438\ \frac{Q^{0.43}}{(3.2281)^{0.47}}$$

$$\text{i.e. } Q^{0.43} = \frac{3800}{438}\ (3.2281)^{0.47}$$

$$\text{i.e. } Q = 550 \text{ c.f.s.}$$

By comparison with this value, the discharge of the former Jordan River estimated from Dury's equation is:

$$Q = \left(\frac{L}{30}\right)^2$$

$$= \left(\frac{3800}{30}\right)^2$$

$$= 16043 \text{ c.f.s.}$$

Most certainly the figure arrived at using Schumm's equation is the most reasonable, but realizing that reasonableness carries no logical force it was decided to check Schumm's relationship against present discharges.

M is the percentage of sediment smaller than 0.074 mm. in the perimeter of the channel defined by

$$M = \frac{(Sc \times W) + (Sb \times 2D)}{W + 2D}$$

where Sc is the percentage of silt and clay in the channel alluvium, Sb is the percentage of silt and clay in the bank alluvium, D is the channel depth and W is the channel width (Schumm, 1960).

Unfortunately channel sampling using a sediment grab was most unsuccessful due to dense channel vegetation, however the small collections from several grabs over approximately 50 yards of channel in Run 3 have been grouped for this analysis. This sample was split and approximately 100 grams were analysed giving a silt-clay content of 8.5%. The results of four bank samples were averaged giving a value of 56.9% for Sb. (Appendix C)

$$\text{Hence } M = \frac{8.5 \times 38.92 + 56.9 \times 17.52}{56.44}$$

$$= 23.524$$

$$\text{Hence from eqn. 3, } q^{0.43} = M^{0.47} \frac{1}{438}$$

$$= (23.524)^{0.47} \frac{300}{438}$$

$$\text{i.e. } q = 13.1 \text{ c.f.s.}$$

On the basis of the record of stream gaugings for the period 1961 to 1968 inc. (no earlier recordings available), such a value of discharge is far below the expected bankfull discharge.

The estimate of M in this analysis may well have suffered from the small number of samples used. However Schumm (1960) established a relationship between channel type and sediment in the form $F = 255\ M^{-1.08}$, where F is the channel shape expressed as a width-depth ratio and M is the weighted mean percent silt-clay.

The width-depth ratios for Run 3 were averaged and using this value ($\bar{F} = 4.46$), by substitution in Schumm's formula we get $M^{1.08} = 255/4.46$

$$= 57.174$$

Hence from Schumm's (1968) eqn. (3):

$$q^{0.43} = (57.174)^{0.47}\ \frac{300}{438}$$

i.e. $q = 28.4$ c.f.s.

Even a discharge of 28.4 c.f.s. seems too low on the basis of stream gauging records. Over the 8 year recorded period, this discharge is equalled or exceeded approximately $2\frac{1}{2}$ times per year (i.e. return period 0.36 years), and on the basis of observations for example from Wolman and Leopold (1957) and Woodyer (1968) this would seem to be far below bankfull stage. Woodyer for example has observed return periods of 1.02 to 2.69 years.

By contrast, the estimated present bankfull discharge from Dury's formula is $q = (1/30)^2$

$$= 100 \text{ c.f.s.}$$

which on the basis of the 8 years record has a return period of approximately 1.2 years, suggesting that 100 c.f.s. would be a more likely figure.

Obviously estimates from such a short period of record are bound to be unreliable, however the data presented does reveal the difficulties and shortcomings in applying such formulae to determine discharges. Certainly, if such uncertainty occurs in the determination of present discharges, the values obtained for past discharges must be even more so. Consequently, until more adequate formulae become available it is impossible to give any reliable estimate of past discharges — all that can be said at this time is that past discharges were higher.

EROSION GULLIES.

The thick unconsolidated sheetwash deposits of the valley floors have facilitated rapid gullying in many places, so that arroyo-like channels up to 35 feet in depth are now found. The gullies have cliffed walls kept continually steepened by slumping at the edges, and have flat sandy floors (Plates 14 and 15).

As Leopold and Miller (1956) have observed in arroyos in central New Mexico, down-cutting appears to proceed slowly after the initial development of gullying. In one gully at 5125E, 52838N the downstream section is now almost stabilized with vegetation including mature trees, even though at least 4 feet of loose easily eroded sand is found on the gully bed. Further upstream, this gully shows a transition through progressively younger trees to the actively degrading gully-head.

Gullying is chiefly developed in the sandstone areas where presumably the particularly unconsolidated sandy valley alluvium has been readily eroded. Everywhere within the sandstone areas, evidence of severe erosion is present. Recently cleared land has been stripped of its loose sandy top soil almost to bedrock in many places. Subterranean channels are a feature unique to the sandstone areas. Underground drainage removes the sandy material beneath the topsoil

PLATE 14.

Slumping of gully walls.

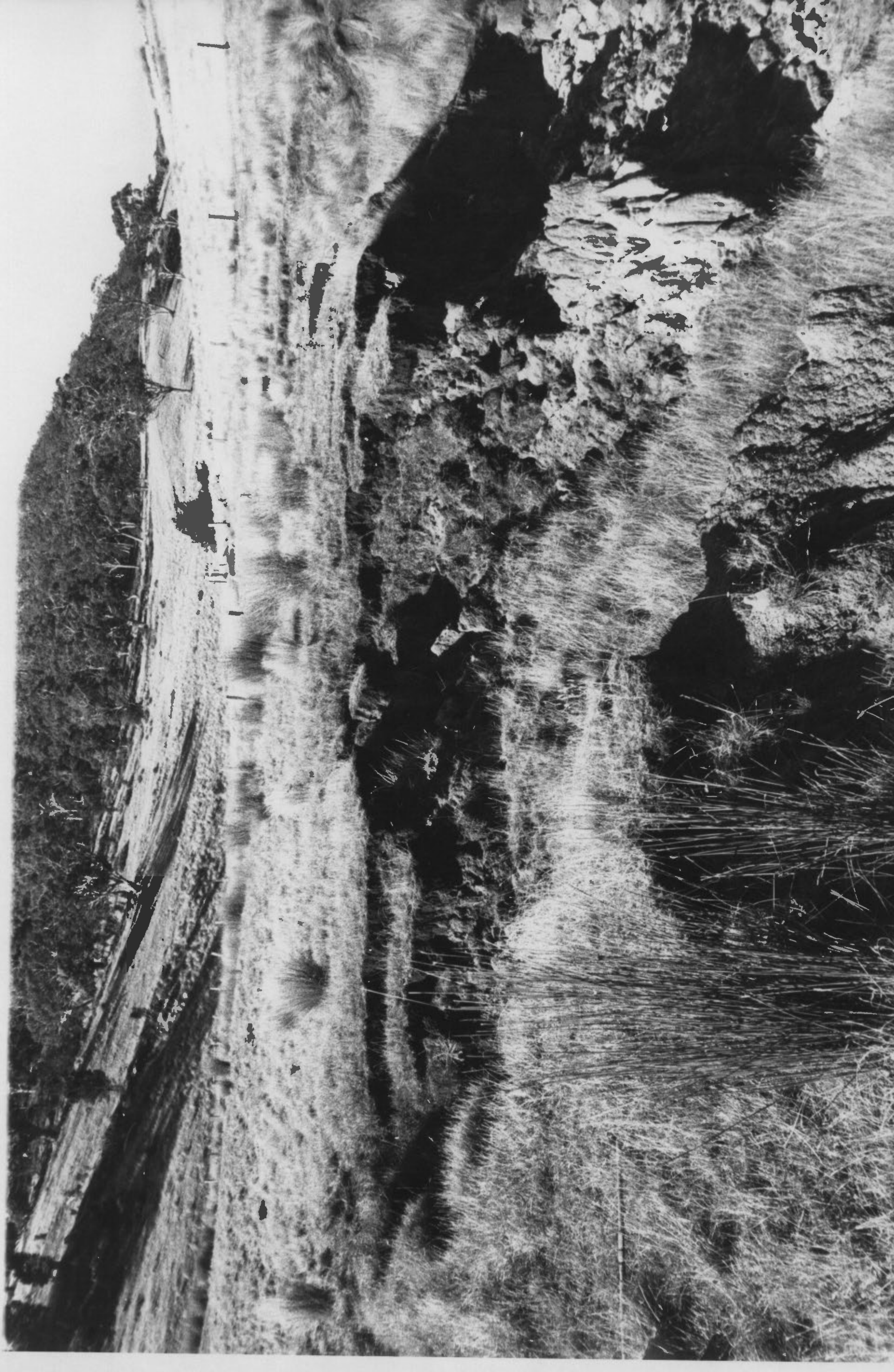
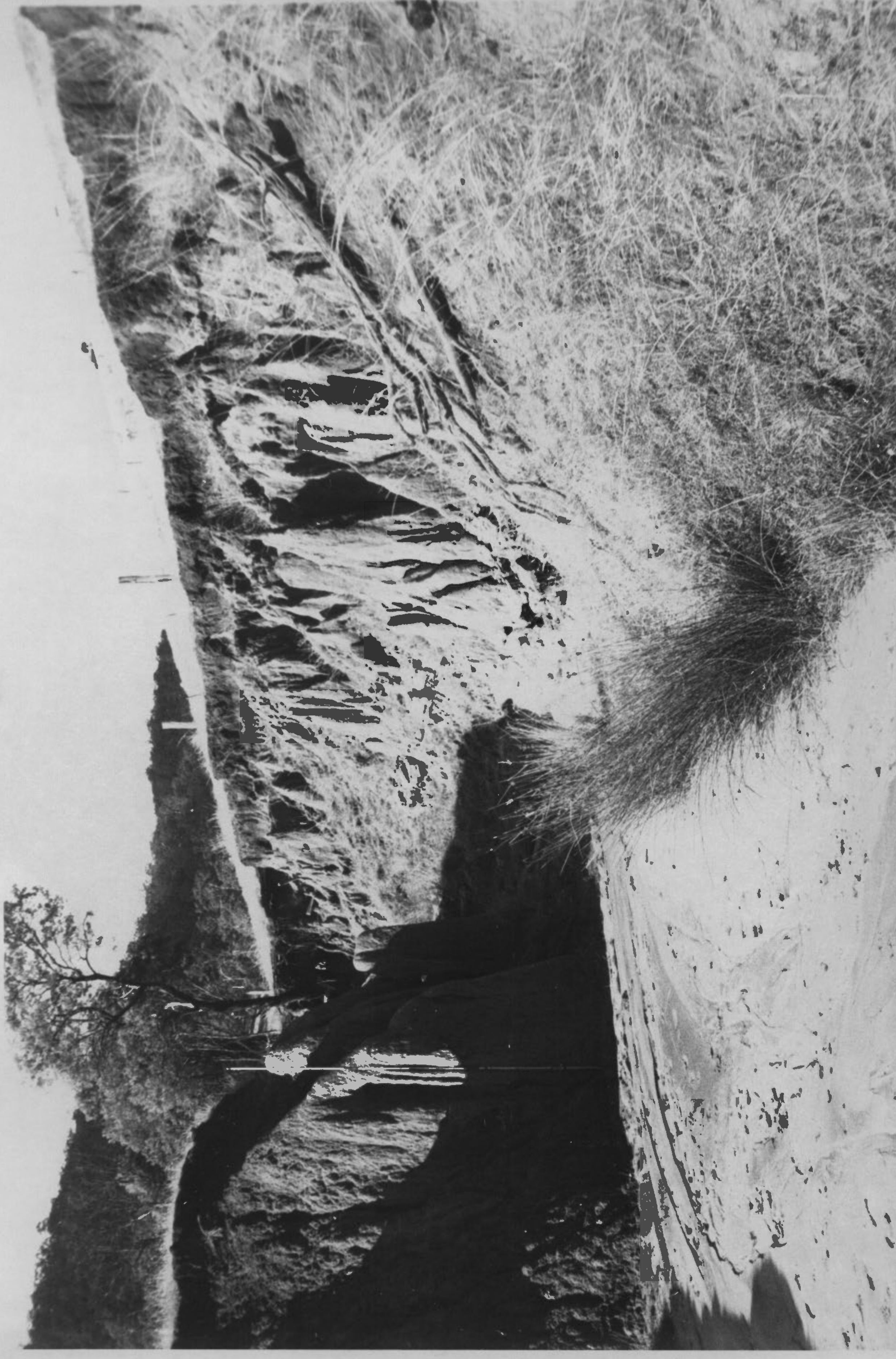


PLATE 15.

Erosion gully at 5082E, 52883N. (Note the flat sandy channel fill. Here the walls are 11 ft. high.)



which remains due to the binding effect of vegetation. When these underground channels widen, the unsupported roofs collapse, and in many instances, gullying may well have been initiated by these 'collapse-trenches'. However most commonly the underground channels are found on valley sides and in several instances, the continued rapid development of the gullies at least must be attributed to recent clearing of the land. The gully at 5082E, 52883N for example clearly shows rapid gully extension and development as the result of over-clearing. Comparison of aerial photographs taken in 1946 and 1966 shows that considerable extension has occurred within this period, and above the upper reaches of the main gully, further gullying is being initiated independently. Here a sequence of small depressions have developed. These depressions increase in depth downvalley where they form small elongated plunge-pools. Natural reed vegetation is found on the valley floor and in the past has no doubt prevented erosion. But it has now been cut and largely destroyed, and the grasses which have been reintroduced are ineffective in preventing erosion.

AEOLIAN DEPOSITS.

Windblown sands are found at several locations along the Jordan River valley. Reference to these deposits was first made by Nicolls (1958) and they are by no means unique to this area. Six samples (S_1 to S_6; Fig. 1) were collected for analysis. These sands are particularly loose and unconsolidated and the samples collected were light- to pale-brown in colour (Munsell notation 7.5YR to 10YR sheets). Each sample was dried and sieved and the individual fractions were weighed (Appendix C). The average cumulative percentage frequencies were plotted on arithmetic probability paper. Percentiles were determined and graphic grainsize parameters (Folk and Ward, 1957) were calculated.

The grainsize distribution of this material is symmetrical (S_{ki} = 0.11) and mesokurtic (K_g = 0.99) with a notable absence of coarse fractions (% wt. of grains 0.75 mm. in diameter and greater is only 0.12) and in particular is characterized by a very small grainsize range: the average of five samples gave a mean value of 0.2 mm. and 80 percent by weight of the whole sample consisted of particles within the size range 0.35 mm. to 0.1 mm. The very close agreement of these figures with those noted by Nicolls in other areas (mean 0.2 mm.; greater than 70 percent by weight in the size range 0.36 mm. to 0.11 mm.) even from such a relatively small sample, indicates the uniformity of this material over very wide areas.

The most extensive deposit of aeolian sands in the area occurs on the broad flat surface at the south-western foot of Goats Hill. Here dolerite outcrops for a few feet above the surface at one point and excavations to 3 feet in depth indicated that this outcrop is the highest exposed point of an otherwise completely blanketed area. This surface lies 41 ft. above river level and is quite out of character with the higher terrace remnants at approximately 30 ft. found nearby, and it seems likely that up to 10 ft. of aeolian sand covers the higher terrace here, although the depth of these deposits has not been proven through lack of time.

Discussion.

The occurrence of the aeolian deposits raises the question of the past climatic conditions during the period of their formation. Nicolls (1958) observed that with exceptions due to local clearing of the vegetation, the aeolian sands are stabilized throughout the State, so that their accumulation occurred under different conditions than the present, and he considered that

> A sufficient source of sand on the river floodplain implies periods of severe flooding with streams

> temporarily overladen with debris, alternating with periods when the stream deposits are dry enough to be eroded by wind. This could happen either in semi-desert conditions with occasional 'flash floods' or in periglacial conditions, with floods following the thaws.

From evidence in the Launceston Basin, Nicolls decided in favour of periglaciation, however Davies (1967) has shown that windblown features in Tasmania are almost exclusively confined to the subhumid province, and are bounded approximately by the 30 inch isohyet. In particular, Davies has directed attention to

> ....the evidence of the lunettes (particularly numerous in central Tasmania) which are generally agreed to be the result of drier conditions, and the contention that saltation of the sands over appreciable distances from the river channels must have required some diminution in vegetative cover.

Throughout the Broadmarsh-Elderslie area the broad alluvial fans and aprons, and the flat-bottomed valleys (Plate 16) provide ample evidence of extensive alluviation. Gullying in various places has exposed sections of up to 35 ft. through the sandy and pebbly debris of the valley floors. The smooth debris aprons and the apparent stratification in some sections of these gullies suggests that

PLATE 16.

A typically flat-floored valley
in the sandstone area.
(Note the alluvial fan developed
at the mouth of the valley.)

the material has been deposited during large sheet floods. Certainly these deposits would have provided a ready source for the aeolian sands when dried.

The periglacial hypothesis requires large amounts of meltwater during periods of thaw, washing debris down into the valleys. But in many cases these thick deposits occur in valleys having only small catchment areas and it is difficult to envisage a sufficient runoff unless these periods were quite wet, at which time vegetation must surely have been significant. Furthermore, melting would be by no means sudden, and a period of steady flow before and after the main thaw might be expected to have caused channelling through the deposits, yet everywhere the evidence suggests that sheet flooding has occurred. In fact, channelling seems to have occurred following this main period of alluviation. Excavations through the alluvial apron in the valley north of Elderslie show a dark brown soil horizon containing rounded to subrounded pebbles overlying the stratified clays and sands. U-shaped channels have been cut some 10 ft. below the level of the apron, and a 1 ft. layer of grey leached sandy topsoil has developed across both zones following the form of the channel. These channels are now stabilized by shrub vegetation and it seems likely that following the sheetwash alluviation, channelling developed in a wetter period and that the present period is again significantly drier.

Certainly a semi-arid environment seems the most likely for the alluvial period. Under such conditions sparse vegetation would enable ready removal of large quantities of material and the increased runoff during flash floods would readily distribute this material in large fans at the mouths of valleys.

The arid period inferred from the alluvial fans and aeolian deposits post-dates the wetter periods suggested by the valley meanders. It seems likely that this arid period was again followed by a more humid period so that the present climate represents yet another drier phase (though much less severe than the former period of aridity). The present rapid dissection and gullying is primarily due to clearing of the vegetation and the narrowing of the present channel by development of reed-benches may be the result of this recent over-supply of material to the river.

APPENDIX

APPENDIX A.

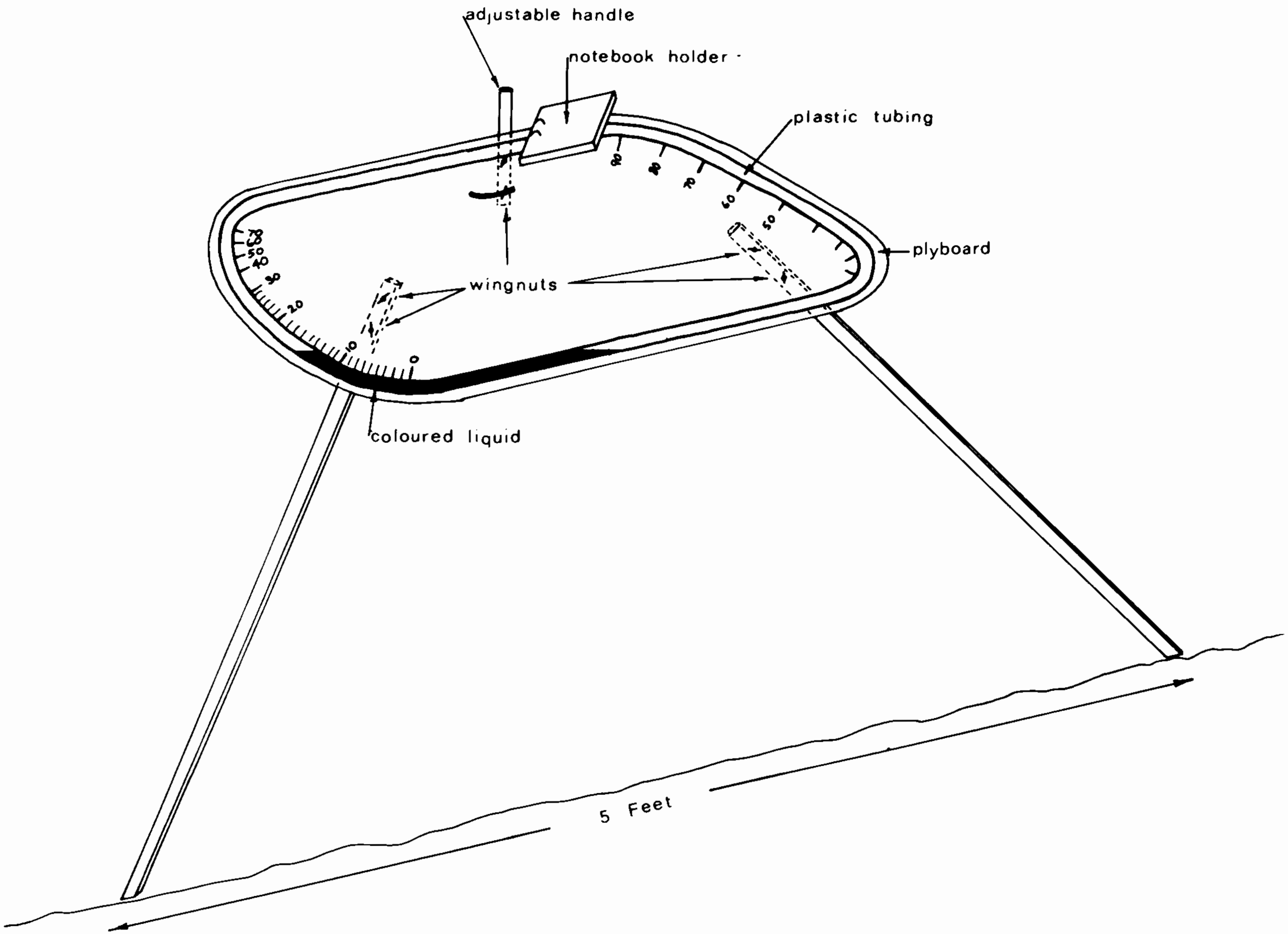
A New Hillslope Device.

Because of the large number of readings involved in the scheme of hillslope analysis used in this study, it is important that each reading can be taken as rapidly as possible.

Centring the bubble of the abney level using the 'inclined board' technique is time-consuming and although Pitty's (1968) slope pantometer is certainly a great improvement on this technique of slope measurement, again this device is levelled by a bubble, and towards the end of a day's work this can become a most tiresome process. Primary consideration therefore in the construction of this device was given to the development of a self-levelling mechanism. Also, because of the small variations in inclination of the hillslope, it was necessary that this mechanism should have a high degree of accuracy.

Most pendulum-type self-levelling mechanisms are either too small to give accurate readings or, if large enough, oscillate too freely. However the device shown in Figure 24 does succeed in giving a high degree of accuracy with rapid dampening, while being simple and inexpensive to construct. It consists of a continuous clear plastic tube

FIGURE 24



A NEW HILLSLOPE DEVICE

containing coloured liquid (blue kerosine proved most satisfactory) — it was found that by using $\frac{1}{4}$" (inside) diameter tubing the liquid will settle quite quickly.

Because this device rests on legs (detachable for easy handling) the problem of vegetation noted earlier is largely eliminated. The device has an adjustable handle so that it may be held ready at the approximate required angle of inclination. This leaves the other hand free for note-taking on an attached notebook stand. Although such fine attention to detail may appear trivial, it was found that these small improvements were invaluable aids.

The device constructed for this study had 'angled' aluminium legs and pine wood mountings, and weighed altogether less than 3 lbs. — so it is by no means cumbersome, and because it is entirely rigid, requiring no adjustment whatsoever during measurement, more rapid progress was facilitated.

HYPERSPACE PLOT.

The program shown below computes the distances between points plotted in a 6-dimensional hyperspace, but is readily adapted for calculations within any dimension. The program shown here compares 40 points.

SLOPES IN HYPERSPACE U1993.

```
begin   integer i,j,k,l;
        real array a[1:40,1:6];
        integer array title [1: 18];
        real x;
        digits (2);
        aligned(2,8);
        sameline;
        i:=1; instring (title,i); outstring (title,i);
        l:=0;
        print ££ls5?i£s6?j£s11?x£s9?i£s6?j£s11?x£s9?i
              £s6?j£s11?x?;
        begin for i:=1 step 1 until 40 do
              for k:=1 step 1 until 6 do read a[i,k];
        begin for i:=1 step 1 until 39 do
              for j:=i+1 step 1 until 40 do
        begin x:=sqrt((a[i,1]-a[j,1])↑2+(a[i,2]-a[j,2])↑2
                  +(a[1,3]-a[j,3])↑2+(a[i,4]-a[j,4])↑2
                  +(a[i,5]-a[j,5])↑2+(a[i,6]-a[j,6])↑2);
```

```
                l:=l+1;
                if l>4 then    begin l:=0;
                                     print ££l??;
                               end;
                print £ * ?,i,££s4??,j,££s4??,x
            end
            end
            end
end of program;
                  ↑↑
```

SLOPE PARAMETERS.

Slope No.	D_1	D_2	S_k	K	U	P_{50}
1	2.592	5.857	-0.369	-0.006	0.150	25.171
2	4.167	6.323	0.039	0.983	-3.150	17.840
3	6.036	10.247	0.083	-0.311	1.900	24.295
4	3.102	5.667	0.037	-0.108	1.510	19.205
5	1.979	3.837	-0.215	0.051	-1.900	16.515
6	1.889	4.000	0.037	0.270	0.380	15.898
7	3.400	5.250	0.079	-0.610	0.060	16.083
8	3.262	7.915	-0.415	0.570	8.510	26.596
9	1.600	3.700	0.097	0.468	0.463	15.225
10	6.316	10.200	0.098	-0.460	-0.432	21.750
11	2.756	5.120	0.007	1.193	0.562	18.150
12	4.700	9.338	-0.145	0.110	-0.600	27.150
13	2.984	6.019	0.046	0.149	-2.594	17.321
14	3.350	5.193	0.117	-0.600	-2.700	17.417
15	2.778	5.640	-0.097	0.170	7.101	24.660
16	1.726	3.215	0.240	-0.050	0.460	12.863
17	2.841	5.540	0.254	0.066	2.136	15.850
18	8.312	10.754	-0.126	-1.230	5.000	26.083
19	6.796	11.833	-0.049	-0.245	-5.300	24.296
20	4.850	9.066	0.011	-0.045	7.982	21.083
21	2.459	6.422	-0.175	0.730	0.085	20.395
22	3.887	7.286	-0.096	-0.040	0.716	20.397
23	3.165	5.508	-0.297	-0.002	1.380	18.977
24	2.800	6.080	-0.049	0.310	1.543	18.365
25	3.355	6.983	-0.150	0.230	0.144	21.550
26	4.000	7.750	0.049	0.050	-1.120	20.615
27	2.150	4.826	0.052	0.046	2.695	20.607
28	3.382	7.840	0.014	0.472	-6.800	25.099
29	3.323	5.720	0.123	-0.278	-1.460	20.801
30	3.207	5.235	0.027	-0.434	3.110	15.937
31	2.402	4.858	-0.016	0.155	-1.035	16.036
32	4.344	6.587	0.075	-0.670	-0.900	18.295
33	1.729	3.197	-0.001	-0.075	0.050	15.380
34	1.851	3.578	-0.009	0.045	-2.530	29.893
35	2.191	4.300	0.203	0.083	-6.000	28.042
36	3.083	5.350	0.056	-0.250	3.160	18.000
37	5.000	7.680	-0.036	-0.645	-12.730	18.750
38	3.928	25.430	0.815	1.858	-11.990	28.750
39	5.037	25.716	0.862	1.650	-0.750	21.917
40	7.453	12.364	0.097	-0.385	-0.385	22.083

STANDARDIZED SLOPE PARAMETERS.

Slope No.	D_1	D_2	S_k	K	U	P_{50}
1	-0.632	-0.178	-1.700	-0.170	0.162	1.083
2	0.351	-0.125	0.030	1.600	-0.488	-0.650
3	1.578	0.316	0.217	-0.715	0.507	0.879
4	-0.311	-0.199	0.023	-0.352	0.430	-0.327
5	-1.016	-0.400	-1.045	-0.068	-0.242	-0.962
6	-1.062	-0.387	0.022	0.375	0.207	-1.109
7	-0.128	-0.246	0.201	-1.248	0.144	-1.067
8	-0.214	0.049	-1.885	0.860	1.805	1.423
9	-1.248	-0.420	0.275	0.677	0.244	-1.270
10	1.690	0.312	0.279	-0.980	0.049	0.276
11	-0.530	-0.260	-0.106	1.973	0.243	-0.577
12	0.683	0.240	-0.745	-0.038	0.001	1.554
13	-0.387	-0.159	0.060	0.017	0.378	-0.774
14	-0.159	-0.273	0.359	-1.230	-0.399	-0.750
15	-0.516	-0.202	-0.547	0.145	1.529	0.967
16	-1.170	-0.475	0.881	-0.248	0.222	-1.827
17	-0.476	-0.213	0.940	-0.041	0.552	-1.120
18	2.935	0.373	-0.666	-2.355	1.120	1.302
19	1.987	0.495	-0.341	-0.597	-0.912	0.879
20	0.776	0.184	-0.087	-0.239	1.705	0.118
21	-0.715	-0.114	-0.874	1.190	0.290	-0.045
22	0.176	-0.017	-0.542	-0.231	0.273	-0.044
23	-0.274	-0.217	-1.392	-0.162	0.403	-0.380
24	-0.502	-0.152	-0.340	0.394	0.437	-0.526
25	-0.156	-0.051	-0.770	0.252	0.160	0.228
26	0.247	0.035	0.075	-0.070	-0.088	0.007
27	-0.907	-0.294	0.084	0.567	0.663	0.005
28	-0.139	0.055	-0.075	0.684	-1.286	1.070
29	-0.176	-0.193	0.389	-0.655	-0.155	0.051
30	-0.248	-0.249	-0.020	-0.935	0.742	-1.098
31	-0.750	-0.290	-0.202	0.118	-0.072	-1.075
32	0.461	-0.095	0.183	-1.355	-0.045	-0.543
33	-1.169	-0.477	-0.141	-0.293	0.142	-1.231
34	-1.193	-0.434	-0.173	-0.079	-0.366	2.205
35	-0.882	-0.353	0.725	-0.011	-1.049	1.764
36	-0.326	-0.234	0.102	-0.605	0.755	-0.612
37	0.870	0.027	-0.288	-1.310	-2.372	-0.433
38	0.210	2.020	3.300	3.580	-2.320	1.936
39	0.895	2.055	3.540	2.790	-0.002	0.316
40	2.400	0.555	0.275	-0.847	-2.750	0.355

APPENDIX B.

Channel Dimensions

Run	Site No.	B'full W	B'full D	W/D
1	1	20.5	5.8	3.53
	2	36.0	7.6	4.74
	3	59.5	9.0	6.61
	4	64.0	10.0	6.40
	5	76.0	12.0	6.33
	6	29.5	6.0	4.92
	7	57.0	14.7	3.88
	8	26.0	6.0	4.33
	9	47.0	7.0	6.71
	10	26.0	8.7	2.99
	11	70.0	12.3	5.69
2	12	17.5	4.4	3.98
	13	51.5	7.5	6.87
	14	18.5	4.2	4.40
	15	42.0	6.0	7.00
	16	52.0	7.2	7.22
	17	57.5	9.2	6.25
	18	36.5	8.0	4.56
	19	55.0	8.6	6.39
	20	66.0	11.0	6.00
	21	79.5	13.3	5.98
	22	20.5	4.2	4.88
	23	58.5	12.9	4.53
3	24	47.5	10.5	4.52
	25	29.25	9.3	3.14
	26	36.0	7.5	4.80
	27	27.2	7.7	3.54
	28	31.5	5.8	5.43
	29	49.0	10.6	4.62
	30	37.0	9.6	3.85
	31	63.0	11.6	5.43
	32	33.0	7.0	4.71
	33	38.5	7.5	5.13
	34	32.0	8.0	4.00
	35	43.0	10.0	4.30
4	36	30.0	5.7	5.2
	37	24.5	7.8	3.1
	38	34.0	9.6	3.5
	39	66.0	11.6	5.6
	40	38.5	7.0	5.5
	41	52.0	13.3	3.9
	42	83.0	13.0	6.3
	43	36.5	11.7	3.1
	44	31.5	10.2	3.0
	45	27.0	6.5	4.1
	46	54.5	8.5	6.4
	47	34.0	8.0	4.2
5	48	31.0	8.0	3.8
	49	45.5	8.0	5.6
	50	80.0	21.0	3.8
	51	44.5	7.3	6.0
	52	60.5	9.9	6.1
	54	18.5	3.6	5.1
	56	34.0	8.5	4.0

APPENDIX C.

SEDIMENT ANALYSES.

1) Aeolian Sands.

Each sample was oven dried at a temperature of approximately 105°C and weighed. The aeolian sands are so unconsolidated that very little disaggregation was needed. This was done using a porcelain mortar and rubber pestle to avoid breaking the grains. The sample was then sieved for fifteen minutes in a mechanical sieve shaker.

PERCENTAGE WEIGHTS.

Ø Units	Sample No. 1	2	3	4	5	Mean %
Less than 0.5	0.0179	0.3392	0.1307	0.0981	0.0163	0.1204
0.5 - 1.0	0.4261	0.3853	1.5501	0.1780	0.2352	0.5549
1.0 - 1.5	3.3726	2.9460	8.6161	0.9687	3.4290	3.8665
1.5 - 2.0	28.1024	24.4137	35.0460	14.9410	23.1102	25.1227
2.0 - 2.5	29.8830	26.3247	28.7170	23.6543	26.5175	27.0193
2.5 - 3.0	27.2324	28.8720	20.4469	32.9915	29.8227	27.8731
3.0 - 3.5	8.0145	11.8321	4.0196	16.4231	11.3008	10.3380
3.5 - 4.0	2.0182	3.9530	0.9115	7.1887	4.0046	3.6152
Grtr than 4.0	0.7669	1.2338	0.4855	3.2761	1.4837	1.4492
						99.9593

2) Channel Samples.

Each sample was oven dried at 105^{o}C and weighed. The sample was then disaggregated roughly using a mortar and pestle. The sample was split and approximately 100 grams in each case was selected for analysis.

Each sample was then boiled and stirred for about 10 minutes in a 600 ml. beaker, and 20 ml. of N sodium hydroxide was added after cooling. The sample was then dispersed for 30 minutes using a motor dispersing unit. The dispersed sediment was then stirred in a sedimentation cylinder (using a perforated disc to avoid swirling) filled to a height of 30 cm. and allowed to settle for a time appropriate for a 30 cm. fall for the given water temperature and the particle size to be poured off (50μ) (tables given by Brewer, 1962).

At first, as suggested by Brewer, several decantations at twice the suggested time were made, to reduce the density of the suspension which may possibly upset sedimentation times.

In this analysis, lack of time prevented removal of organic matter. Some bank samples did in fact have a large amount of fine rootlets and were discarded.

When the water had become clear after the decanting time, the sample was again oven dried and reweighed so that the percentage of silt-clay removed from the sample, could be calculated.

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