Photogrammetria, 32 (1977) 161—182

LANDFORM PATTERN DESCRIPTION FROM AERIAL PHOTOGRAPHS

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(Received January 23, 1976; revised and accepted August 10, 1976)

ABSTRACT

Speight, J.G., 1977. Landform pattern description from aerial photographs. Photogrammetria, 32:161—182.

A system is proposed to facilitate the delineation and description of regions of homogeneous landform pattern as perceived in aerial photographs. From resource survey experience in Papua New Guinea, a comprehensive suite of some sixty landform attributes is erected on the concept that a landform pattern may be described by altitude, relationship to planes of accordance, development of networks and lineations, proportional occurrence of landform elements and the organization of these landform elements in toposequences. It is argued that flexible landform classifications based on explicit attributes should replace classifications in which landforms are allocated to preconceived categories (pigeonholes) if landform classification is to contribute to the study of the genesis of landforms and their relationships to other phenomena.

INTRODUCTION

Land resource surveys, as practised by the Division of Land Use Research, CSIRO, and by other organizations in Australia and elsewhere (Christian and Stewart, 1968), make use of the patterns of landform and vegetation seen in aerial photographs to predict those attributes of land that most strongly affect its potential uses. Some attributes of landform, such as slope, directly affect many forms of land use, but landform attributes are also important as means of extrapolating soil properties from the very small number of field observations that are taken in this type of survey. Description of landform ought, therefore, to be made as adequate and as appropriate to the prediction of soil and of potential land use as possible.

Land resource surveys are commonly carried out by an interdisciplinary team of a geomorphologist, a plant ecologist and a pedologist, sometimes augmented by other scientists and sometimes reduced to a single scientist working alone. Boundaries are drawn on aerial photographs on the basis of patterns of landform and vegetation, to enclose areas, commonly called *land systems*, that are considered to be reasonably homogeneous, and to separate areas that appear to differ significantly. It is implied that the perceived homogeneity and differences are of relevance to potential land use. Usually, the criteria for mapping are not specified but the judgment of members of the team acting in committee is relied on for the delineation of valid boundaries. A limited degree of support for the mapping decisions may be achieved by field work, but in most surveys this has been a secondary objective after the collection of information that is inherently unobtainable from aerial photographs.

The attributes used in mapping, and the assumptions underlying the extrapolation of point data (such as soil properties) to mapped areas, are thus not explicit. This has several drawbacks. The validity of extrapolation and of boundary drawing varies between mapping units and is not readily susceptible to critical analysis. Areas surveyed by different teams are difficult to compare, for in the absence of an established procedure, scientists tend to use different criteria according to their inclinations. Finally, there is very little accumulation of data in a form that would facilitate a systematic improvement in techniques of mapping or extrapolation.

The first two of these drawbacks may be met by rigorously defining the categories of landform and of vegetation that are to be recognized and mapped. Such definition is practised, although seldom rigorously, by survey teams who use identifying symbols in regions defined by photographic mapping, using one letter or letter group respectively for relief, geology and vegetation. This approach would be satisfactory if the critical values of the mappable attributes significant for prediction of soil and potential land use were adequately known, but this is not the case, partly as a result of the absence of critical review of the predictive performance of past land resource surveys. The specification of "pigeonholes" into one of which every naturally occurring landscape is to be put does not allow for the possibility of advances in the understanding of relationships between landform, vegetation, soil and potential land use, nor can it contribute towards such advances. Those that have been achieved owe nothing to the prevailing attitudes towards survey data organization.

The more flexible alternative scheme proposed here is (1) to list all those attributes of landform and vegetation that may be evaluated by photo-interpretation and are known or thought to have predictive value, and (2) to ensure, by use of a formal descriptive technique, that mapping boundaries are drawn to enclose regions that are internally homogeneous, and that differ from each other *in terms of these attributes.* This implies that each boundary must mark a change in the value of at least one attribute, and preferably in the values of numerous attributes. Using this technique, every mapped region is considered to be unique rather than merely an occurrence of a preconceived type of land, and the values of all of its attributes are estimated and recorded. The decision as to whether to declare it to be similar to another region may be taken any number of times on the basis of selecting or weighting the descriptive attributes, each time with reference to some specific purpose. Such purposes may include the extrapolation of a particular attribute measured in the field, or the prediction of hazards for a particular form of land use. Since the photographic mapping data remain on record, decisions on similarity between mapped regions can be amended at any time in the light of an accumulating body of data on the relationships between the descriptive attributes and the attributes to be predicted. This is in contrast to the pigeonhole technique in which, if it is rigorously applied, areas are declared to be the same as, or different from, other areas at the time that they are mapped, and this identity or difference becomes the sole formal basis for associating attributes with mapped regions.

A major motivation for the proposed procedure is to provide the kind of explicit data on which terrain classification may be based. The procedure accomplishes the first two steps of the process of classification, which may be analysed as follows:

(1) specification of attributes;
(2) evaluation of attribute values;
(3) comparison of individuals attribute by attribute;
(4) grouping of individuals with similar attribute values.

Once a comprehensive list of more-or-less independent landform attributes has been specified, the techniques of numerical taxonomy (Sneath and Sokal, 1973) provide a wide variety of explicit procedures for classifying large numbers of individual parcels of land.

On the other hand, the prior definition of "pigeonhole" categories implies that a survey will not involve the concept of *classification* at all, but merely the simpler related concept of *allocation* by which parcels of land are judged to fall into predetermined categories. Using classification, the types of land distinguished by a survey arise from the survey data; using allocation the survey data have no influence on the types that are distinguished. In view of the embryonic state of the science of landform classification it seems preferable to classify the landforms of a survey area *a priori* rather than to adopt the categories of any existing scheme.

The descriptive technique elaborated in this paper was developed for use in land resource surveys in Papua New Guinea and has been implemented for a survey of a 5000 km^2 area in the Chimbu District of the central highlands using 1 : 40,000 scale aerial photographs. It is appropriate to rugged terrains produced by fluvial denudation in humid climates. The description of terrains of different origin, or of very low relief, or the use of aerial photographs with scales much larger or smaller than 1 : 40,000 may call for modifications to the technique.

The methodical recording of attributes of individual mapped regions implies an ability to manipulate the resulting large volume of data. For this purpose a system is being developed around a data bank that contains both descriptions of mapped regions and graphic information including region boundaries and topographic data. This paper is concerned with the description of landform, the description of vegetation being a separate project.

It will be objected that the implementation of this technique is too time-consuming and does not contribute to the efficient completion of a given land resources survey. These claims are arguable, but are not germane to this paper, which is concerned with marshalling and organizing a number of the most useful concepts of landform description applicable to aerial photographs, with specifying a list of descriptive attributes, and with demonstrating the kinds of descriptions and mapping boundaries that result from their use. Any technique that purports to delineate geomorphically homogeneous mapping units that is less explicit concerning the attributes employed can hardly be sufficiently accessible to scientific evaluation of its validity. This applies whether the units are intended for the prediction of geological formations, soil types or any kind of potential land use. Nor does the incorporation of other information, such as vegetation, absolve the surveyor from the obligation to be explicit regarding landform attributes. In so far as the mapping attributes are inadequately specified, one may properly be sceptical as to whether defensible logic underlies the production of the resulting map.

EXISTING ATTRIBUTE-BASED SYSTEMS

In the terrain-classification system developed from the land system concept in the CSIRO Divison of Applied Geomechanics (Grant, 1968, 1973) four levels of generalization are distinguished: province; terrain pattern; terrain unit; and terrain component. The definitions of these levels are partly recursive: terrain patterns are associations of terrain units which in turn are associations of terrain components. The system embraces soil, mantle materials, rock, and vegetation as well as landform, the province being defined solely on the basis of rock-stratigraphic group. Considering only the landform aspects of levels below that of the province not many attributes are actually explicit. Relief amplitude is cited at all three levels: terrain pattern, terrain unit and terrain component. In addition, terrain pattern attributes include drainage pattern, stream frequency and "geomorphology" (not further specified), and terrain unit attributes include "physiography", length and width. A geometric model is specified for the terrain component, requiring evaluation of slope and slope curvature both down and across the slope, as well as microrelief, length, width, and relief amplitude as mentioned above.

The classification *system* as described, however, makes use of only six of the attributes given. The terrain unit, which is the primary entity to be recognized and described, is classified without reference to any of the attributes other than "topography" (= physiography?). Observed areas of terrain are allocated to one of thirty-three categories of terrain unit that are neither exhaustive nor mutually exclusive, nor related to any more explicit physiographic attributes. These pigeonhole-type categories include, for instance:

1.4 Strongly undulating surface (to 10°)
2.2 Eroded surface
2.8 Strongly dissected surface
3.3 Gentle slope
4.8 Elongated rounded hill
5.1 Low ridge (to 5° slope)
9.4 Incised gully, ravine, etc.

Thus, although Grant's system is more rigorously specified than the procedures it replaced for surveys in an engineering context, it retains much of the inflexibility and faulty logic that are typical of pigeonhole classifications.

R.B. King of the British Directorate of Overseas Surveys has also advocated a parametric (i.e. attribute-based) approach to description of land systems with the object of facilitating the comparison of land systems with each other (King, 1970). Of his twelve descriptive parameters, seven describe the landforms as observed: altitude, relief, stream frequency, drainage pattern, characteristic plan-profile, dominant facets and characteristic facets. King attaches first significance to an eighth, more inferential attribute called "process", expressed in such categories as "peneplanation", "pediplanation", "karst", "aeolian" and "marine", and also categorizes "geomorphic position", primarily in terms of inferred age. The degree of inference required in evaluating these two attributes detracts from their usefulness in a classification that is intended to be objective and susceptible to multivariate correlation. King's other three attributes are geology, comprising lithology and structural attitude; morphoclimatic zone; and a non-geomorphic attribute indicating photograph tone or vegetation. Geology is somewhat similarly treated in this paper; morphoclimatic zone is considered of dubious significance generally, and too coarse for the geographically restricted area surveyed here.

Scott and Austin (1971) experimented with a numerical classification of terrain based on a set of attributes developed from those normally expressed in reports of land system surveys by the CSIRO Division of Land Use Research at the time. Their fifteen attributes were: altitude, stream pattern, peakedness of highs, orientation, relief, grain, width of highs, angle of crest, length of hill slope, angle of hill slope, prominence of spurs, width of lows, curvature of crest, curvature of slope, and tidal influence. Nearly all of these attributes are incorporated and further developed in the system described here.

Neither King nor Scott and Austin discussed the desirability of basing the delineation of region boundaries on the same explicit criteria that they employed in subsequent classification.

In Sweden, Moller (1972) has suggested a system for describing and classifying landforms. The system is split into two parts. On the one hand he has set up some 300 arbitrary pigeonholes with a mainly genetic basis for landform elements as seen in the field, taking into account both their materials and processes of formation. This system is only partially structured, as indicated by the following examples:

- 0 Bedrock
  - 02 Weathering
    - 024 Precipices
- 1 Form elements of loose soils
  - 12 Glaciofluvial
    - 123 Esker
      - 1231 Esker mounds
  - 13 Fluvial

131 Strand plain
1312 Gravel
134 Fluvial terrace.

On the other hand, for the purpose of aerial-photographic interpretation he has outlined a tentative organization of some sixty of these landform elements according to geometric attributes including relative vertical extent (positive or negative), plan shape and cross-sectional shape. Möller concedes that the relationship between the two parts of the scheme requires further development. It is doubtful whether his approach to landform geometry is sufficiently comprehensive to describe terrains other than those dominated by relics of Pleistocene glaciation.

The concepts of relief and grain employed in landform pattern description owe much to the classic paper by Wood and Snell (1960), and the concept of characteristic plan-profile is due to Van Lopik and Kolb (1959). Parry and Beswick (1973) have evaluated these two techniques for aerial-photographic analysis of terrain in Canada. Ollier (1967) proposed a more general form of the profile model of Van Lopik and Kolb to incorporate the nine categories arising from combinations of rounded, flat and angular interfluves with rounded, flat and angular valley bottoms.

DESCRIPTIVE MODELS

The many attributes of landform that may be evaluated on aerial photographs so as to describe and delineate homogeneous landform regions have been organized in this paper in terms of two descriptive models (Speight, 1974), the first concerned with landform patterns and relief, and the second with elements of landform within the relief.

These models are an extension and rationalization of concepts implicit in the work of land resource survey geomorphologists. They embody the concept of a *land system* (Christian and Stewart, 1953) as a pattern of land made up of simpler elements or *land units* (Christian, 1952), the land system being a mapped region and the land unit a subregion that is not mapped but is described and placed in context within a land system (traditionally with the aid of a block diagram) (Mabbutt and Stewart, 1963). The descriptive models place severe restrictions on the concept of the land system, which becomes rather a *landform pattern* or relief unit (Young, 1969), and on the land unit, which must approach its simplest form, the *landform element* (Speight, 1968). These concepts have been discussed fully elsewhere (Speight, 1974).

The following sections refer to the description of landform pattern regions when they have already been delineated. It should be noted that the delineation of regions is also governed by the same attributes, as the photo-interpreter endeavours to ensure that he draws boundaries only where there is an observable, and preferably an abrupt change in at least one of the specified attributes, and that the regions he delineates are broadly homogeneous in terms of the attributes. The only additional constraints embodied in the photo-mapping technique are that the delineated regions should not vary greatly in area from a modal value, in this case 6 km^2, nor should they be very elongated or very digitate.

It may be argued that circular reasoning is involved in this procedure but, if so, it is a fundamental and unavoidable problem rooted in the region concept. In practice, given that the acceptable size of regions has been specified, most boundaries may be delineated without difficulty once the interpreter fully appreciates the implications of the descriptive attributes. Cases where boundaries are difficult to delineate, or where they have been erroneously delineated, may usually be resolved by more intensive consideration of the attributes of the neighbouring regions.

With so many attributes to be evaluated from observations through the stereoscope, it has been necessary to make the evaluation of each attribute as brief and convenient as possible. Thus many attributes that could in principle be evaluated with precision have simply been rated on a scale of 1 to 5 or 1 to 3. It is possible that proper discrimination between mapping regions requires greater precision in some attributes, but this is not apparent from such analyses of the data as have been completed so far.

The complete list of attributes to be evaluated is given in Table I. To facilitate reference, superscript numbers have been inserted against corresponding attributes in the table and in the following sections of the text.

The landform pattern model

The first model sandwiches the terrain between two planar or simply curved surfaces of accordance, the upper passing through the highest summits and the lower (Dury, 1951) passing through the major stream channels (Fig.1). The average vertical separation of the two surfaces is a measure of *relief*[6] and the average horizontal spacing of those summits and stream channels that approach the upper and lower surfaces respectively is the *grain*[4] (Wood and Snell, 1960). The surfaces need not be horizontal, and it is of value to note the dip angle[9] of the upper surface and its direction[10]. The average loss of height in crossing the mapped region by way of the upper surface of accordance[11] (the "maximum height range", see Fig.1) also gives a measure related to relief that may be thought appropriate where the upper surface of accordance is steeply sloping, as in the case of a mapped region forming the face of an escarpment. Having visualized an upper surface of accordance, it is possible to assess qualitatively the degree of accordance of all crests and summit surfaces to it[8] — an attribute traditionally considered to have genetic implications. The degree of convergence or divergence of the two surfaces in a downslope direction[12], expressed in metres per kilometre, is also likely to be genetically significant.

The pattern properties of crest and channel networks have commonly been described by terms such as "dendritic", "trellis", "radial" etc. (e.g. Thornbury, 1958, pp. 120—126), and by drainage density; that is, the length of stream

TABLE I

Information to be recorded for each mapped landform pattern region

Geomorphic category (allowance for 30 letters)[1]

Altitude
Minimum (m)[2]; maximum (m)[3]

Accordance relations
Grain[4]; grain variability[5]; relief[6]; relief variability[7]; degree of accordance[8]; upper surface of accordance dip inclination[9], dip azimuth[10], maximum height range[11]; rate of down-dip convergence of upper and lower surfaces of accordance[12]

Networks
Connectedness of crest network[13]; number of stream channels intersecting a circle of 2 km circumference[14]

Lineations
Strength of orientation[15]; strike azimuth[16]; dip inclination[17]; dip azimuth[18]; number of lineaments[19]; spacing of lineaments[20]; sharpness of lineaments[21]; dominant element type expressing the lineaments[22]; interpretation[23] (allowance for three axes of lineation)

Landform elements
Summit surfaces (M)[24]
Label[25]; name[26]*; width[27], width variability[28]; length[29]; length variability[30]; modal slope[31]; slope underestimate[32]; strength of orientation[33]; downslope azimuth[34]; percent occupance[35]; process number[36], status[37] and distribution[38] (allowance for one element)

Crests (C)[39]
Label[40]; name[41]*; width[42]; width variability[43]; modal slope[44]; maximal slope[45]; percentage occupance[46]; process number[47], status[48] and distribution[49] (allowance for two elements)

Slopes (S)[50]
Label[51]; name[52]*; length[53]; length variability[54]; modal slope[55]; slope underestimate[56]; strength of orientation[57]; downslope azimuth[58]; percent occupance[59]; process number[60], status[61] and distribution[62] (allowance for four elements)

Plains (P)[63]
Label[64]; name[65]*; width[66]; width variability[67]; length[68]; length variability[69]; modal slope[70]; slope underestimate[71]; percent occupance[72]; process number[73], status[74] and distribution[75] (allowance for four elements)

Streams (W)[76], other than small streams (W1)
Label[77], name[78]*; width[79]; width variability[80]; width trend[81]; curvedness[82]; sinuosity[83]; number of channels[84]; activity[85]; percent occupance[86]; process number[87], status[88] and distribution[89] (allowance for one each of W2, W3, W4)

External elements (M, C, S, P, W)[90]
Label[91]; number of adjacent region containing the element[92] (label incorporates a number greater than the relevant allowance e.g. C3; P5)

Non-sequential elements: rises (R)[93] depressions (D)[94]
Label[95]; name[96]*; length[97]; length variability[98]; width[99]; width variability[100]; curvature[101]; percent occupance of containing element[102]; label of containing element[103] (allowance for three R elements and three D elements)

TABLE I (*continued*)

Process, generalized[104]
Process number[105], status[106] and distribution[107] (allowance for five processes, either generalized or referring to an element that has already had one process attributed to it)

Toposequences[108]
Serial number[109]; labels of included elements in sequential order[110]; length[111]; height[112] (allowance for eight toposequences, in order of significance; allowance for six elements in each toposequence)

Indexing[113]
Region number[114]; map sheet number[115]; photo sheet name[116]; photo run number[117]; photo number[118]; geological formation name[119]; land system name[120] (prior survey); field observation serial number[121], element[122] and toposequence[123] (allowance for 45 field observations)

*Specific names for landform elements, using up to 24 letters, are optional.

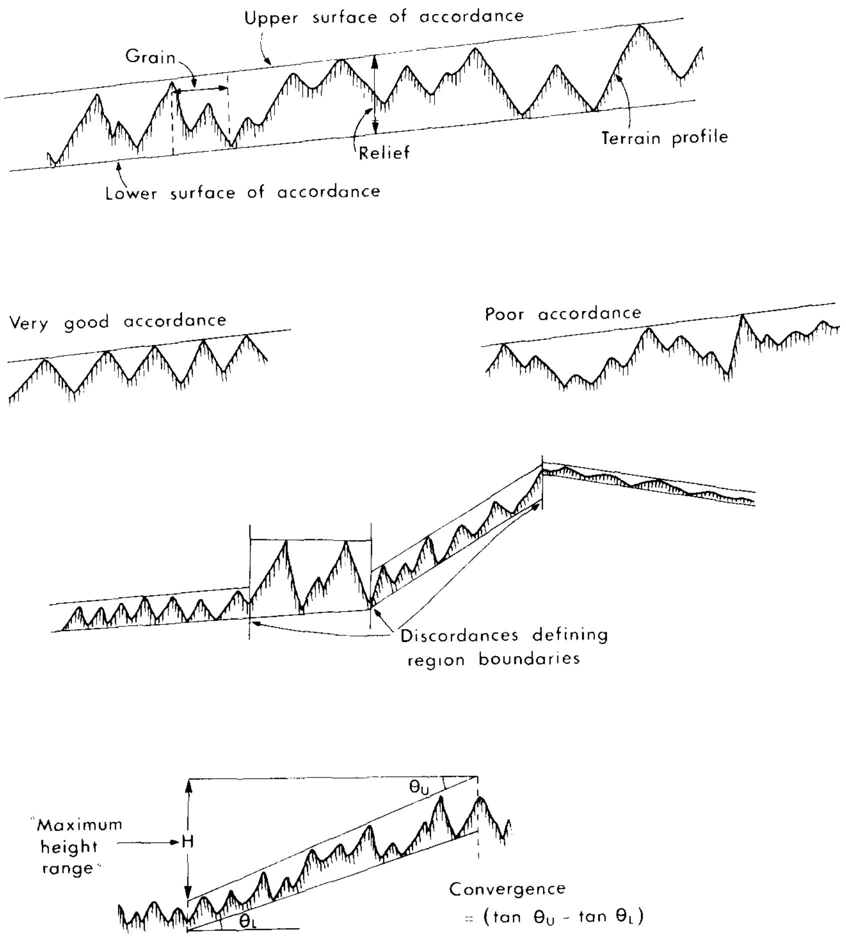

Fig. 1. Relations of landform patterns to upper and lower surfaces of accordance.

channel per unit area (Horton, 1945). Unfortunately, the estimation of drainage density is a time-consuming operation that depends so heavily on the accurate identification of stream heads that its use in aerial-photographic study of the forest-dominated New Guinea landscapes is not warranted. In its place, channel frequency[14] is estimated by the simpler procedure of counting the number of stream channels intersecting a circle 2 km in circumference (Fig.2a).

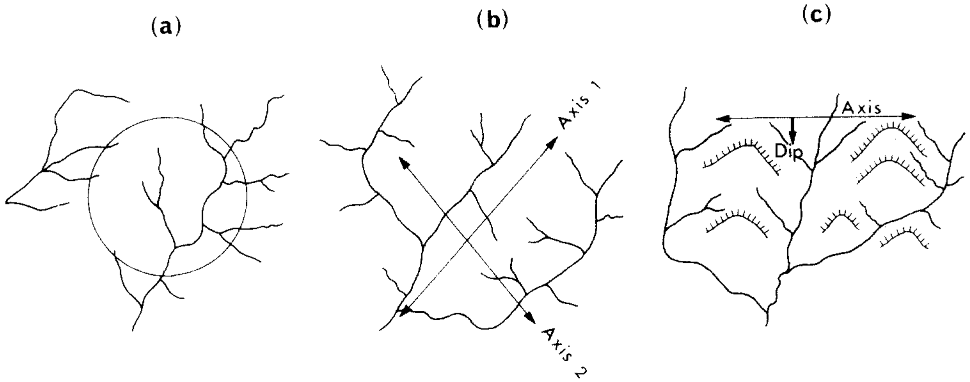

Fig. 2. Attributes expressing properties of networks and lineations. a. Channel frequency (9 per km). b. Lineation axes. c. Lineation with dip.

This circle, whose size has been found to be convenient, is placed randomly within the mapped region in several locations so as to provide a mean figure. The development of ridge-crest networks is characterized by an assessment of their degree of connectedness[13], in five classes from "complete", where every crest is part of a single network, through to "isolated peaks" as in a tower-karst terrain. It is a subjective assessment of crest *reticulation* (Speight, 1968) as expressed in maximum length of crest network. The connectedness of channel networks is not evaluated because they tend to have complete connectedness in all but a few kinds of terrain, whereas crest connectedness exhibits all degrees of development.

Directional properties of linear features in the terrain[15–23] have been evaluated non-quantitatively because of the limitations of both time and statistical methods. They are assessed by judging whether there is any preferred direction of alignment of crests or channels, and if so, whether there is a secondary or even a tertiary direction of alignment (Fig.2b). If no such alignments are recorded, then the pattern is assumed random. Since stereoscopy is used in the photo-interpretation one may take advantage of the simplification obtained by projecting the line of outcrop of a geological structural feature such as a bedding plane, joint or fault onto a horizontal datum plane, and record the true strike[16] of the feature rather than its zig-zag expression as it crosses the relief (Fig.2c). The dip[17,18] of such structural features is also readily determinable. Clearly, the projection of non-structural linear features onto a horizontal plane is the same as if they had a dip of 90°; that is, their projection is identical with their actual alignment.

The strength of orientation of each alignment is expressed as weak or strong[15] depending on how well the linear features conform to a particular orientation, and the number[19], spacing[20], sharpness[21] and nature[22] of the individual linear features is characterized in broad terms. Thus the number may be "one", "few" or "many", the spacing "close" or "wide", the sharpness "sharp" or "vague", and the linear features may be "crests", "streams" or "both crests and streams". The alignment is then interpreted[23] as an expression of (1) drainage consequent on some pre-existing slope, (2) the outcrop of resistant strata, or (3) faulting or jointing.

The channel pattern of individual large streams[76] is inadequately characterized by such terms as braided, meandering and straight (Leopold and Wolman, 1957) which are neither exclusive nor exhaustive. Attributes discernible on aerial photographs and selected for assessment (with their classes) are (Fig.3):

(1) Width trend[81]: parallel; tapering (particularly for tidal streams);

(2) Width variability[80]: ratio of maximum to minimum width locally: low, < 3 : 2; moderate, 3 : 2 to 4 : 1; high > 4 : 1;

(3) Curvedness[82] : angular; transitional; curved;

(4) Sinuosity[83] : low, < 1.5; moderate, 1.5 to 2.5; high, > 2.5;

(5) Number of parallel low-water channels[84] at a given point, expressed as a mean to one decimal place,

(6) Activity[85] : relict; semi-active; active.

The landform element and toposequence model

Crests (represented by the letter "C")[39] and channels (W)[76] are classes of *landform element*, of which three other broad classes are distinguished: summit surfaces (M)[24], slopes (S)[50] and plains (P)[63]. More than one element in each class may be recognized in a given mapped region, and for this reason the elements are labelled S1, S2, for instance, for the first and second slope elements. The label has no significance other than as an identifier except in the case of stream channels, for which a convention has been set up as follows:

W1 Small streams;

W2 Largest streams originating within the region or an adjacent region;

W3 Streams entering the region but dissipating within the region;

W4 Streams originating within a non-adjacent region and flowing through the region (through-going streams);

W5 Sea or lake.

Each mapped region is examined to determine the minimum number of landform elements necessary to achieve an adequate description. At the same time the proposed elements are assembled into down-slope toposequences[108], commonly from crest to one or more slope elements to small stream (Fig.4). The toposequence that is considered the most significant for the description of the mapped region is listed in symbolic form: C1-S1-S2-W1[110], for instance, followed by its characteristic length[111] and height[112] (altitude difference from top to bottom). Other toposequences are listed in order of significance [109] as

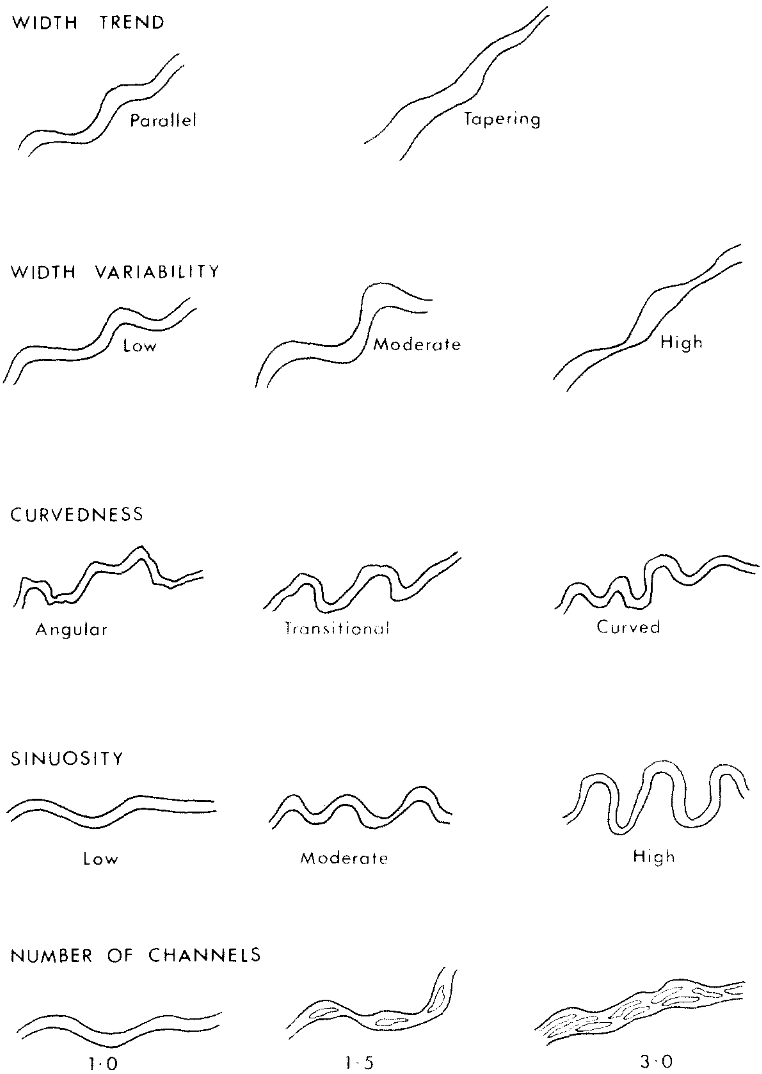

Fig. 3. Stream channel pattern attributes.

required to complete the description. In achieving an economical terrain description it is useful to allow the perception of the most significant toposequences to influence the identification of significant landform elements and *vice versa*. Landform elements are given short, distinguishing name tags[26,41,...] where necessary, such as "footslope". In the absence of such a tag the broad class name, such as "crest" for a "C" element is assigned.

Each element is described by dimension[27,29,42,...], slope[31,44,45,...] and orientation[33,34,57,...] (if relevant). The dimension most frequently to be assessed is down-slope length[29,53,...], but in the case of crests the width[42] perpendicular to the crest line is specified instead. For plains and summit sur-

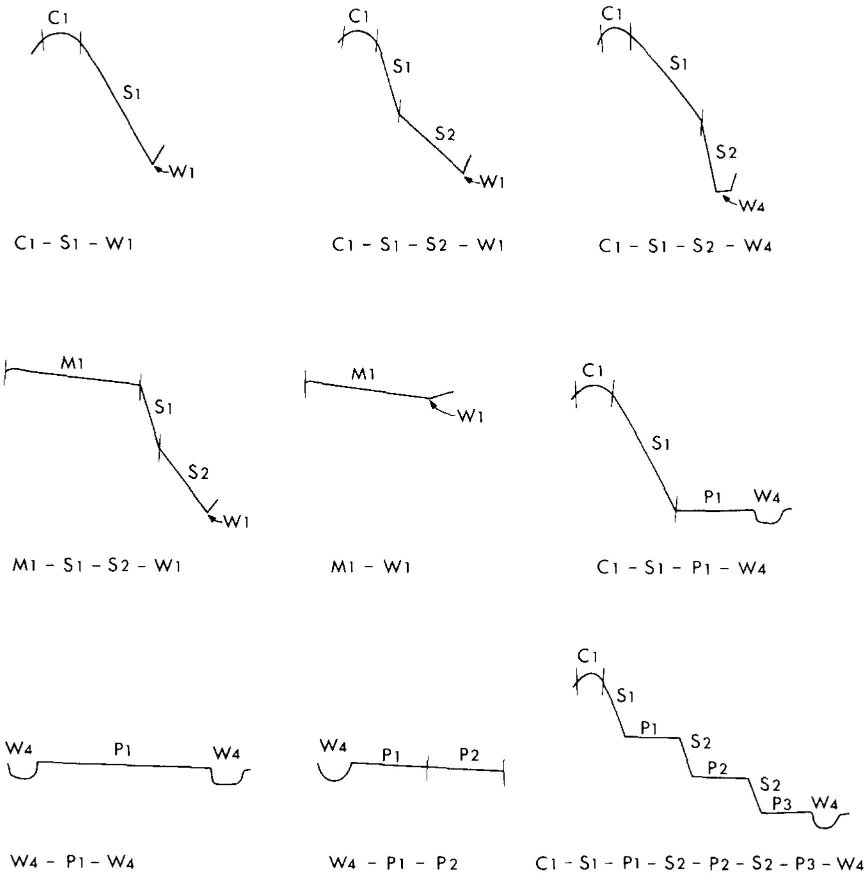

Fig.4. Profiles showing typical toposequences comprised of landform elements.

faces both width[27,66] and length[29,68] must be estimated. The omission of either length or width from the landform element model is based on difficulties in both observation and definition that arise from actual patterns of landform geometry. To the slope value for each landform element there is attached a statement[32,56,...] as to whether the slope has been underestimated and, if so, whether to a small or large extent. This is intended to allow for the occurrence of microrelief consisting of a mosaic of convergent slopes up to 20 m long, nearly all of which are steeper than an enveloping slope that alone is large enough to permit evaluation of a slope gradient.

Where a particular slope element may be seen to display a preferred orientation the azimuth[34,58] of its dip is to be recorded, with a rating for the strength of the tendency to show the orientation[33,57].

Finally, the percentage of the mapped region that each element occupies[35,46,..] is estimated.

The development of a comprehensive list of parameters for landform elements out of the data set specified in this paper, and their use in classifying landform elements to form landform element types, is reported elsewhere (Speight, 1976).

Some landform elements whose relief is too small to be evaluated from the photographs, such as oxbows on alluvial plains, do not readily fit into a toposequence. Such non-sequential elements[93,94] are considered separately, as inclusions occupying a percentage of the area[102] of particular sequential elements and are described in terms of length[97], breadth[99] and curvature[101].

INTERPRETATIVE ASPECTS

Although the interpretative process has been resolved as far as possible into assessment of values for the attributes that appear to be the basis of interpretation, it is desirable to record the immediate morphogenetic interpretations of the geomorphologist during the mapping process. For some phenomena it may never prove practicable to sort out all the criteria involved in their interpretation by a skilled observer, but such a record of interpretations may permit correlation of interpreted phenomena with recorded attributes of the photographic pattern and may also focus attention on phenomena to be assessed in the field.

Certain geomorphic processes[104,36,...] whose present or former action may be inferred from the landforms of Papua New Guinea as seen on aerial photographs have been numbered[105,36,...] for convenient recording as listed below. A more comprehensive or more systematic list could easily be devised.

(1) Lava flow	(9) Longshore drift
(2) Volcanic ash flow	(10) Rockfall
(3) Volcanic ash fall	(11) Fluvial deposition
(4) Volcanic mud flow	(12) Coral growth
(5) Deep mass movement	(13) Wave erosion
(6) Earthflow	(14) Solution
(7) Slump	(15) Glacial erosion
(8) Debris avalanche	

Where these processes are recognized, as either active or relict[106,37,...], their distribution[107,38,...] may be assessed as localized, widespread or ubiquitous.

Interpretations may be assigned to particular landform elements or to the mapped region as a whole[104], in which case they may be automatically attributed to every landform element of the region.

GEOLOGICAL INFORMATION

In the study of the Chimbu District geological information from a prior survey (Bain et al., 1975) has been subsumed under the name of the rock stratigraphic unit (usually a formation)[119] that underlies each mapped region. Since the geological boundaries had been delineated by an intuitive photographic interpretation technique similar to that made more explicit in the present survey, serious discrepancies between geological boundaries and landform pattern boundaries are not common. The name of each rock-stratigraphic unit provides access to a separate list of lithological attributes. It was very difficult to abstract such attributes from the geologists' report, which set out to elucidate structure, stratigraphy and geological history rather than to serve as a source of lithological data. Nevertheless, it has proved possible to abstract crude values, classes or states of the following attributes. These may be evaluated for each named rock-stratigraphic unit, whether igneous, metamorphic or sedimentary:

(1) Proportional occurrence of the most common two rock types present;
(2) Names of the most common two rock types present;
(3) Geological age;
(4) Degree of tectonic disturbance;
(5) Angle of dip;
(6) Permeability rating for unweathered rock;
(7) Average bedding or parting plane spacing;
(8) Average spacing of joint planes;
(9) Silica content;
(10) Clasticity (from 0 for massive plutonic rocks to 5 for loose sediments);
(11) Grain size;
(12) Grain size variability between included beds;
(13) Reiche's weathering potential index: weighted mean value for the most common minerals present;
(14) Reiche's weathering potential index *range* for the most common minerals present;
(15) Tone (i.e. Munsell colour value);
(16) Colouration (i.e. Munsell colour chroma);
(17) Hue (Munsell).

This collation of available lithological data for each mapped region was intended to facilitate the study of relationships between rocks as soil parent materials, landform characteristics, and soil properties. Ideally, both the rock properties and the soil properties might be inferred from the aerial photographic patterns.

THE FORM FOR RECORDING LANDFORM DATA

The form on which the landform data for each region is recorded consists of three quarto pages with blanks for insertion of numbers and words written in block letters. The layout has been organized so that, when it has been completed, the form may be presented to a punch-card operator for immediate production of computer input cards.

The complete data specification for this form is given in Table I. The first item, "geomorphic category"[1], is a short verbal description that, like the element names, is mainly for use in the initial phases of the work when different scientists and technicians are handling photographs and forms and require

TABLE II

Sample description of a denudational landform pattern region

Geomorphic category
Low hill ridges

Altitude
From 1900 m to 2300 m above sea level

Accordance relations
Grain 500 m (moderately variable; relief 150 m (highly variable); accordance of summits poor; the upper surface of accordance dips at 4° towards a direction of 020° and is parallel to the lower surface of accordance

Networks
Crest network moderately well developed; channel frequency 3.5 per km

Lineations
One weak orientation is present: direction 135°, dipping 20° towards 225°, represented by several moderately spaced vague lineaments, mainly crests, formed by resistant strata

Landform elements
C1 — Crest: occupies 4% of the region; length indefinite; width 20 m (moderately variable); slope 10°, maximum 15°
S1 — Steep slope: occupies 65% of the region; length 100 m (highly variable); width indefinite; slope 25°
S2 — Earthflow slope: occupies 30% of the region; length 300 m (moderately variable); width indefinite; slope 7°; process: earthflow, active, ubiquitous
W1 — Small stream
W4 — Through-going stream: width 20 m, moderately variable, not tapered; angular and moderately sinuous; 1.3 active low-water channels
P5 — External plain of regional number 1277

Toposequences
(1) C1—S1—W1 (crest—steep slope—small stream): 100 m long and 80 m high
(2) C1—S1—S2—W1 (crest—steep slope—earthflow slope—small stream): 400 m long and 90 m high
(3) C1—S1—W4 (crest—steep slope—through-going stream): 100 m long and 90 m high
(4) C1—S1—P5 (crest—steep slope—external plain): 100 m long and 80 m high within the region

Indexing
Region number 1265; map sheet N 23; photograph KEROWAGI Run 4, No. 26
Stratigraphic unit: Chim Formation — Koge land system
Field observations: No. 5453 on C1 of toposequence (1) and No. 5455 on S1 of toposequence (1)

plain-language clues to the general character of the terrain. The remainder of the form covers information outlined in earlier sections of this paper and concludes with an indexing section[113] that contains a region-identifying number[114] and refers to the original aerial photograph[116,117,118], to previous land resource[120] and geological[119] surveys, and to field observations of the current survey[121—123].

TABLE III

Sample description of an alluvial landform pattern region

Geomorphic category
Floodplain of vertical accretion

Altitude
From 0 m to 10 m above sea level

Accordance relations
Grain indeterminate; relief zero; accordance of summits excellent (assigned conventionally); the upper surface of accordance dips at less than 0.5° towards a direction of 160° and is parallel to the lower surface of accordance

Networks
Crests network completely developed (assigned conventionally); channel frequency 1.0 per km

Lineations
None

Landform elements
P1 — Floodplain: occupies 90% of the region; length 800 m (highly variable); width 1200 m (highly variable); slope less than 0.5°
W4 — Through-going stream: occupies 10% of the region; width 80 m, slightly variable, not tapered; curved and strongly sinuous; 1.0 active low-water channels
R1 — Point bar: occupies 10% of element W4; length 300 m (highly variable); width 40 m (highly variable); strongly curved
D1 — Ox-bow: occupies 20% of element P1; length 400 m (highly variable); width 65 m (moderately variable)
P5 — External plain of region number 3148

Toposequences
(1) W4—P1—P5 (through-going stream—floodplain—external plain): 800 m long and 0 m high (within the region)

Indexing
Regional number 3076; map sheet s31; photograph TAURI Run 1, No. 75
Stratigraphic unit: Alluvium — Malalaua land system
Field observations: No. 7812 on P1 of toposequence (1)

The form is a compromise between convenience for the scientist or technician who must fill it in and convenience in card-punching and data processing. To give an impression of the information content of a from, translations of the data for two mapped regions to plain language have been prepared as Tables II and III by the application of a standard set of phrases and a re-ordering of the data.

APPLICATION OF THE TECHNIQUE

For the survey of the Chimbu District the photographic mapping using 1 : 40,000 scale aerial photographs was carried out by the author and the soil scientist R.M. Scott, and the mapped regions were described with the help of two technical assistants, B. Ferris and P.A. Healy. Members of the team worked partly independently and partly in pairs, using Old Delft scanning stereoscopes. The delineation of boundaries was generally done somewhat in advance of region description. However, from time to time difficulties arose in completing the description of a region that seemed best dealt with by alteration of the region boundaries, requiring amendments to adjacent region descriptions and, in some cases, quite extensive re-mapping of regions to which similar considerations applied.

In delineation of regions as illustrated in the stereogram (Fig.5) certain attributes, such as relief, grain and structural lineation, tended to be the most immediately useful, whilst some attributes such as the occurrence of significant "W2" streams (the largest rising within the region or an adjacent region) could be evaluated only when region boundaries had been fixed. Nevertheless, almost all attributes were employed to some extent as discriminators during the process of region delineation.

The description of a region was constrained by the time available to complete it which, in practice, could not be allowed to extend beyond one hour per mapped region and was commonly about fifteen minutes. This constraint was needed to cut down both survey costs and tedium for the person concerned. It was practicable to measure only a small number of representative values of a few quantitative attributes, and these were based on the use of distance scales constructed to match the photographs, relief estimation templates (C. Maffi, unpublished record, 1969), and stereo-models for slope estimation (Van der Bent, 1969).

In the course of the photo-interpretative mapping the 5000 km^2 survey area was divided into 870 homogeneous landform pattern regions in somewhat less than 2000 man-hours.

DISCUSSION

In terrains that are partly or wholly degradational in nature, the application of the descriptive model proved to be straightforward. There was a strong interaction between boundary-drawing and description: coarse or careless boundary-drawing delineated an area whose internal heterogeneity made a single value for a parameter such as relief meaningless, and called for a long list of elements and toposequences. Excessive detail in mapping was not a common fault, because of the extra labour involved. However, in this mapping system there need not be any loss of information on broader relationships as a result of delineating small, homogeneous regions that could alternatively have been embodied in broader but equally valid regions. There is scope in the data bank system for

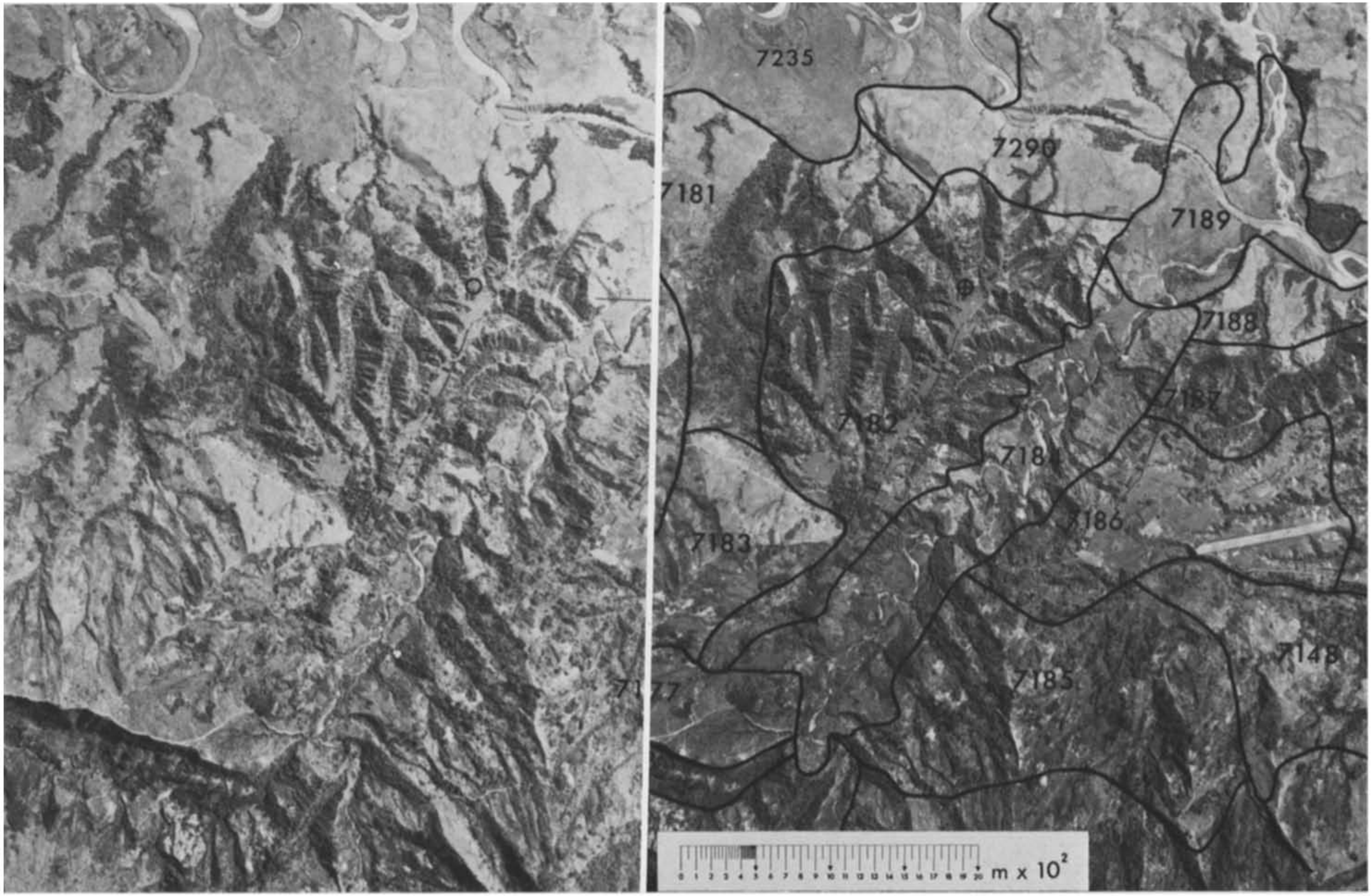

Fig. 5. Stereo-pair of aerial photographs of the Wahgi River at Kup, Papua New Guinea, showing regions of homogeneous landform pattern mapped by the use of explicit landform pattern attributes. This photograph has been made available by courtesy of the Director, Division of National Mapping, Department of National Resources, Canberra.

amalgamation of regions on the basis of any defined relationship, such as adjacency, similarity, upslope/downslope relativity, or back-to-back relativity for surfaces of accordance that have opposing dips. There is also provision in the specification of toposequences on the geomorphic form for beginning or ending toposequences on external elements that are in adjacent regions, so that, for instance, a toposequence in a region described as a gorge may commence on a slope of a region of gentle hills above the gorge. Both of the examples given in the Tables have external elements: the dimensions of the toposequence in such cases refer only to the part of the toposequence that falls within the region.

The surfaces-of-accordance concept of relief allows an ambiguity in the extreme case of an isolated ridge with spurs, which may be considered either as a single region with a high relief defined relative to horizontal surfaces of accordance, or as two regions meeting at the crest of the ridge, each having low relief relative to surfaces of accordance that slope steeply down the flanks of the ridge. An arbitrary rule adopted to cope with this ambiguity is that a symmetrical ridge should be treated as a single region, but a large asymmetrical ridge, having distinctly different dipslopes and scarpslopes for example, should be divided into two regions.

The model proved adaptable to the description of plains, but its application involved some shifts of emphasis. On bar plains and meander plains in the classification of Melton (1936) the most significant toposequence is represented by a flow from a through-going stream to a plain and back to the through-going stream (W4—P1—W4). On relatively small "covered" alluvial plains, i.e. floodplains of vertical accretion, the main toposequence is W4—P1—P2 where P2 represents a swamp (See Fig.4). On larger plains the relief and slope may be negligible over long distances, providing no objective grounds for delineating landform regions, yet hydrological conditions may vary, profoundly affecting potential land use. Such variations are often reflected in vegetation regions of similar dimensions to those defined by homogeneity of landform in degradational terrain. When such a vegetation region is delineated, preferably by an ecologist, it is possible to complete the geomorphic form for it, producing a description that is in all ways compatible with those of degradational terrain. The parameters of the landform pattern part of the model nearly all degenerate to either zero or very large values; in the landform element part of the model there may be only a single element to be described (a plain), and toposequences may pass completely through the region. Considerable significance must then attach to the position of the region in a long toposequence that commonly runs from a large river to a terminal swamp.

The extreme contrast in toposequence length relative to the dimensions of a mapped region in degradational and in alluvial terrains points up the fact that size of mapped regions is not directly related to the dimensions of the landforms themselves, but is fundamentally determined by considerations of photographic scale, survey cost, and the detail required in the final result. The present model is more informative about degradational than alluvial terrains, and it is specifically designed for use with 1 : 40,000 scale aerial photographs (on which few features of 20 m dimension can be resolved), and with the practice of delineating areas whose average dimension ranges from 500 m to 5 km. It is less appropriate to much larger or much smaller scales. However, the problem of predicting land use potential from landform is not resolved at any scale as yet, and this particular scale appears to show as much promise of success as any other.

CONCLUSION

A practical technique of landform description from aerial-photographic data has been developed that is capable of specifying a considerable range of types of terrain in Papua New Guinea and of discriminating between them with some precision. Typical landform-pattern descriptions such as those in Tables II and III contain values of some sixty terrain attributes. Most of these attributes contribute, implicitly or explicitly, to a variety of terrain models concerned with such diverse subjects as weathering and slope morphogenesis, denudation chronology, soil development, geological mapping, environmental hazards, agricultural potential and transport route engineering. In surveys that have been intended to provide data for such purposes the failure to evaluate some of the attributes, or the omission of map boundaries marking substantial changes in their values have undoubtedly hindered scientific progress. The recognition of further terrain attributes capable of evaluation by practical means would be an advantage.

It is not true that a classification based on a large number of attributes is less meaningful than one based on fewer attributes, as stated by King (1970, p.43). A classification should be based on as large a suite of relevant and essentially independent attributes as can conveniently be evaluated and processed. Techniques are now available for the handling and reduction of large volumes of such data (cf. Speight, 1976). Only at the stage of communicating survey results or research conclusions is it essential to restructure the information so as to express terrain characteristics succinctly.

The evaluation of all the attributes mentioned for all the landform pattern regions of extensive tracts of land is more time consuming than the implicit techniques commonly employed. The survey of the Chimbu District is experimental, and it is not claimed that such comprehensive surveys are essential for routine evaluation of agricultural potential either in Papua New Guinea or elsewhere. However, the urgent need for improvements in the reliability and economy of practical geological, soil and land resource surveys based on aerial photographs calls for some such explicit surveys to be done to provide information from which principles may be derived. Only in the light of such principles can one confidently reduce the number of attributes to be evaluated, or exclude from survey any tracts of land on the grounds of their irrelevance to the survey purpose.

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