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EARTHFLOWS IN THE YANKALILLA DISTRICT OF SOUTH AUSTRALIA.

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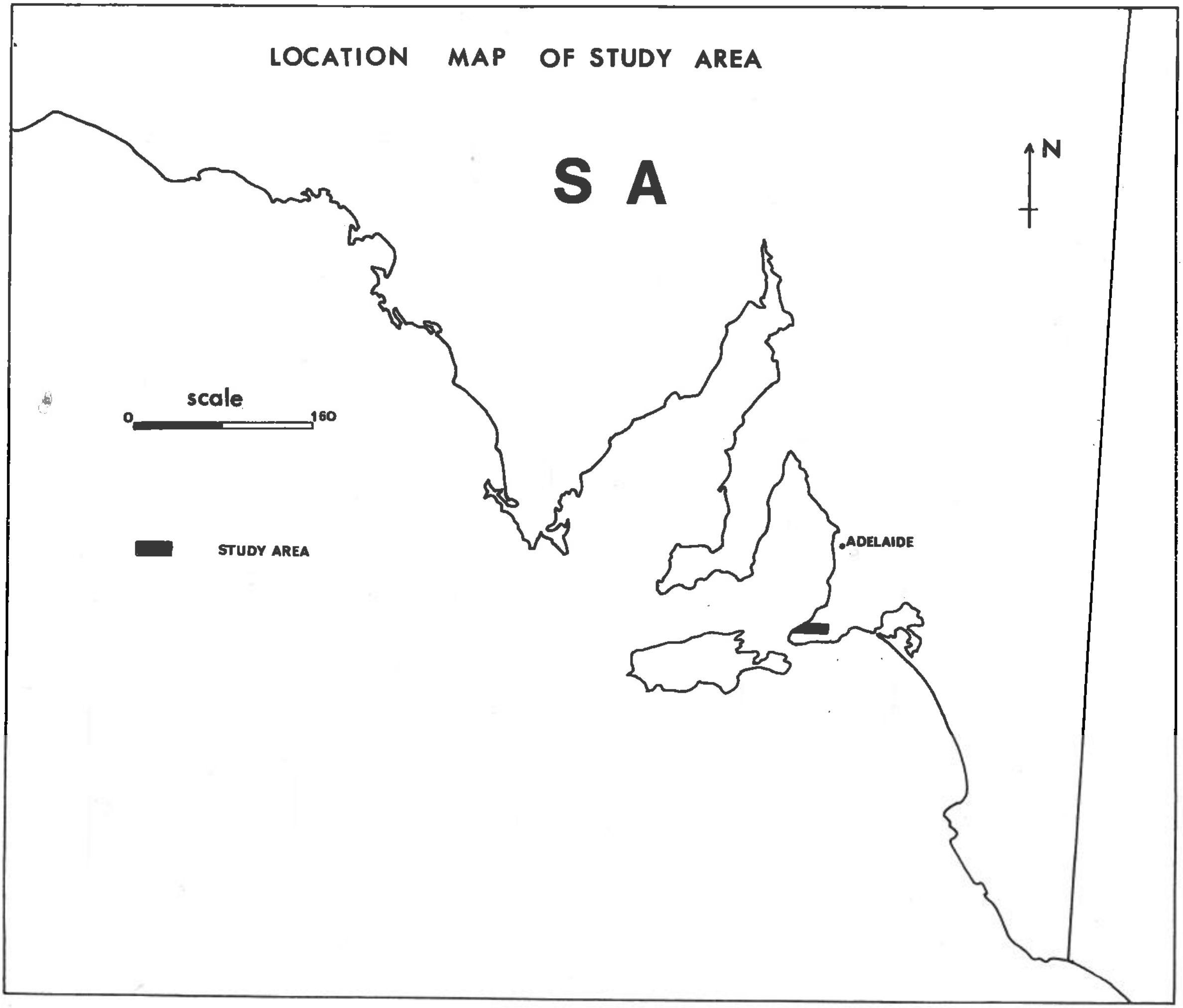


LOCATION MAP OF STUDY AREA

INTRODUCTION.

> ' Icannot conceive of a physiography from which man is excluded' (Krapotkin,1893).

The anthropgenic factor is a recent addition to the science of geomorphology, although, as early as 1864 G.P. Marsh warned of the deleterious erosional consequences of the overclearing of vegetation.

The Fleurieu Peninsula,eighty kilometres south of Adelaide, South Australia (fig. one), affords the opportunity to study in detail the results of man's activity upon the landscape, wrought by settlement in the second half of the last century. Cleared initially for the growing of wheat, the area now shows the consequences of erosion in the form of deep gullies and mass-movements. Gullying results from the concentration of run-off in the vertical furrows employed before the introduction of contour ploughing.

Landsliding is considered the most significant process of mass-movement operating in the area and while there has not been a disaster in the sense of loss of life such as occurred in Hong Kong (So,1971) or Yungay, Peru, where twenty-five thousand are known to have perished (Cooke &Townshend,1970), landsliding represents a serious economic loss of productive land. With gullying, it is estimated by Campana (1954) that landsliding causes a twenty percent reduction of arable land.

These landslides pose a number of problems, first in relation to distribution, morphology and active and passive causes as suggested by Sharpe (1938) and second to the time lapse between the initial clearing and subsequent movement of the land. These problems are investigated in this study.

DEFINITIONS.

The term 'mass-movement', which involves the bulk transfer material down slope under the influence of gravity, is generic, in relation to morphology and process, in that it encapsules a wide variety of different landforms and their means of formation. Similarly,

> 'Landslides are the perceptible downslope movements of rock, soil or artificial fill. The motion may be either that of a slide, flow or fall, acting singly or together. All are forms of slope failure arising from a high shearing stress along a potential surface of rupture which exceeds the shearing resistance along that surface' (Varnes, 1958).

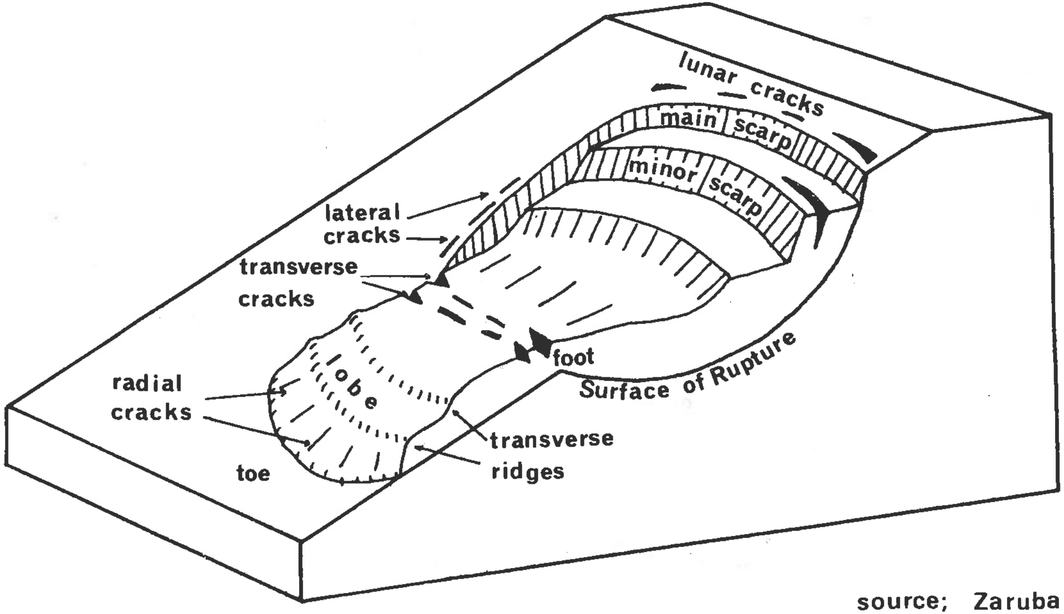
A classification scheme to describe individual movements or groups of movements is therefore necessary. However, as Terzaghi(1950) suggests, ' A phenomena involving such a multitude of combinations between materials and disturbing agents opens unlimited vistas for the classification enthusiast.'

Sharpe (1938) proposed a classification based on the nature and rate of movement, the water content and the type of material involved. Four main categories were established, namely slow flowage, rapid flowage, sliding and subsidence. This classification has been adopted in many geomorphological texts.

Varnes(1958), modifying Sharpe, introduced a now widely used classification which considers the type of movement derived from morphology and the type of material involved. Falls, slides and flows are the major divisions.

The occurence of mass-movement is an event rarely witnessed by man and thus process must be extrapolated from the

DIAGRAM TO SHOW MAIN FEATURES OF EARTHFLOW



source; Zaruba and Mencl

resultant morphology. Crozier (1973) following Skempton (1953) has used this concept to establish a statistical classification of landslides based on a group of indices derived from the measurement of the main features of any one movement. (eg. the ratio of length to depth) This morphometric technique has led to the defining of five process groups differentiated by statistically significant ratios.

Sharpe, Varnes and Crozier distiguish between slides and flows in that the former results along a surface of rupture where shear failure has occurred. Further, the mass when undeformed, may be either on a rotational slip-surface with a backward tilting of the block, or on a planar surface usually parallel to the ground and displaying no backward rotation. It is commonly assumed (Sharpe, 1938) that water acts as a lubricant which induces movement along the slip-surface. Brundsen (1971) has drawn attention to this error by noting that a slip-surface does not exist until movement has occurred and therefore water could not act as an initiating agent.

Flows, however, need not possess a slip-surface as they tend to move as a semi-liquid or viscous mass, often following pre-existing drainage channels. Mudflows occur where there is abundant, but intermittant water, lack of vegetation and unconsolidated, deeply weathered regolith. These conditions are best satisfied in semi-arid regions (Blackwelder, 1928) An earthflow is defined by Sharpe(1938) and Varnes (1958) as a mass moving by viscous deformation, but containing less moisture than a mudflow and not being confined to pre-existing drainage channels. Slumping is considered by Varnes (1958) to be an essential process in earthflow. Sharpe however, had

Plate one. Mass-movement of the 'earthflow' type displaying single flow.

Plate two. Earthflows of the coalesced type.

defined slump as the 'downward slipping of a mass of rock or unconsolidated material of any size... usually with backward rotation' (Sharpe, 1938). Since a backward rotation is not always present, the term subsidence shall be employed in this investigation.

Landslides within the study area are earthflows. These occur in isolation (plate one) or in coalesced groups (plate two) at some sites. The volume and extent of these earthflows varies from narrow with elongated lobes, to broad scarped but only minor downslope extension. In all cases movement is a superficial phenomena restricted to a range of depths from a half to four metres. Variations in profile relates to the stage of development of the earthflow, the 'classic' mature shape consisting of a spoon-shaped hollow bounded by a steep arcuate, head scarp which levels at the foot before bulging above the turf surface to form an elongated lobe extending downslope. (fig two) Recently developed earthflows are distinguished by arcuate,tension cracks resulting from subsidence and low level, sub-turf bulging. Older earthflows are present although their main features such as the head scarp or lobe have been reduced by secondary erosional processes .

SETTING.

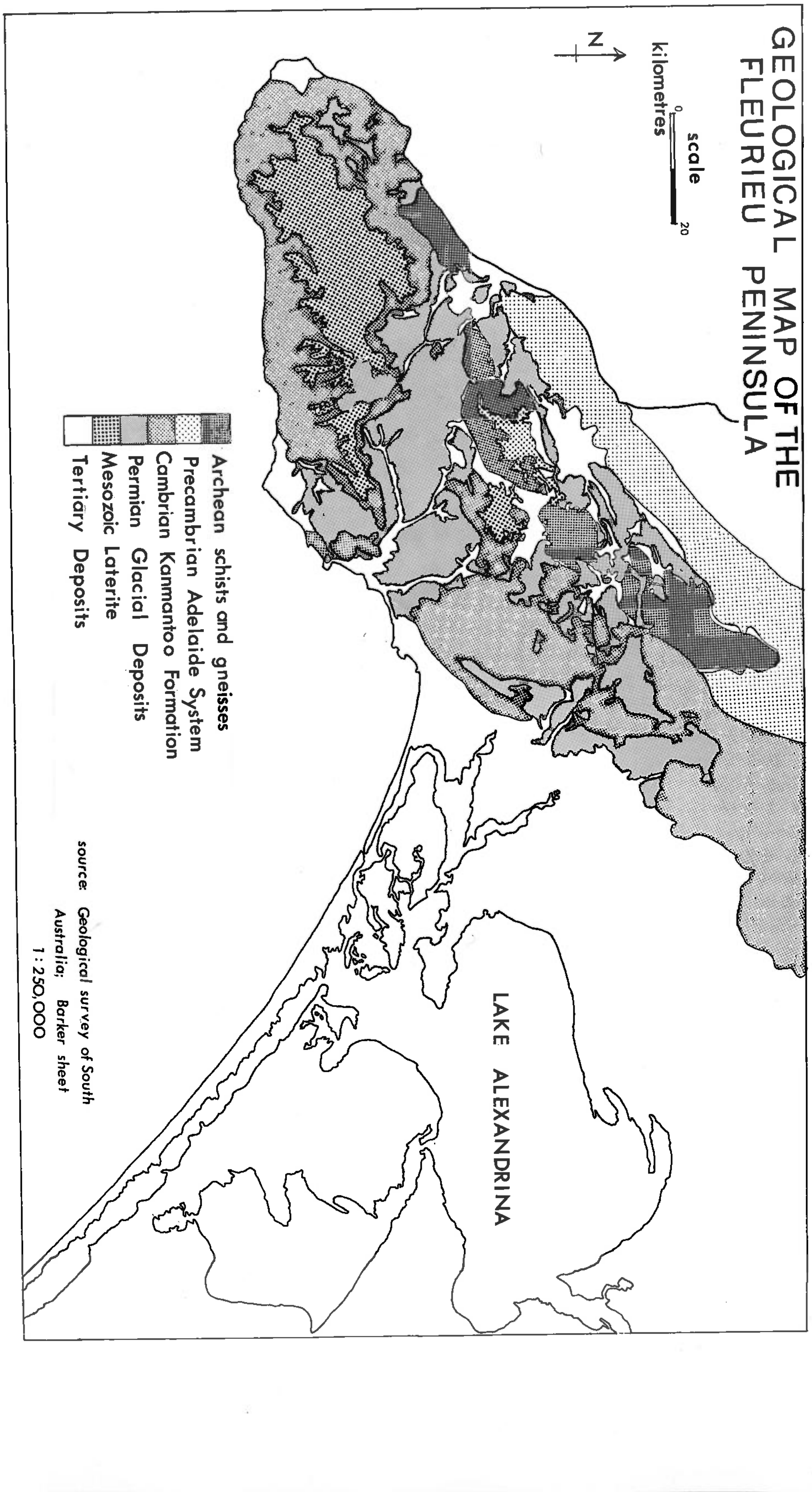
Geology.

Earthflows are confined to Permian, glacial, depressions filled with unconsolidated,glacial, fluvio-glacial and glacio-lacustrine drift resting unconformably on Precambrian and Cambrian rock.

Evidence of glaciation was originally noticed by the Victorian geologistA.R.C. Selwyn in 1859, in the form of striations and glacial gouges, in the bed of the Inman river. Thought at first to be of Pleistocene age, they were shown to be Permian by Tate in 1877, from evidence in the region of

Hallet Cove (Howchin, 1926).

This glaciation is considered to have been of a mountainous type as evidenced by overdeepened valleys (Back Valley


GEOLOGICAL MAP OF THE FLEURIEU PENINSULA

source: Geological survey of South Australia; Barker sheet 1:250,000

Hallet Cove (Howchin, 1926).

This glaciation is considered to have been of a mountainous type as evidenced by overdeepened valleys (Back Valley is presently overdeepened in relation to sea level by two hundred metres, implying that prior to the Miocene uplift overdeepening was in the order of five hundred and fifty metres), and remants of cirques(Campana, 1954). The direction of ice movement as ascertained by striations and other glacial features, was from present day Encounter Bay towards the north-west (Howchin, 1926).

These readily eroded deposits were protected during the Mesozoic peneplanation because they lay below the baselevel of erosion (Campana, 1954). Tertiary faulting caused denudation to be rejuvenated, allowing rivers such as the Yankalilla, Bungala and Inman to actively cut back into the plateau region. Consequently the Permian deposits were eroded and transported faster than the resistant bedrock thereby forming an area of comparitively low relief.

The resistant uplands consist of heavily metamorphosed and folded Precambrian and Cambrian deposits. To the north, Kemmiss Hill comprises Archean micaschists, with locally injected kyanite-sillimanite schist; gneisses migmatites and ilmenitic, quartz veins, upon which the deposits of the Adelaide System rest unconformably. This suggests that the Archean complex was folded, metamorphosed and injected before the formation of the Adelaide geosyncline(Campana, 1954).

To the east and south, deposits laid down in the deep (nine thousand metre) Kanmantoo Trough, were heavily folded, faulted and metamorphosed during the Cambrian-Ordovician orogeny(Alderman, 1973). Towards Victor Harbour, intrusion of a granite batholith has caused more extensive, contact metamorphism. This 'Kanmantoo' group consists of greywackes, phyllites, quartzitic schists and micaseous quartzites.

Erosion of the orogeny, the first Flinders- Mount Lofty ranges, is assumed to have taken place throughout the Silurian, Devonian and Carboniferous peroids, a span of two hundred million years, yet peneplanation had not occurred. Evidence for this is derived from the nature of the Permian glaciation, that is mountainous (Campana, 1954. Alderman, 1973 Howchin, 1926).

Peneplanation is assigned to the Mesozoic and early Tertiary. The lateritic capping found on the present plateau surface has generally been considered to be of Tertiary age (Hossfeld,1926; Fenner, 1930). However, this assumption has been discounted in favour of a Mesozoic, possibly Triassic age (Daily, Twidale &Milnes, 1974). Peneplanation presumably also dates from this time.

Climate.

The climatic characteristics of the Fleurieu Peninsula have been determined by Mason (1954) largely from official rainfall records taken since the mid-eighteen hundreds, as well as the records of local farmers where accurate. Temperature records are however, limited and thus correlation is made to the recording station at Stirling. In reference to this investigation, rainfall is the most important factor to be considered.

Distribution of rainfall, as may be expected, fluctuates according to the season and with topography. The main source of rainfall is frontal uplift during the winter months, which when accentuated by topography on the western margins of the Peninsula, results in falls of up to nine hundred millimetres per annum(Mason, 1954). Within the study area rainfall varies between five hundred and fifty m.m. along the coast in the vicinity of Normanville, to six hundred and fifty m.m. near Inman Valley (Mason 1954). Variability of distribution occurs over relatively small areas,which in conjunction with other factors, helps explain the distribution of earthflows.

Unusually heavy periods of rainfall are considered inducers of earthflows (So, 1971; Sharpe, 1938 & 1942; Crozier, 1969). Total yearly amounts are however, not as important as distribution throughout the year for when well spaced, excess water can be removed without precipitating mass-movement. Median rainfall amounts and deviation from these amounts must therefore be known.

During summer, the median amount of rainfall is sixty three m.m. Variation ranges from thirty eight m.m. in the lowest quartile range to one hundred and twenty five m.m. in the highest quartile range (Mason, 1954). The amount of moisture required to prevent the total loss of soil water is one hundred and fifty m.m. Since this exceeds the highest quartile figures for summer, we can expect desiccation of soil to occur. The opening up of the surface layers of soil is considered to be of the utmost importance for it allows the deep penetration of moisture when the first rains break, usually in April.

Winter rainfall ranges from a median of two hundred and fifty m.m. to a lowest quartile figure of two hundred m.m.

with an upper quartile maximum of three hundred m.m. (Mason, 1954).

Knowing these variations, extrapolation of periods of potential earthflows can be determined statisically. Used in conjunction with other techniques, dating of movement is possible.

Vegetation and Settlement.

When one considers the Aboriginal term 'Yankalilla' means long walk, big timber (Stevens,1953) and the present landscape is viewed, one must agree with Williams(1974) who stated,

> 'Of the many activities which have gone into the making of the South Australian landscape, the clearing of woodland must have brought about the most striking and widespread transformation.'

The natural vegetation of the study area consisted of savannah woodlands on the glacial lowlands, grading to sclerophyll on the plateau surface. The lowland cover included blue gum (Eucalyptus leucoxylan) and peppermint gum (Eucalyptus odorata), while the river courses were lined with Eucalyptus camaldalensis. An understory of herbaceous scrub and grasses was widespread, altough less dense than found on the uplands. Light (1837) described the lowland area as an, 'abundance of wood all the way, yet not so thick that agriculture might be practiced without the trouble of clearing.' The plateau vegetation consisted of stringy bark (Eucalyptus obliqua) with a dense understory (Boomsma,1948: Williams, 1974)

Selections for settlement were opened on the twenty sixth of December, 1839, and by 1857 thirty six and a half thousand

LOCATION MAP OF EARTHFLOWS IN THE STUDY AREA acres had been sold (Pridham, 1955). Wheat, grown between 1840 and 1875, was abandoned as a result of adverse competition from new settlements to the north of Adelaide, as well as declining yields due to a lowering of fertility in the soil. The only method of fertilization employed was the ploughing in of burnt wheat stubble, a process which exposed a surface highly susceptible to erosion.

The planting of wattle trees, the bark of which was used in the manufacture of tannic acid, between 1875 and 1910 (Pridham, 1955), is believed to have arrested erosion to a minor degree only. After 1910 clearing continued so as to allow the grazing of sheep and cattle, which themselves cause the destruction of vegetation.

The time gap between clearing and earthflow is difficult to ascertain because rates of clearing are not positively known (Williams,1974). It would seem that the cohesive physical and chemical properties vegetation lends to soil deteriorate differentially over time. This deterioration is investigated in this study.

METHODOLOGY.

Field work and analysis were undertaken in 1975 in an endeavour to relate the development of earthflows to a number of variables including climate, geology, soil mechanics and the role of man.

An initial reconnaissance was made in mid- February in order to locate mass-movements and demarcate the area of study. Aerial photographs (18-1-1974, scale 1:59,900) were employed to this end. The boundary of mass-movements was found to correspond to areas of Permian glacial deposits as indicated by the geological map (Campana, 1954. 1:63,360). Aspect and slope were measured, while general features of morphology were noted, from which a review of the literature was undertaken. It was felt that the investigation should be commenced in this period as the physical features produced by hot, summer conditions are substantially different from those found in winter, and relate directly to the cause of earthflows.

During March and July the area was visited in order to interview local inhabitants in the hope of eliciting information on the time of occurence of individual earthflows. Tape and compass traverses were used to measure and map a number of movements(numbers 1,2,3,5,8,12, &13.) in accordance with Crozier's (1969) morphometric technique. An attempt to measure the rate of movement on earthflow number eight(fig. 4) during March was unsuccesful as shall be mentioned in the description of that earthflow given below.

The main body of investigation took place in August in relation to movements number four and eight, although observations of remaining earthflows was continued. Number four was contour mapped by means of level and staff relative to a bench mark located half a kilometre to the west.

Soil profiles were established by five bore holes sunk on earthflow number four, using a ten centimetre, manual auger. Three of these bores were on the body of the earthflow while two were sunk on the adjacent, stable slope. A single bore was placed on movement number three to determine if there were any significant variations in physical and chemical properties, as number three is suggested to occur in an area of 'Biscay' soils (D.K. Crawford, per. comm.).

Samples from these drillings were analysed. Clay type and proportions analysis was carried out by separation and X-ray diffraction (C.S.I.R.O. Division of Soils.). The Atterberg limits were established by the Casagrande technique, by utilizing theequipment of the Department of Civil Engineering, University of Adelaide. Water contents of soils found on movements number four and eight were determined at the same time, the results being discussed in relation to the two earthflows. Rates of motion were also measured for both mass-movements over a peroid of three weeks.

It was hoped that interstitial, ground water pressures could be measured, but the cost of piezometric equipment prohibited this line of investigation. To establish shear strength values, tri-axial shear tests should have been undertaken.

DATING TECHNIQUES.

The role of European settlement in the creation of earthflows can only be evaluated consequent to the dating of such movements in relation to vegetation clearing. Unfortunately the rate of clearing is not accurately known, while the original cover was not complete, there being areas clear of all but minor scrubs and grasses (Mr. Putland, per. comm.). Further, it must not be assumed that all earthflows post-date European settlement, there being evidence in the form of fossil 'flows that this process of mass-wasting existed prior to 1839. It is certain that man has merely accelerated a geomorphological process already acting on unstable slopes. However, this investigation concerns itself largely with earthflows post-dating settlement. Four methods of dating are used in conjuction to elicit the time of these movements.

(1) Aerial photographs, which had been used to locate earthflows, were also employed in dating. In most cases, ranges of dates only were possible since runs occurred in random years (1949,'56,'59,'60,'61, '66,'67,'72,'74). Problems in the application of this method, result from the variations in scale and clarity, especially in the drier periods when difficulty is experienced in distinguishing earthflows from surrounding ground.

(2) The geological maps of Yankalilla and Jervis (Campana, 1954.scale 1:63,360 inches) indicate areas of 'landslides', but do not distinguish the type, size or nature of movement. Further, a number of omissions occur. Earthflows number one, two and three, for example, are not indicated, but their existence at this time is testified by the 1949 aerial photographs. These display a morphology distictly similar to today. By correlation in the field, earthflows 11,14,17,19,24,31, and 33 are shown to have been present in 1953 when mapping was undertaken(Campana,1954).

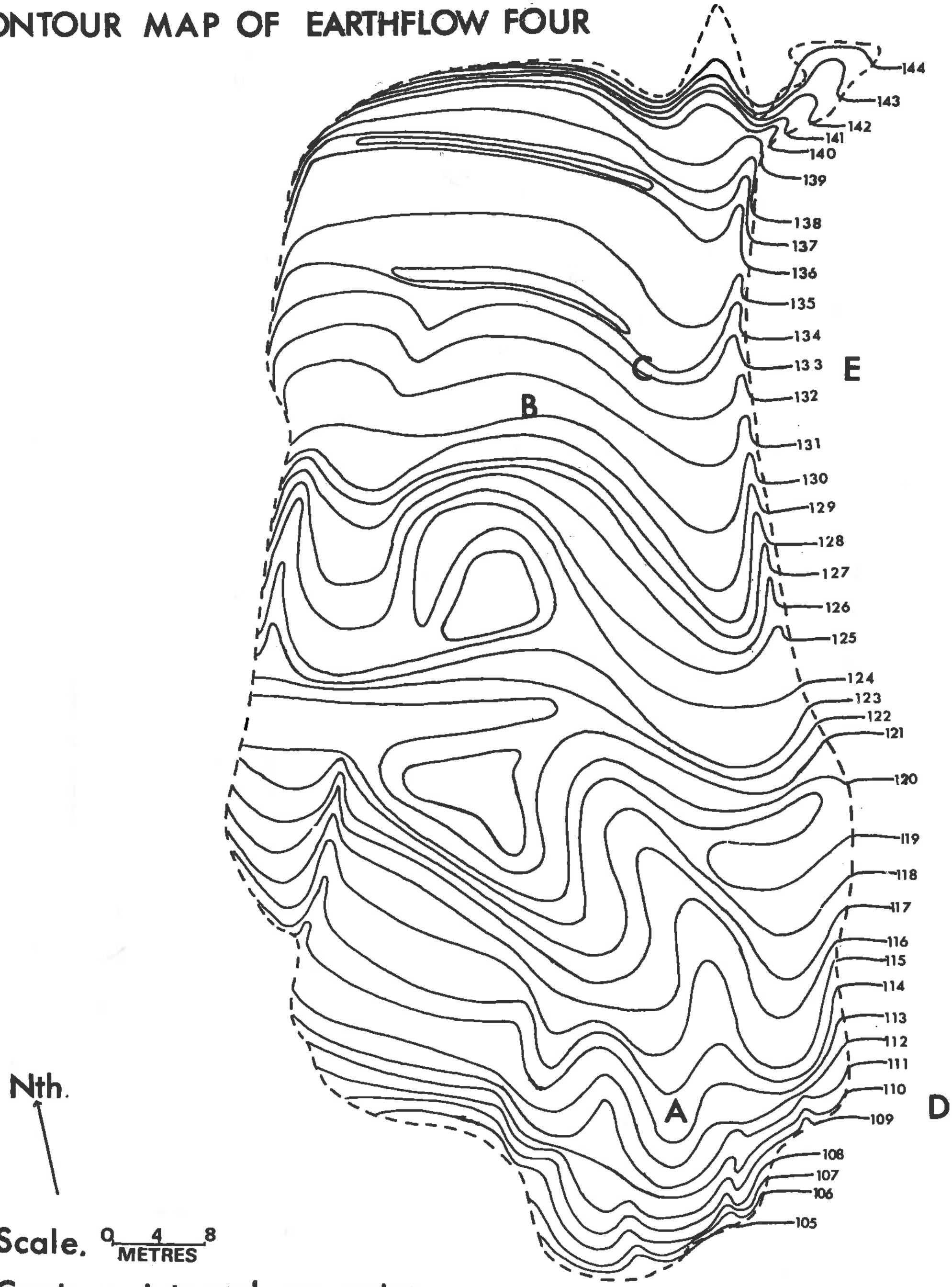
(3) The third dating technique consisted of interviewing local inhabitants, from whom much useful imformation was derived. Unfortunately, a number of problems are associated with this line of investigation. Recollection of the time of occurrance of any one earthflow decreases with time, so that exact dating over a period of fifty years, is considered unreliable. Migration of peoples to and from the area results in some witnesses being unavailble, while others purchased the land with an earthflow already developed. The owner of the property which contains earthflows 23, 26, and 27, acquired the land

in 1952, at which time numbers 23 and 27 were already in existence (Mr. Harvey, per, comm.). In most instances, a definite date could not be given for earthflows greater than ten years. Ranges of activity were however, obtained, these being approximately twenty five to thirty years for 'middle-aged' earthflows and over fifty years for 'old' movements. More importantly, a group of earthflows of 'younger' age (numbers 13,16, 17, &22), were positively dated as having occurred in 1971.This information was the basis for the fourth dating technique.

(4) Using 1971 as a base year, the deviation from median rainfall was established to determine what amounts of excess moisture are necessary to precipitate earthflows. From the Yankalilla, Normanville and Inman Valley records, this deviation from the median, was found to be 150 m.m. As mentioned, distribution is more important than total figures and thus this factor was checked. The following years were revealed to be periods of possible movement; 1974,'73,'72, '71, '64,'56, '47,'46, and '42. Correlation of these dates can be made by the methods described above. Beyond 1942 however, this is not possible and thus the use of the statistical method alone is not considered valid in eliciting dates.

The dates of occurance for all earthflows in the study area are presented in Table one.

CONTOUR MAP OF EARTHFLOW FOUR



Scale. 0 4 8 METRES

Contour interval one metre

INVESTIGATION AND ANALYSIS.

Earthflow Four.

Earthflow number four was selected to establish the nature of the processes operating in the formation of mass-movements. In size it is the largest single earthflow within the study area, although, larger are known to have occurred in the past. Earthflow eighteen, for example, is reported to have extended from the foot of the Precambrian uplands to the Yankalilla river, a distance of over five hundred metres. Active earthflows of the coalesced type are in some instances, larger than number four; a single movement was however, considered more amenable to study. Further, the lobe zone was known to be stationary by measurments taken on two test lines placed at the toe, three weeks before mapping. Verbal confirmation of stability was also derived from the owner (D.K. Crawford, per. comm.). A line of eucalypts is believed responsible for this cessation of movement, although, the felling of some of these trees during the period of fieldwork, may reactivate motion. The scarp zone is active in comparison to the lobe, but not on sufficient a scale to interfere with mapping. In dating, the nature of movement was also revealed and shall therfore be discussed.

The initial series of aerial photographs(27-4-1949, scale 1:15,840 imperial) shows no earthflow present. The ground however, displays a hummocky appearance, with suggestions of sub-turf, lobal bulging, although, no tension crack is as yet visible. The immediate area of the earthflow was prone to water retention, thereby forming a soak (Crawford, per, comm.). The distrurbed ground is believed to have resulted from heavy rainfall in 1946 and 1947.

No further photographs were taken until 1956 (23-1-'56, scale 1:48,000 imperial) when flowage is revealed, although, not to the present limits. A scarp of shallow depth is visible, while the primary lobe is, on average, some ten metres upslope from the present position. Further, the lobe has overridden the turf surface by approximately a half to one metre (Crawford, per.comm.). Planimetrically, the earthflow displays a 'tear-drop' shape, being broad at the base and narrowing to an extremely arcuate scarp.

Statistical analysis of rainfall had indicated 1955 and 1956 as times of possible movement, while the geological map of 1954 does not show a landslide at this location. Noting the time of the 1956 photographs (January), movement must have occurred in 1955, probably between May and August when rainfall was 140m.m. above the median amount.

By 1959 (9-9-'59, scale, 1:25,000 imp.) the earthflow has developed to approximately its present position. Subsidence and horizontal extension have produced a head scarp of around three metres. The lobe, which now rose four metres above the slope (Crawford, per, comm.) has extended downslope, levelling a medium size gum tree in the process.

From meteorological data, 1959 was an exceptionally dry year, while 1957 was only average. Two dates are therefore possible, 1956, or 1958. Interviewing could not resolve the problem. 1958 however, had rainfall only slightly above the median amount, while 1956 was well over. Between March and October, 225 m.m. of above median rainfall occurred and thus it is felt that the movement commenced in 1955 was continued, with only a minor halt in summer, during 1956.

The scarp zone is considered to have been active since 1956 and continues to be so today, by means of headward, block slumping. During the time of investigation (February to September) movement of such blocks was discernible. Further, in the eastern sector of the scarp, secondary earthflow has occurred from two areas (fig 5), one from upslope and a second from the eastern scarp face. The material from these secondary movements has exuded downslope, overriding the original subsided surface in a three tiered lobe. Extrapolation from aerial photographs and rainfall data, suggests these occurred in 1974.

The present day morphology of earthflow four may be described as follows (fig.5).

Above the headscarp, which ranges in height from a maximum of four metres at its centre, to zero metres at the foot, a number of minor lunar cracks appear. These result from pressure release at the scarp face and tend to act as water traps, inducing and aiding further block slumping.

Below the headscarp, there exists an area which, due to subsidence, bears a slight backward tilting. Two transverse ridges of approximately an half a meter, cross this flat surface. Numerous desiccation cracks are also present.

Downslope of this area, a large depression is centrally located between two minor lobes, the eastern one resulting from secondary earthflow as described above. The floor of this depression leads into the level foot zone, which in turn joins the stable slope on either side. This depression is continued across the lobe to the toe, where it is terminated in a number of radial cracks. Both the depression and the radial cracks are exploited by surface run-off. This depression is explicable in two fashions. It may follow a former watercourse of a shallow but wide cross-section as is thought to have existed by the owner (Crawford, per. comm.). Such a watercourse is however, not evident on the 1949 aerial photographs. Differential eluviation and subsidence is a more plausible explanation, for the upper-most section of the depression coincides with the 1955 arcuate scarp. The possible presence of a watercourse must however, not be discarded.

The lobe proper may be considered as comprising two main sectors. The eastern consists of a central ridge approximately four metres in height, the depression described above and a second high ridge which forms the eastern edge. This sector constituted the main body of the 1955 movement, the western sector at this time being some twenty metres upslope and of shallow height (Crawford, per. comm.) Today this western sector is broadly level, although of a hummocky appearance in detail and stands in the vicinity of one and an half to two metres above slope. Differential motion has occurred between the two sectors, while in both,layers of differential flow is evident. In the western sector, for example, the toe is seen to consist of a number of steps. It is believed that the lower of these has flowed out beneath the overlying layers due to the higher concentration of water at this point. Plastic and liquid limits are therefore attained in this layer before the upper layers, with consequent motion. The surface of both sectors is broken by numerous transverse and desiccation cracks,while the toe displays a series of radial cracks.

Physical Analysis.

To appreciate the morphology of earthflow four (plate 4) in terms of processes operating, an intensive investigation of soil properties was undertaken. Superficially, the earthflow appears to consist of sand and minor humic material, except at the scarp face. Here sand particles have been partially cemented by clay to form a weak sandstone. (plate 5) Although a profile of the soil was revealed at this location, it was felt that exposure could have produced minor physical and chemical changes. A series of five bores were therefore sunk.

Bore A (fig. 5) situated at the edge of the depression, obtained a depth of 3.5 metres, while B and C only penetrated to one metre. In both cases the soil proved too liquid to extract by means of the open-ended auger, the sample oozing out of the bit.

Upon the stable slope east of the earthflow, two further bores (D and E) were sunk to allow comparison. Each of these bores achieved a depth of slightly over three metres, at which point the cohesion of clay to the auger made manual extraction impossible. The results of all borings are presented in table two and figure six.

In all bores, below the sandy horizon, a zone of clay and sand in varying proportions, is present to a depth of three and a half metres. Beneath this, a layer of highly compressed,'pure' clay is found, which in turn is underlain by a zone of angular debris set in a clay matrix (plate six). It can be suggested that since the sand layer on the upper slope is of approximately the same depth and nature as is found on the lobe, while on the lower stable slope it is of a markedly different depth, then the material of which the lobe is constituted, was derived from the upper slope with little or no deformation. Flowage however, would necessitate some degree of deformation. Sharpe (1938) has pointed out that flowage is greatest in the central layer, which in this case would be the sandy clay layer and thus the surface may be little deformed.

To establish the clay to sand fraction, as well as the physical and chemical properties of the clay, samples were taken at depths of one and a half metres and three metres, from bore A. These were analysed by means of separation and X-ray diffraction, the results of which are presented in table three.

The most important feature of these results, is the decrease in stable kaolinite and quartz with depth, while illite and montmorillonite show an increase. Illite (which consists of interlayered mica and montmorillonite) and montmorillonite are crystalline, hydrous, aluminium silicates made up of a three layered lattice which, in the presence of water, expands along the C-axis. Further, clay has a low porosity which would cause ground water to be confined, allowing time for absorption into the crystal lattice. The saturation conditions produced by heavy rainfall, renders the clay highly unstable in that it causes swelling and uplift of the overburden. The instability of the slope is therefore increased.

Although borings were not taken on the other earthflows, observations in gullies and man-made cuttings reveals the presence of such a clay, of varying thickness and at different depth, throughout the area. The role of the clay in the formation of earthflows is therefore extremely important.

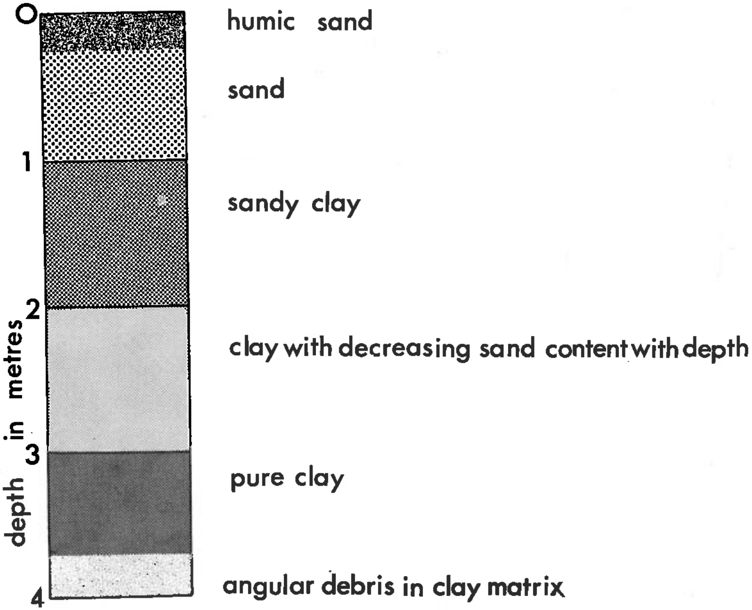
The sample from one and a half metres was tested by the Casagrande technique to establish the Atterberg limits of plasticity and liquidity. Adopted from civil engineering, the application of these limits to the study of mass-movements has been criticized, largely because the samples used are out of situ. However, the understanding of the processes operating derived by the use of the Atterberg limits, warrants their application. (eg. Crozier's study, 1969) The liquid limit of the sample was found to be 38%, the plastic limit 13.5% and the plasticity index 24.5%. These figures are in accordance with the perimeters suggested by Nasmith (1964) for a sandy clay soil formed by glacial deposition (liquid limit 41%, plastic limit 19%).It is possible that the lower figure given for the study area, is due to error in technique and thus the figure quoted from Nasmith is used in relation to plastic limits.

To find whether these limits had been attained, water content by weight had to be established. The samples from bore hole A (1.5 and 3 metres) were analysed after being transported from the site in air-tight, glass containers to prevent evaporation. It was found that the water content at one and a half metres was 19.79%, while that at three metres was 32.69%. In both instances the plastic limit has been surpassed and therefore deformation by plastic flow under the influence of gravity may be expected. It is believed however, that this does not occur until higher water contents, such as after heavy rain, are experienced, for the slopes are of low declivity.

Nature of Movement, Earthflow Four.

During 1946 and 1947, extremely heavy rainfalls caused subsurface eluviation and flowage, possibly in the vicinity

COMPOSITE SOIL PROFILE DIAGRAM



of the three metre clay layer. This resulted in a disruption of drainage (hence the description as a soak), while the surface became hummocky in appearance. The process of flowage continued until 1955, producing a sub-surface bulge at the foot. This flow however, subjects the upper slope to tension, which when coupled with subsidence, results in the formation of a tension crack.

Movement in 1955,again occasioned by excessive rainfall, resulted in the lobe breaking the surface, forming a minor recumbent fold and then sliding downslope on a planar glide surface composed of vegetable matter. Further, this glide plane was lubricated by water, as was observed on earthflow eight (described below). The draining of lobal material at a sub-surface level, from the upper slope,results in further subsidence. A head scarp is therefore formed. Subsidence however, is differential, relating to varying rates of flowage and eluviation, thereby forming minor scarps, depressions and transverse cracks. 1956 saw the continuation of flowage, with subsequent extension of both lobe and scarp. A similar development is visible on earthflow eight at present (plate 3).

Deformation due to flowage, is usually considered to be at a maximum in the central layer, as friction at the edges and base, slow movement, while vegetation and lower water content retard surface flow. The problem exists however, as to whether or not basal sliding occurs. From correlation of bore hole data, a compact clay layer was located at approximately three metres on the lobe and stable adjacent slope. Since the height of the lobe at A was between three and four

Plate three. Highly active earthflow (number eight) with incipient transverse extension in the form of a tension crack and bulge.

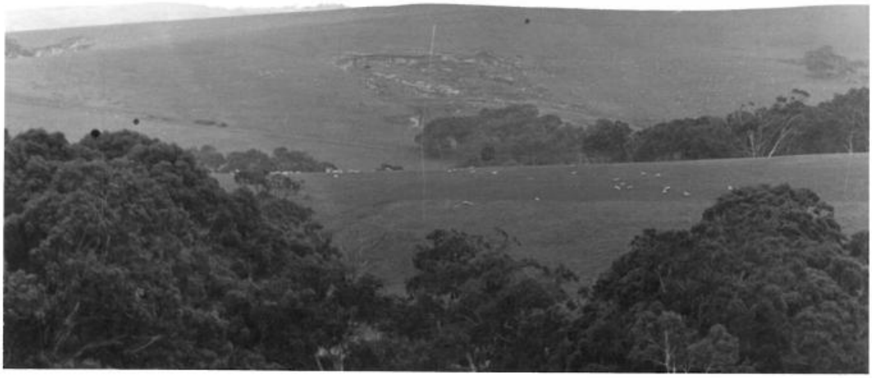


Plate four. Earthflow four.

metres, this clay must have been transported from the upper slope. Several explanations are possible.

The clay layer may have sheared internally, due to the drag of the overlying, flowing material. This would suggest motion changed from flowage to basal sliding. It is also possible that shearing occurred between the clay layer and the underlying layer of angular debris; again this suggests basal sliding. However, 'plucking' of sections of clay by the flowing mass may have occurred. The section in bore hole A would therefore be a chance occurrence. To resolve the problem conclusively, a series of bore holes covering the entire earthflow is necessary. Unfortunately, the difficulties experienced in boring at this time of the year, prevented this line of investigation. As previously stated, once the lobe overrides the slope surface, sliding becomes the main mode of movement. Movement at the rupture surface is however, considered to result from plastic flow.

INVESTIGATION OF EARTHFLOW EIGHT.

To ascertain the rates of motion of the lobe of an active earthflow, developed in recent years, number eight was selected.

By means of interviews it was established that initial large scale movement occurred between seven and eight years ago. Aerial photographs from 1966 (15-4-66, scale 1:57,000 imp.) reveal a possible tension crack of small scale, although no lobal development is evident. It is however, probable that sub-surface drainage disruption had resulted from heavy rainfalls in 1964. The next series of photographs show no movement, as is to be expected for 1967 was an exceptionally dry

Plate five. Scarp displaying partial cementing.

Plate six. Angular debris in clay matrix.

year throughout the State, an average of 395 m.m. falling within the study area, as compared to the median of 620m.m. (photographs taken 20-10-67, scale 1:52,000 imp.). In 1968 however, rainfall was above the median and when coupled to the desiccated soil resulting from the previous year, movement is believed to have occurred.

The dimensions of earthflow eight are as follows: total length 90metres, lobe 50 metres, concave head zone 40 metres, width 51metres. The lobe is dissected by numerous transverse cracks, achieving depths of one to one and a half metres. The toe is broken by a series of radial cracks, which act as drainage channels for run-off. The maximum height of the lobe is in the order of three and a half metres, although the western sector consists of a hummocky platform of only one and a half metres height. A pre-existing drainage channel between the two sectors is exploited by the earthflow, a minor depression being formed on the lobe surface in consequence.

The head scarp at present, extends between three and four metres above the subsided mass and in planimetric view, consists of a number of arcuate 'scallops' rather than a smooth curve. This appearance results from differential slumping off the scarp face subsequent to initial movement. In contrast to earthflow four, the subsided area immediately below the head scarp, comprises a remarkably undisturbed surface, in that transverse cracking is absent. It is suggested that this zone has experienced uniform subsidence to a large degree. The exception comprises a remnant block, much like a small butte in appearance, standing approximately one metre above the subsided surface. A two to three metre minor scarp demarcates the downslope boundary of this surface.

Nature of Movement.

Although no bore holes were placed, the soil profile exposed at the scarp face corrosponds to that of earthflow four and as such the physical and chemical properties of the latter shall be utilized.

Two soil samples were taken, one from the toe region and the second from the scarp. The water content by weight was found, by drying, to be 28.13% at the toe and 18.15% at the scarp, which means the soil in the former location has exceeded the plastic limit (19%). Although the amount of water above the plastic limit was not great, motion was found to be comparatively rapid, supporting the hypothesis (Skempton,1964) that once an earthflow is in motion, lower water contents than those that initiated movement, can cause a continuation of that movement. Further, as previously discussed, flow is replaced to a large degree by planar sliding on the former slope surface. The scarp is felt to contain a lower water content, not because of geological differences, but due to the ready drainage afforded by the exposed scarp face. This water is seen to accumulate in pools at the base of the scarp, although no rain may have fallen for a number of days. (plate 7) Further, this water is observed to drain out from beneath the lobe at the toe, largely because the vegetated slope surface inhibits infiltration. This moisture acts as a lubricant for planar gliding by the lobe.

An initial attempt to measure the rate of motion of the lobe was undertaken in March by placing marker pegs a short distance downslope of the toe. It was hoped any variations in distance could be measured. Unfortunately, not enough amplitude was given, as movement over the next week caused the markers to be buried. An attempt at location proved unsuccessful.

A second attempt was made in August, when observations were carried out over a three week period. At each of three locations at the toe, two pegs, separated by 3.05 metres of rope, were placed (the odd unit results from the conversion of imperial measurements to metric,ie. 10 feet became 3.05 metres). Line one was located below the westerly sector of the lobe; line two within the pre-existing drainage channel, while line three extended downslope from the central, high section of the lobe. Measurements were made from the downslope marker to the edge of the toe, along the connecting rope. These measurements are presented in table five.

Transversely, differential movement of the lobe is occurring, while a given section of the lobe moves at varying rates over time. The latter feature is explicable by reference to the level of rainfall, but the former poses a problem.

It is possible that variations in the physical nature of the material occurs, but observations, albeit without borings suggest a homogeneous character. If it is considered that the energy for plastic flow is derived from gravity and that the degree of energy depends on mass, then where mass is greatest the energy level is also greatest. For a given unit area of sliding surface, this is where the lobe has maximum height. Further, the increased friction expected due to greater mass, is compansated by the lubrication provided by water. Mass however, comprises not only the material of the lobe; absorbed water also increases mass and the higher sections of the lobe have the capacity to retain more water. Once in motion, these sections of the lobe also possess greater inertial energy and thus will continue to move, even after the cessation of rainfall.

Taking a mean of the motion of the three test lines, the rate of movement is 23 centimetres per week. Since slope is constant to the valley floor, movement will continue until this point is attained.

The area above the scarp is clear to the crest of the hill and as such headward growth of the scarp by block slumping, will continue. Rates of movement are unobtainable, as the size of the blocks varies. Observations were taken during a number of visits to the area since February and thus indicators of scale of slumping can be given. By reference to a sheep track immediately above the scarp, a distance ranging from one to five metres, headward growth is clearly evident. Besides slumping, it was also noticed that deformation of the scarp face by flowage occurred.

To the east of earthflow eight, a tension crack resulting from subsidence of the ground surface by thirty centimetres, is present. This crack is in line with the scarp face of earthflow eight and thus may be considered an extension of that flow. Downslope, sub-turf bulging of approximately thirty centimetres has occurred, adjacent to the foot zone of earthflow eight. In time this bulge will override the slope surface in the form of a lobe. An earthflow of the coalesced category will therefore result.

FACTORS PRODUCING EARTHFLOW.

When attempting to assign a process to mass- movement, the causation of individual earthflows is considered, although, ' In most cases a number of causes exist simultaneously and so attempting to decide which one finally produced failure is not only difficult, but also incorrect. Often the final factor is no more than a trigger that sets in motion an earth-mass that was already on the verge of failure' (Varnes, 1958). However, what factors caused a mass to be on the 'verge of failure'?

When considereing earthflows within the study area, a general link is established with high rainfall, but in fact it is a combination of climate, geology, soil properties and the role of man. All these variables must be weighed to extrapolate the reason for movement.

In all cases, for motion to have occurred, shear stress must have exceeded shear strength, that is, the resistance of a soil to stress. Shearing strength in a normally unconsolidated soilis dependent upon the cohesion between soil particles and friction due to granular interlocking of these particles. A sandy soil possesses negligble cohesion when pure, but high levels of internal friction. The angle of repose of a sandy soil may therefore be quite high, especially when compacted. Clay, by comparison, has low internal friction, but high levels of cohesion. For slope failure to occur, two factors must act singularly or in conjunction; either stress is increased beyond the shear strength, or the latter is reduced. Shear stress may be increased by long term loading of the soil, either naturally or artificially, while short term loading may result from heavy rainfall. Undercutting of slopes and transitory earth stresses such as produced by earthquakes, also increase shear stress. Independently, when applied to the study area, these are not considered sufficient to induce motion. A decrease in shearing strength is also required.

Within the area, the shear strength varies with the sand to clay ratio and the degree of compaction. The superficial sand layer lacks intergranular cohesion, but is held by adhesion due to water and intergranular friction. The latter varies with grain size, shape, roughness and compaction. Further, sand is found to have 'bulked' (when the water content of a sandy soil exceeds 10%, the sand particles settle and compact themselves, a process known as bulking- Zaruba and Mencl, 1969), increasing granular friction and the angle of repose. Hence, it is believed that within the study area no earthflows involving sand alone, has occurred. (Further, sand possesses no plastic properties.) The increasing clay content with depth is therefore responsible for the plastic nature of the soil. The cohesion afforded by this clay is however, decreasing.

The process of wetting and drying, which causes expansion and contraction of the illite, montmorillonite lattice, over time significantly reduces the cohesive force between clay particles. Desiccation is a common occurrence during summer months, when evaporation exceeds precipitation, not only on the body of the earthflow, but on the stable slopes of the area. Where an overburden of sand is present, capillary removal of groundwater is sufficient to allow subsurface desiccation to occur. Further, the cohesive strength of clay decreases with an increase in soil moisture and thus the subsequent replacement of groundwater results in a reduction of effective cohesion. Failure, as has been demonstrated by Skempton (1948), is not immediate and is considered to vary with slope. This variation ranged from a matter of weeks in the case of a six metre, vertical face composed of a high colloidal clay, to fifty years on a clay slope of eighteen degrees. Acknowledging the difference in clay type and proportions, it is felt that the low slope angles in the study area, contribute to the time lag between the clearing of vegetation and earthflow.

Infiltration of groundwater causes an increase in pore water pressures, which bring about a further loss of cohesion, as the normal intergranular forces are taken up by the interstitial water. The superincumbent mass of soil is therefore partially supported by this groundwater, resulting in a further decrease in shear strength.

Cohesion is also reduced as a consequence of clearing, as a change to the clay-humus colloid results. Humus, which 'is a complex and rather resistant mixture of brown or dark brown amorphous and colloidal substances modified from the original tissues or synthesized by the various soil organisms ' (Brady 1974), differs from clay colloids which possess a crystalline structure. Like clay however, the micelles carry a negative charge to which cations of calcium, magnesium, potassium, sodium and hydrogen are bonded. In humus the anions consist of carbon and oxygen, rather than an aluminium-silicate lattice.

Humus has the important role of improving soil texture

Plate seven. Water trap formed between scarp and subsided surface.

Plate eight. Comparison of uncleared, native vegetation in background, with cleared land in the foreground.

and structure by the creation of granular aggregates. In clays, movement of water is increased by the formation of pore spaces, while in sand, individual grains are bonded.

More important however, humus has the propensity to absorb between eighty and ninety percent of its weight in water, whereas clays can absorb only fifteen to twenty percent. If a sufficient quantity of humus exists, rainfall is retained to a certain degree, thereby decreasing the amount of water in contact with the substratum. Since earthflow occurs at this layer by plastic deformation, it is possible that the humus layer slows or prevents the attainment of plasticity. Further, during summer drying, water is held by the humus and thus desiccation is reduced.

It has been suggested that vegetation stabilises slopes by root anchorage. Various studies have indicated the relationship between mass-movements and the depth and type of root systems (Rice,Corbett,and Baily, 1969: Crozier,1973). So (1971) however, doubts whether this relationship is as clear cut as suggested and infers that vegetation holds only the surface layer, but allows plastic deformation at a lower depth.

Within the study area, the role of vegetation is vitally important. No large scale mass-movements are discernible on the little remaining vegetation (plate 8), although minor movement has occurred in the case of earthflow twelve, where isolated trees and gorse are found. Rafting of trees was not noticable, although it is attested to have occurred (per. comm.) Overall, earthflows are located on cleared slopes, while some are known to have been stabilised by vegetation (plate 9).

The time lag between clearing and subsequent earthflow is

Plate nine..A dormant earthflow, apparently stabilized by vegetation.

attributed to a number of factors. First the general slope angle is low and thus gravitational shear stress is limited. More importantly the cohesion supplied by clay and the clay-humus colloid (the shear strength), is decreased gradually over time by wetting and drying and base exchange on the clay-humus colloid. The holding power of roots was lost rapidly, but it was not till shear stress,due to saturation of the soil by heavy rainfall, exceeded shearing strength, that earthflow occurred. Once movement causes minor subsidence, a water trap is formed and thus an autocatalytic process eventuates. Why an earthflow occurred at one point and not another, may be related to minor differences in soil profile, rates of cohesive breakdown, humus colloid deterioration and clearing of vegetation. Allowing all these points to be constant, motion may result in only one location. Wright (1966) suggests, 'The answer seems to lie in the presence of subsurface water at the critical points', these points reflecting minor differences in geology.

Although earthflows are known to have occurred before settlement, these were of limited distribution, being confined to the higher slopes of the area. The clearing of vegetation is considered to be the factor which set in motion the sequence of events, such as soil deterioration, which finally resulted in earthflow.

CONCLUSION.

Mass-movements within the study area were, after investigation, found to be earthflows as defined by Sharpe (1938) and Varnes (1958). These earthflows were established to have occurred during periods of heavy rainfall, when shear stress was increased. However, stress was only sufficient after a decrease in shearing strength, brought about by a breakdown of cohesion supplied by clay and the clay-humus colloid. This cohesion was initially of a low value, as the soil consisted of glacial deposits of Permian age. The main reason for the rapid deterioration of this cohesion, was the clearing of vegetation by European settlers after 1839.

In summary, it can be seen that earthflow results from a combination of factors both natural and anthropgenic.

APPENDIX.

During investigation, measurements were taken of earthflows in order to apply the morphometric technique outlined by Crozier (1973). A number of problems were posed however.

Of the indices supplied by Crozier, only the length to depth is statistically valid according to Cooke and Doornkamp(1974). The depth is considered to be the distance from the surface of the subsided section of the earthflow to the rupture surface. This rupture surface is in many instances not a point but a layer of plastic deformation. Even allowing that movement was along a slip surface, this surface in the case of all but the most recent of earthflows, is difficult if not impossible to establish with any degree of accuracy. As such, the technique was not applied.

TABLE ONE. CLASSIFICATION,DATING, ACTIVITY AND ASPECT.

Number.	Classification	Date	Activity	Aspect
1	earthflow- single	50+	dormant	south
2	earthflow-multiple	50+	dormant	south
3	earthflow-multiple	50+	dormant	south
4	earthflow-single	1955	active	south
5	earthflow-single	1974	active	south
6	earthflow-unknown	25+ ?	extinct	south
7	earthflow-single	?	dormant	north-east
8	earthflow-single	1968	active	north
9	earthflow-single	1947	active	south
10	earthflow-single	?	extinct	south
11	earthflow-single	1955-56	dormant	east
12	earthflow-multiple	1973-74	active	east
13	earthflow-single	1971	active	north
14	earthflow-single	1946-47	dormant	south-west
15	earthflow-single	1964	active	south-east
16	earthflow-single	1971	active	south-east
17	earthflow-single	1946-47	dormant	south-east
18	earthflow-?	?	extinct	north-west
19	earthflow-multiple	50+	dormant	south
20	earthflow-multiple	1955-56	active	south-east
21	earthflow-single	1971	active	south-east
22	earthflow-single	1971	active	south-west
23	earthflow-multiple	25+ ?	active	east
24	earthflow-single	25+	active	south-east
25	earthflow-single	?	active	east
26	earthflow-single	1968	active	south
27	earthflow-single	25+	dormant	south
28	earthflow-multiple	20+	active	south
29	earthflow-single	30+	dormant	south-east
30	earthflow-single	?	active	east

Table One continued.

Number	Classification	Date	Activity	Aspect
31	earthflow-?	25+ ?	extinct	south
32	earthflow-?	25+ ?	extinct	south-east
33	earthflow-single	25+	dormant	south

The classification table records the number given to the earthflow as its presence was detected in the field, the nature of movement, age, aspect and present activity. Numbers refer to a location of movement and as such, earthflows of the coalesced type are given a single number (eg. number 20, plate2) Aspect refers to the direction the main body of an earthflow is facing. Age, when assigned to a single year, was derived and verified by the four techniques described. Where two dates are given, earthflow could not be assigned to one year although all four techniques were employed. A plus sign is added when only two sources of dating confirm the age. When a question mark appears after a date, a single source of dating has been used. A question mark without a date implies no information was obtained.

The nature of present activity is considered under three general headings: active, dormant and extinct (Zaruba and Mencl, 1969). An active movement is one in which motion of either the lobe or scarp is produced consequent to sufficient rainfall and as such represents an unstable state. Since earthflows are autocatalytic, this rainfall may be considerably less than that required to initiate movement. A dormant earthflow, which is prefered to the classification 'stable', possesses no movement of scarp or lobe, except under abnormal circumstances such as extraordinarily high rainfall, undercutting of the toe or transitory earth stresses. Earthflow number three for example, has appeared to be 'stable' since 1949, when morphology is examined for the present as compared to the 1949 aerial photographs. During the summer of 1973/74 roadwork carried out by the Yankalilla District Council (per. comm. council supervisor) caused approximately two metres of the toe to be removed. Rainfall in 1974 resulted in the reactivation of the lobe, which dislocated a fence and blocked the road.

An extinct earthflow is one in which the possibility of reactivation, even under extraordinary circumstances, is impossible. In such cases the scarp is leveled and the lobal material dispersed.

TABLE TWO. RESULTS OF BORE HOLES.

Depth. (metres)	A	B	C
0-.3	sand and humus	sand and humus	clay and sand
.3-.6	sand and humus	sand	clay sand
.6-1	sand	sand	clay sand
1-1.3	sand		
1.3-1.6	sandy clay		
1.6-2	sandy clay		
2.0-2.3	sand, decreased clay		
2.3-2.6	sand, increasing clay		
2.6-3	increased clay		
3-0 .3.3	pure clay layer		

Depth. (metres)	D	E
0-.3	humic sand, very wet	humic sand, damp
.3-.6	clay sand	sand, damp
.6-1	clay sand	sand, damp
1-1.3	increasing clay	sand, increasing water
1.3-1.6	sand slightly increased	appearance of clay
1.6-2	clay sand	increasing clay, more compacted
2-2.3	increasing clay, more compacted	clay sand
2.3-2.6	increasing clay	clay sand
2.6-3	pure clay layer	clay sand, increased clay
3.0-3.3	angular material in clay matrix	pure clay layer

TABLE THREE. X--RAY DIFFRACTION ANALYSIS OF BORE HOLE SAMPLES.

	Bore one 1.5m	Bore two 3m	Bore three 1m
Kaolinite	30-40%	20-30%	10-20%
Illite	20-30%	40-50%	40-50%
Quartz	10-20%	0%	10-20%
Montmorillonite and or randomly stratified material	20-30%	20-30%	20-30%

TABLE FOUR. PLASTIC AND LIQUID LIMITS.

Liquid limit	Plastic limit	Plasticity Index
38%	13.54% **	24.46%

** Nasmith's (1964) figure of 19% used in analysis.

TABLE FIVE. RATES OF MOVEMENT, EARTHFLOW EIGHT.

Date	Initial length.			Present length			Movement		
	Line			Line			Line		
	1	2	3	1	2	3	1	2	3
5-8-'75	3.05	3.05	3.05	3.05	3.05	3.05	0	0	0
12-5-75				2.78	2.96	2.53	0.27	0.09	0.52
17-8-75				2.65	2.71	2.14	0.12	0.24	0.40
22-8-75				2.53	2.56	1.98	0.12	0.15	0.15

** Observations 30-10-75 show line three to be completely covered. Movement of over 3.05 meteres has therefore occurred.

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