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PAPER D

TERRAIN EVALUATION FOR MATERIALS SURVEY

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PAPER D - TERRAIN EVALUATION FOR MATERIALS SURVEY

ABSTRACT

Terrain evaluation consists of the examination of an area of ground to determine all factors that will influence the planning, design and execution of a project. The appropriate technique used to gather information depends upon the size of the project and the required level of accuracy. This paper describes the three main techniques that are used to gather information by indirect methods, with examples of their application to highway engineering.

Landscape analysis, which is usually based on a study of aerial photography, can be used to subdivide an area into survey units. The addition of engineering information to those units extends the survey into a terrain evaluation, which may be on a regional scale for broad feasibility surveys, or related to small terrain features for detailed investigations. The use of terrain evaluation before field work commences can provide advance warning of possible difficulties, and direct the survey team to the most important areas that need to be examined. In addition to recording the properties and behaviour of soil, it is possible to recommend broad engineering designs for each terrain unit, such as thickness of road pavements or maximum slope for cuttings. The reference of information to a basic classification system means that data can be stored for future use, possibly in a different geographic area where similar terrain conditions exist. Examples of terrain evaluation are described for the pre-feasibility survey for Trans African Highway and for the design of a road in Malawi.

Air photo interpretation of panchromatic prints is still the main remote sensor used to interpret ground conditions. The accuracy of interpretation is increased by background information such as knowledge of geology, soils and vegetation and a land system analysis forms an excellent air photo key as an aid to photo interpretation. The first stage of an air photo survey is to determine regional features, such as major faults and geological boundaries, using air photo mosaics. To examine the terrain in detail in the individual prints, it is essential to observe the three dimensional image through the use of a stereoscope. The scale of the photographs imposes a limit on the size of feature that can be identified. Extra information can be obtained by using colour film or films that record reflectance of infra-red energy (e.g. 'false colour' film). Other forms of electronic sensors include infra-red line scan and radar (SLAR). An advantage of radar is that it is possible to obtain an image through cloud, but the resolution of present systems is only 10-30 metres.

The main geophysical techniques used in engineering surveys are seismic refraction and electrical resistivity. Both methods predict the thickness of soil layers and give a measurement of a geophysical property. Seismic surveys tend to be more accurate, but require more field work. The interpretation of material type and its depth should be correlated with boreholes or trial pits. The seismic method can be used to predict the depth to hard rock, either for quarry location or in assessing performance of earth moving plant. Resistivity can be used to determine depth to water table, and to detect horizontal variation of material. Geophysical techniques can be used at an early stage of survey to help plan more detailed investigations, and also to extend detailed knowledge of one site over a broad area. The equipment and field techniques are described in the appendix.

1. INTRODUCTION

A materials survey and the consequent specification for road construction are the last two steps in the planning of a highway scheme. Although the materials survey comes at the end of the planning procedure, the variations of soils, rocks and topography will have influenced earlier stages of the project including both engineering and economic decisions. The effect on decisions such as route location and choice of geometric standards can be easily seen, but variations in soil type also affect agricultural development of the area, leading to the generation of different levels of traffic. The study of this wider influence of geology and topography on engineering and other forms of land use is called terrain evaluation.

A terrain evaluation consists of the examination of an area of ground to determine all factors that will influence the planning, design and execution of a project, in this case road construction. Different stages of survey need different levels of accuracy and detail, and these constraints will influence the choice of various techniques to gather the required information. It is obviously desirable to use techniques that can be applied to all stages of survey, thus carrying information through from the feasibility studies to final design.

Before describing the main techniques used in terrain evaluation, it is necessary to define the various stages of road design.

1) Choice of route. The initial decision to build a road in a certain area is largely a planning decision in response to a political or military pressure. The building of the road between Addis Ababa and Nairobi, and the Trans-African Highway project are both examples of decisions to build roads in response to international pressures; the actual location of the road line is determined by local variations of topography and land use. On a smaller scale, a planning decision may be made to build feeder roads in an agricultural area with a high population density; the actual location of each individual road would have to be closely related to the terrain to minimise the cost.

Although such planning decisions may be greatly influenced by political or military considerations, the relative merits of alternative schemes are determined on economic grounds by relating the estimated benefits due to the development to the estimate of cost. For this sort of exercise, the costs can be simply determined by multiplying the expected length of road by a cost proportional to the quality of the road pavement, modified by a factor depending on the terrain conditions. The variation of terrain conditions may be defined by a terrain evaluation, but the identification of the correct costs and their local variations pre-suppose the existence of a suitable data store. At present this is normally based on the knowledge of experienced highway engineers, but a start has been made in relating this information to the terrain types.

2) Feasibility study. A feasibility study is normally divided into two parts, the engineering and economic assessments. The engineering part consists of locating alternative road lines and estimating their cost of construction. The economic study evaluates the benefits of each road line and recommends the best alternative. The question of suitable standards of construction is of joint concern to engineers and economists at this stage.

3) Final design. When the line is fixed, the last stages of materials survey and preparation of final design may commence. The scope of the work needed will have been defined in preliminary surveys which should identify particular problems of construction without defining in detail their extent. Typical problems might include

a relative scarcity of gravel in certain areas, the presence of rock in some cuttings, defining a safe slope for cuttings in unstable ground, or the location of water. If the problems are recognised correctly in the early stages of survey, then the most appropriate techniques may be used to provide the solutions.

4) Data storage. When the project is completed, all the data gathered during design and construction should be collated for future reference. In the first place this is needed to assess the performance of the road, and for this purpose the data should be classified for the different sections of the road line. In order that different sections of the road may be compared, and also to compare one road with another, it is necessary to have a classification of ground conditions; it is considered that a system based on terrain units and offering a suitable combination of accuracy and flexibility should be used.

2. THE TECHNIQUES OF TERRAIN EVALUATION

The techniques employed in terrain evaluation range from a broad assessment by an experienced engineer to a highly intensive site investigation. The most important factor is to select the correct level of expertise for the particular task, and to use experience gained in early stages to modify later work, eg previous experience, possibly in a different area, should be used to plan a materials survey and to direct the field work to the most important parts of the survey area. The techniques particularly relevant to terrain evaluation are those that gather ground information by indirect methods or record and present data in such a way that a reasonable interpretation may be made with a high degree of confidence. The use of landscape mapping has been widely used in recent years as an efficient method of recording data and an effective way of communicating the results gathered by specialists to people in other disciplines.[1] The major techniques used to gather data indirectly are air photo interpretation, other forms of remote sensing, and geophysical techniques. In the following sections the existing use of these techniques is described with particular reference to highway engineering.

2.1 Landscape classification

The increasing use of air photography, particularly at the reconnaissance stage, has led soil surveyors in different countries, working in different disciplines, to consider the merits of landscape units as a basis of mapping. At first, soil surveyors used the air photographs to assist them in placing the boundaries round their normal soil units, such as roadmaking gravels for the civil engineer, zones of trafficability for the military engineer, or soil series for the agriculturalist. In much of this early work, the relation between soil type, landform and soil behaviour was emphasised - "similar soils are developed on similar slopes under the action of weathering of similar materials.[2] It was also noted that the different patterns of features seen in photographs corresponded to major changes in soil conditions. Detailed examination of these patterns showed that the differences could be caused by a variety of features, such as soil type (affecting the air photo tone) drainage intensity, vegetation, land use etc, all features relating to soil conditions. Thus it was realised that the air photo patterns provided a breakdown of terrain into mapping units which could be defined in terms of surface expression, mainly topography and vegetation. It was also felt that this approach offered the opportunity to evolve a basic form of mapping which was not biased by the user's requirements. In this way it is possible to make an engineering evaluation of a map which may have been originally commissioned for agricultural purposes.

The concept of survey by land classification was first developed and used in Australia to express the agricultural potential of ground.[3] Subsequently, these concepts were expanded and modified in the United Kingdom by the Department of Agriculture at Oxford University, working under contract to the Ministry of Defence.[4] The development of this work has been summarised in a paper by Webster and Beckett.

Similar studies have been made in South Africa and Australia, and in 1964 a joint meeting was held to define a common system of nomenclature which has since gained acceptance.[5] The units are, in decreasing order of size;

Land Zone
Land Division
Land Province
Land Region
Land System
Land Facet
Land Element

For most purposes, users are only concerned with the last three units, with occasional use of the land region. These are described first as they constitute the basis of the classification from which the higher units are derived.

2.1.1 Land system, land facet, land element The basic pattern of terrain features which can be seen in print laydowns is called a land system (Plate 1). A land system is defined by the geology, climate, and small range of topographic features, called land facets, which make up the pattern [6] (Fig 1). The pattern persists to the limits of the geological formation upon which it is developed, or until the prevailing land-forming process gives way to another. At this point, a new land system is developed, characterised by a different group of land facets. Although land systems may be tentatively mapped by outlining the patterns on print laydowns at a scale of about 1:100 000, they can only be properly defined by describing their complement of land facets.

Land systems maps are usually prepared at scales of 1:500 000 or 1:1 000 000, but more detailed maps may be necessary in complex terrain.

The land facet is the basic unit of mapping. Like the land system it is defined by its geology, water regime and topography, but in a much more restricted way. A land facet has a simple form, on essentially homogeneous parent material, and a single water regime (both surface water and ground water). There may be variations within the land facet, eg a 'homogeneous' parent material may consist of alternating beds of sandstone and shale, or the depth of water-table may vary seasonally or according to the shape of the ground. But the variations are definable, and therefore predictable. The important factor is that the materials developed on a land facet are fairly uniform, such that a pedologist would map its soils at approximately association level, and an engineer would accept a single design specification for a section of road built on it. Land facets vary in size but may be mapped on air photographs at scales between 1:10 000 and 1:60 000. In humid areas, the larger scales are generally necessary, while in arid areas the smaller scales are adequate.

It frequently happens that a very small feature of the landscape is of particular significance to a proposed scheme. The feature is too small to be mapped, but is nonetheless important enough to warrant a special category. In this case a land element is recognised, the smallest unit of landscape that is normally significant. For example, a hill slope may consist of two land elements, a steep upper slope and a gentle lower slope. To an engineer each slope element will be treated differently when considering slope stability or amounts of cut and fill. Other examples of land elements are very small river terraces, gully slopes and small rock outcrops.

The land system, land facet and land element are the main units of the terrain classification, and the relationship between them is shown in Fig 2. The occurrence of one or more land elements in a particular facet is predictable, although they are not necessarily always present. Similarly, within a land system the land facets occur in a certain relationship, but some facets may not appear in all parts of the system. In some cases it is necessary to recognise a variant land facet which has unpredictable differences from the standard facet. Such differences generally occur below the

ground and have little or no surface expression, but they may be forecast from a knowledge of the area. Variants can only be mapped by field investigation. Thus the land element is a part of a land facet which is definable and predictable; a variant is a different kind of land facet which, though definable, is not predictable.

2.1.2 Higher land units Of these units, only the land region is likely to be used in engineering evaluations, such as large-scale feasibility studies. A land region is made up of a group of land systems having the same basic geological composition and an overall similarity of landforms. They are likely to be mapped at a scale of 1:1 000 000 to 1:5 000 000. The land province and land division are groups of land regions and the land zone is a major climatic region of the world. Perrin and Mitchell[7] have investigated the extent to which analogous land systems occur within a single land zone, the hot deserts.

2.1.3 Landscape mapping The techniques described in the previous section have obviously been developed by specialists, but to become effective they must be integrated into engineering practice. Thus, it is necessary for engineers to understand the basis of these techniques, to realise their advantages and limitations, and to use them where appropriate. The scale of operation can range from the land system mapping of a whole country down to the identification of a particular site, such as the position of a quarry or gravel pit. The relative role of engineer and specialist will depend upon the complexity and scope of the problem.

The compilations of a land system analysis of a large area is basically a specialist task, which is best performed by a team having a variety of experience in such disciplines as geology, geomorphology, ecology and soil sciences. If the main objective of the survey is some particular use, then the relevant specialist is included in the team as this may influence decisions affecting the details of mapping. In general it has been found that land systems maps prepared for agrictultural surveys are suitable for engineering surveys, although some of the early land classification in Australia needed to be subdivided for engineering purposes. Land system maps have been published covering all of Lesotho, Malawi, Swaziland and Uganda, and extensive parts of Botswana, Kenya and Nigeria. Other territories mapped in part include Cameroun, S Africa, SW Africa, Zambia.

Nearly all terrain mapping is at land system level; land regions are not usually detailed enough, and land facet maps are too detailed for normal publication. To convert the land system map to a terrain evaluation it is necessary to describe the relevant land facets and to provide the information by which they can be identified. Most land system maps are accompanied by a memoir giving the basic information used to establish the classification of the survey area. This includes a brief description of the geology and topography of the land systems and usually describes their climate and vegetation. The occurrence of land facets is normally shown on a block diagram, cross-section or a map; maps are more often used in flat alluvial areas where relative relief is very small. The facet descriptions will normally define the slope and soil profile, with vegetation and water regime included where appropriate. Further information may be available according to the purpose of the original survey (see Table 1). An important feature of the report is that it should enable the user to identify the terrain units in the field. The land system may be identified from the map, but to distinguish the land facets and land elements a detailed description of identifying features is needed. A ground photograph may be useful, but the most effective method is to provide an annotated stereo-pair of air photographs and a list of distinctive features used in air photo interpretation (Plate 2)[8]. In this way the land facet descriptions, arranged according to land system, can be used as an index for air photo keys.

2.1.4 Application to highway engineering The present position of landscape mapping is that many areas have been surveyed but there is rarely much engineering information

TABLE I ENGINEERING CHARACTERISTICS OF THE ALOR GAJAH LAND SYSTEM (see Fig 2)

Land Facet	Form	Soils, Materials and Hydrology	Engineering Properties and Comments
1	*Hills* (a) Slope. Very gentle to gentle slopes (5)-10-12°, occasionally smooth but usually bumpy and irregular in detail. Overall straight or gently convex; often slightly concave in upper portion to give a more prominent hill top.	Up to 1 m of red or red-brown sandy clay over nodular or massive laterite up to 4 m thick over a silty clay mottled zone. Weathered rock may occur below about 4 m. The irregular development of laterite on the slopes tends to form the benches on the bumpy slopes, and it may outcrop on the steeper parts of the slope.	Main soil type (CH). Under normal drainage conditions for less than 150 commercial vehicles per day total pavement thickness should be 250 mm. In newly opened cut high natural moisture content may prevent compaction leading to lower bearing capacity. In alternating cut and fill, important to use the nodular laterite for the top layers of fill. Mottled zone in new cuttings is susceptible to erosion. Recommended angle of slope between 40° and 50°. Nodular laterite (GC) suitable for sub-base but not for base unless stabilised with cement. Suitable for gravel roads, therefore useful in stage construction. Easily won from borrow pits.
	(b) Gully. Sides 5 m deep, 20°, unstable. Bottom 6-10 m wide, flat, with a small stream (2 m wide) incised up to 2 m. 100-200 m and occasionally 750 m long.	As 1 (a) Temporary stream.	Culvert across stream.
2	*Minor valley* 30-100 m wide; gently concave or flat bottom with steep (20°) margins to facet 1; narrow stream a few m wide.	Variable soils, the weathering products of local rocks – mostly clays and silty clays. Poorly to well-drained, depending on materials.	Wet plastic soils in minor valleys. Fill usually imported from adjacent hill (facet 1a). Important to use nodular laterite in upper layers. Slopes of embankment may need protection in new construction to prevent erosion. Culverts across streams.
3	*Terrace* Level or very gently undulating, up to 120 m across but varies considerably along its length. Not continuous for more than about 2 km.	Variable according to local materials, usually light buff-coloured sand or clayey sand with poor profile development. Usually freely-draining, depending on composition.	Good subgrade and fill material.
4	*Main river valley* (a) Floodplain. Flat 100-300-(600) m wide.	As Facet 3, but wetter with impeded drainage. Usually flooded for padi.	Weak soils requiring fill embankments for road, about 1·5 m above ground level.
	(b) Abandoned meanders and river channels. Sinuous, about 20 m wide; no topographic expression.	As (a) but wetter. Probably composed of finer materials.	As (a).
	(c) River. Few-20 m wide; meandering.	Permanent flow.	Bridge crossing required.

included in the descriptions. Thus, the engineer has to extend the survey to make an engineering terrain evaluation. The descriptions of the land systems and land facets normally contain the necessary background information needed to make a preliminary assessment of the soil types and conditions in the area. From this it is possible to identify the facets and elements which are likely to need more detailed investigation, either because they are likely to be troublesome, or because they are advantageous. For example, in locating a road line in an alluvial area, (Plate 3), some soils are likely to have a low bearing strength or to consolidate perhaps with differential settling or even failure. On sloping ground, the construction of cuttings can lead to failures if the slopes are too steep, or the area has particular features which could lead to potential instability, eg spring lines or evidence of past landsliding. On the other hand certain soil types associated with land facets or land elements may be useful for construction purposes, such as river terraces or lateritic gravels.

It is not usually necessary to map all of the facets in the area completely, but only to identify and map those relevant to the actual project. It is then essential that there is an adequate amount of field testing to establish the relevant properties of each facet and also the variability of these properties. Although the basis of land system mapping is that there is a direct link between land form and soil type, facets are natural features and do sometimes have a variety of soils.

In addition to recording the properties of soils, it is possible to link other engineering factors to the terrain analysis. A complete evaluation of soil type and strength means that it is possible to recommend broad engineering designs, such as bearing pressure for the foundations of light buildings, together with recommended construction thickness of road pavements, with suggested base material. Recommendations for slopes of cuttings can be made and also for the construction of embankments, eg maximum height of embankment to avoid overstressing an alluvial soil, or the necessity to use a retaining wall in steep terrain. Calculations of earthwork quantities in neighbouring land systems have shown significant differences and the relation of earthwork quantities to land systems should show an improvement over the typical classification of 'mountainous', 'rolling' and 'flat', used to make preliminary estimates. Observations during construction, and when the works are finished, should also be related to the land system, such as the performance of equipment on the site, and maintenance problems that arise on completion, which may lead to alternative designs in the future. In this way a complete engineering evaluation can be built up of the land system and its units.

In the absence of an existing land system map, it will be necessary to make a preliminary land system classification. This may involve the use of a specialist consultant, although in many cases an adequate classification can be made by a soils engineer who is used to handling air photography. The advantages of preparing a terrain evaluation over a wide area is that it can delineate at an early stage of the survey, before a project becomes tied to a particular site or route, the range of conditions likely to be encountered. The later stages of the survey to gather the information about relevant land facets will then follow the same programme described for the evaluation of an existing land system map.

Terrain evaluation provides the techniques to improve the efficiency and accuracy of preliminary surveys; this means that the site investigations will be in the correct place, and will be aimed at the relevant problems. Terrain evaluation also provides a rational basis to correlate known and unknown areas and thus transfer information and experience from one project to another. The ability to correlate between areas has led to the proposals to use a terrain classification as the basis of engineering data stores. From experience it is known that a considerable amount of information could be re-used on different projects if the relevant data could be extracted. Considerable thought has been put to the most suitable design of such a store[9] and projects have been started in Australia, Rhodesia and S Africa.

2.1.5 Development of data stores To be effective, a data store must be capable of accepting diverse information, such as maps, reports and test results, and of providing information on a wide variety of subjects whose only common link may be the engineer. The large amount of data being produced and existing on files also creates a problem of data handling. If the data is reduced by statistical or other techniques, some types of information may not be retrievable, and the addition of new data to existing summaries becomes more difficult. One approach to this problem is to ignore all previous data and build up a data store from new projects. This approach is favoured in S Africa, and information is filed according to terrain units which are broadly subdivided under geology, climate, erosion cycle and relative relief. The alternative approach is to base the data store on a land system map, which could either be national or local. The development of sophisticated methods of data storage means that a national store is a feasible proposition, although the cost would inevitably be high. A local system based on the terrain brief and using simpler data storage is more likely to be useful in the first place to test the difficulties and advantages of indexing data in this way. If national data stores are to succeed they must show that the cost of indexing and storing information can be repaid by more efficient surveys.

3. EXAMPLES OF TERRAIN EVALUATION IN HIGHWAY ENGINEERING

The use of these techniques in two different sorts of survey can be illustrated by work on the Trans-African Highway, and a feasibility study leading to final design in Malawi.

The Trans-African Highway project, to build an all-weather road from Lagos to Mombasa, is still in the early stages of planning. The pre-feasibility study of the whole route has been completed and, using the data accumulated in this survey a final route has been selected. To assist in this work, the Transport and Road Research Laboratory has prepared a land region map of the area[10], shown in Fig 3, covering all the routes which were likely to be considered. Where possible this map was prepared from existing land system mapping, but where this does not exist the best topographical and geological maps were used, assisted by air photography in a few places. A map prepared in this way, without the assistance of field work to check it, is likely to require some revision before a final land region map can be published. However, the proposed boundaries provide workable survey units for collecting and classifying engineering and other land use data for a pre-feasibility survey. For engineering purposes, the map defines regions with distinct topographic and foundation conditions, in which it can be assumed that the costs of road-building are reasonably consistent. Soil changes noted during the ground reconnaissance were supported by boundaries drawn on the map, and it has been used to forecast conditions on routes introduced as alternatives after the completion of field work. The Highway will, of course, eventually form the main spine of a complex network of roads to serve the economic development of a wide area. The land region map prepared for this work can also be used as a basis for future planning of other roads linking with the Highway. The terrain classification can be used to evaluate the development potential of the areas served, whether it be agricultural, mineral extraction or forestry. The main use of terrain surveys to date has indeed been for this type of land evaluation, and the presentation of engineering information obtained in the planning and construction of the Highway in a manner compatible with the developmental resource surveys gives a planning authority a co-ordinated system for directing land use and for providing the data for planning and costing the associated transport system.

For the next stage of work on the Trans-African Highway, a feasibility study of a selected section, more detailed mapping will be necessary over a narrower corridor. Land systems mapping would be suitable for this provided that the air photo cover can be obtained. The land system analysis would be a more detailed version of the land region mapping used for the pre-feasibility study. In this way information gained in early surveys can be carried through to later stages.

An example of terrain evaluation used in more detailed surveys is a recent materials survey for a road project in Malawi. The consulting engineers wished to use the field work carried out for the feasibility study, and to prepare tender documents without further field investigations. The project involved two alternative alignments totalling 130 kilometres (Fig 4). Although the two routes run quite near to each other, the topographical and geological conditions were quite distinct on each. The materials

survey had to start before the final line was chosen, and in fact had to contribute towards the final choice of route. In the absence of a final line, it was necessary to devise a sampling and testing program of the soils in such a way that a pavement design could be prepared for a road in any part of the area. This reason alone meant that a terrain evaluation was necessary, but even if the line had been fixed in advance, this approach would have provided the most economical method of survey.

Before the field work commenced, the area containing the routes was studied to establish the pattern of terrain units. The land system boundaries of Malawi had already been mapped at a scale of 1;500 000 and, using geological maps and air-photo mosaics at a scale of 1:120 000, the boundaries were transferred to maps of the survey area. The published map only contained a general description of each land system, and so the next stage was to identify and describe the land facets and land elements by stereoscopic examination of aerial photographs at a scale of 1:20 000. Having identified all the terrain units, the field survey was arranged to collect at least one major soil sample from all units which would be crossed by either of the alternative routes. Further sampling sites were identified for field examination and, where the soil or moisture conditions of any land facet or land element appeared to be variable, extra samples were collected for testing in the laboratory.

The laboratory testing programme was arranged to determine the strength of the soils for all likely conditions of subgrade density and moisture content. From these data, together with measurements of actual moisture content, it was possible to prepare a pavement design for every land element traversed by the road. In addition, the extent of the individual land elements on each provisional alignment was estimated so that a provisional estimate could be made of the quantities of materials needed. The specification of the pavement for the final alignment will be based on the identification in the field of the land elements, guided by the results of the laboratory soil tests.

4. AIR PHOTO INTERPRETATION

Despite the interest and extensive research into other forms of remote sensing, air photo interpretation still remains the most important technique for obtaining engineering information by indirect methods. The large-scale photography often commissioned for the production of maps and plans for individual engineering projects is generally not suitable for regional air photo interpretation as the scale is too large and the photography is usually limited to the area of the project. The air photo interpreter is normally provided with photography of scales between 1:200 000 and 1:60 000 that has previously been used for topographic mapping. This photography is widely available throughout the world, and is usually black and white. To justify the extra trouble and expense of flying colour photography or indeed using any other form of remote sensing, a clear understanding is necessary of the extra information it will produce.

It is generally accepted that photography between 1:20 000 and 1:30 000 is the best all-round scale for photo interpretation, although it may be more than a coincidence that this is the range of scales normally available. In theory the scale should be large enough to show the smallest significant feature in the topography. In practice this may not be feasible, as a doubling of the scale of photographs increases the number of prints to be examined by a factor of four. One possible solution for this was proposed by Goosens [11] who wished to map the occurrence of deep narrow gullies in alluvial areas. Although these could have been identified at a scale of 1:20 000, he preferred to use 1:40 000 scale photographs which were adequate for all other tasks, amd from these to identify all areas likely to contain gullies. The occurrence of these was then confirmed by visual inspection by light aircraft. Another example of the effect of scale on interpretation is the photo-geological study of the Kainji dam site on the river Niger. Detailed photographs at a scale of 1:6 000 existed and were used to map the position of outcrops. But it was found that for this area of peneplained crystalline rocks the high quality photographs at a scale of 1:40 000 were preferable for locating the major geological features such as faults, shear zones and even geological boundaries.

4.1 Procedure for examining air photographs

Most air photographs are taken with the camera axis as near vertical as possible, each photograph overlapping the previous one by at least 60 per cent to give stereoscopic cover. The first stage in interpretation is to lay out the photographs in the relative positions in which they were taken to form an uncontrolled mosaic or print laydown. In this state the photographs can be used as a map to identify features such as roads, rivers and patterns of vegetation which may show up clearly on the mosaic, but be too large to be seen on individual photographs. Similarly, the first definition of land systems is seen more clearly on the mosaic than on the many separate prints.

Having obtained an overall view from the mosaic, it is then essential to examine the prints in pairs under a stereoscope to obtain a three-dimensional image of the ground. An important feature of the stereo image is that the impression of the relief is exaggerated so that trees appear higher and slopes appear steeper than would be expected. This exaggeration, which normally appears to be about X3, is an important aid to the examination of the terrain, helping the interpreter to see minor changes in slope and very small differences in elevation or relief. In mountainous terrain this degree of exaggeration can be a disadvantage as it becomes difficult to distinguish steep from very steep slopes; in these conditions the use of a camera with a longer focal length lens reduces the exaggeration, and may be preferable.

The image seen under the stereoscope is like a three-dimensional map complete in all its minor details. The first stage in interpreting aerial photographs is to recognise ground features when viewed from above. Familiar objects such as trees and houses are usually easily identified. To assist the recognition of ground features an air photo key can be prepared, annotated to show the points of interest (Plate 2). Land system atlases are air photo keys, illustrating the typical parts of the terrain, which the engineer can compare with his own air photographs.

The use of such a key can assist in the second stage of interpretation, where predictions are made about conditions that cannot be observed directly. This process of deductive reasoning obviously improves with experience and appropriate training, but the provision of a key and the appropriate background information assists both the experienced and untrained interpreter to make more accurate deductions about the ground conditions.

4.2 Other methods of remote sensing

Aerial colour films aim to reproduce the colours as seen by the eye, and the panchromatic films represent the full tonal range of the visible spectrum by the equivalent grey tone. All other forms of remote sensing measure some specified part of the electromagnetic spectrum and, although the final product is often presented as a photographic print, the image cannot be interpreted conventionally. The techniques used can be conveniently divided into two groups: those that record directly onto photographic film, and those that generate an image which is recorded and later reproduced as a photograph.

The direct photographic techniques are limited to the visible and near infra-red part of the spectrum (Fig 5); outside this zone it becomes impractical to shield the film from fogging. The normal method of recording bands of the spectrum is to use optical filters to limit the light to the frequency required and record on a suitable black and white film. Several systems taking four simultaneous images are available. By projecting the images through suitable filters it is possible to recreate a true colour image, or a 'false colour' image if the infra-red band is added.

The normal 'false colour' film contains three emulsions, one of which is sensitive to the near infra-red wavelengths. Thus the colour produced on the film will depend on the amount of near infra-red energy which is reflected. Where a strong

contrast in the reflectivity of infra-red is correlated with an important feature to be identified then the false colour film helps to identify the boundaries. An early use of this was to detect camouflage from the surrounding vegetation and this has led to the use of this type of film to examine variations in vegetation. Healthy vegetation reflects the infra-red more strongly than when it is diseased, and similarly vegetation near streams or other sources of ground water show stronger colours. In the interpretation of the stability of slopes, the presence of high moisture content is a potential sign of danger, and in some cases it is possible to detect damage to vegetation on unstable ground owing to disturbance of the roots. This will show in the reflection of infra-red in the leaves long before the usual observation of trees leaning over due to soil creep. The presence of bare rock on such a slope is also easily seen, normally as a bright blue. Another useful feature of infra-red photography is that it provides a greater contrast between water and damp soil than normal photography, which leads to a quicker and more accurate survey of the extent of water, eg to assess the extent of flooding.

All other remote sensing methods use some sort of detector to produce an electronic signal, from which an image is built up. The two main systems in use are the scanning detectors which include the infra-red line scan equipment and side-look airborne radar (SLAR). The scanning equipment measures both emitted and reflected radiation and, by using suitable filters and detectors, it is possible to limit the measurements to certain spectral bands. Experimental equipment is available to measure 24 bands simultaneously, and this has been used to cover both the visible and infra-red portions of the spectrum (multi-spectral scanning). More experience has been obtained with simpler equipment with one detector, such as the infra-red line scan detectors. This equipment is normally designed to record in the middle and far infra-red sectors with wavelengths of 2 - 5 and 7 - 14 microns respectively. These bands are defined by the low absorption of these wavelengths by the atmosphere. Beyond 25 microns transmission of infra-red may be considered impossible; at longer wavelengths atmosphere absorption is again reduced and it is possible to use this type of sensor to record at micro-wave length.

The radiation measured by all detectors includes reflected solar radiation and emitted radiation. The emitted radiation is determined by the temperature of the object and its emissivity, which can vary with soil type, moisture condition, vegetation coverage and surface roughness. However, assuming a constant or known emissivity, it is then feasible to plot variations in temperature, and this is particularly useful in detecting currents in water. The water discharged from industrial works will be warm, but springs of fresh water discharging into the sea will usually be cooler. The recording of emissivity by line-scan equipment must be made at night when the reflected solar radiation is absent. The near infra-red recording, either by photography or sensor, is made in day-time to measure the reflected solar radiation.

4.2.1 SLAR sensing The SLAR form of sensing records the reflection of a radar pulse transmitted from the aircraft. Thus the system is independent of external energy, and because the wavelengths used are not affected by cloud, it is possible to obtain imagery at any time of the day or year. This ability to produce an image where conventional photographic techniques cannot be used means that SLAR provides an ideal form of reconnaissance survey. It is possible to produce an accurate mosaic which can be used for interpretation. Typical scales of radar imagery available commercially are 1:100 000 to 1:250 000 with a resolution between 10 and 30 metres. Smaller objects than this can appear on the image if they are strong reflectors, and it is possible to enlarge the original material. These mosaics are suitable for the identification of regional and geological features and for a preliminary identification of terrain units. Lateral overlap of radar cover can be used to give a stereoscopic image, which will give a more accurate interpretation of the terrain.

5. GEOPHYSICAL TECHNIQUES

Geophysical techniques have been used for 40 years in engineering investigations, but the production of lightweight portable equipment has encouraged its use in the last 10 years. Much of this work has been for road surveys, and in France the use of geophysics is a routine part of a survey for new construction.

An important difference between geophysical surveys and other forms of site investigation is that there is no direct measurement of geotechnical properties. The instruments produce readings of some physical property of the ground, such as electrical resistivity, and from an array of readings an interpretation is made of the variation of this property with depth. If it can be assumed that changes in the measured property coincide with changes in the material, then the geophysical survey can be used to plot the boundaries of the various layers. Preliminary indentification of the type of material may often be made from a knowledge of the geophysical properties of soils, but all interpretations, both of depth and material, should be correlated to boreholes or trial pits.

Geophysical surveys are most efficiently used to extend the scope of conventional site investigations. They also may be used at an early stage to assist in the choice of sites for more detailed investigation. The portability of the equipment and speed of operation may be a great advantage in such early surveys, for example when comparing the foundation conditions at several different bridge sites. In addition, certain problems of site investigation are best solved by geophysical methods. The seismic refraction technique is the most effective method of determining the rippability of rock, and electrical resistivity surveys are an efficient method for determining the depth of the water-table.

These two systems are those most widely used in geophysical surveys. Other techniques measuring different parameters, such as magnetic field or gravity, have been used for special investigations, but in general such methods have not gained widespread use.

5.1 Siesmic refraction

This technique [12,13] is used to determine the thickness of layers of soil and rock, and also the velocity at which a seismic wave moves through the material. As this velocity is proportional to the elasticity and density, it may be used to predict the geotechnical characteristics of the layer.

In the field the shock waves are normally produced by either an explosive charge or a hammer. Sensitive geophones placed at increasing distance from the shock source record the time taken for the waves to reach each point (see Fig 6). From these data it is then possible to calculate the shock wave velocity and depth of each layer present. Two basic types of field equipment are in normal use. The simplest systems use a single geophone and a sledge hammer source of energy; the recording systems are often deliberately simplified to speed operations, although this can lead to errors in interpretation. The more advanced systems normally record 12 geophones simultaneously, producing a complete record photographically. Either a hammer or an explosive charge is used, the latter source giving a greater depth of investigation. A full description of each type of instrument and the practical field operation is given in the appendix.

5.2 Electrical resistivity [14]

The electrical resistivity of soils and rocks is mainly a function of the quantity and salinity of the moisture contained in the pores and fissures. Assuming a constant salinity, variations in resistivity can be correlated with changes in porosity and the depth of the water-table. Thus, by calculating the vertical and horizontal changes in resistivity, it is possible to predict changes of the materials.

The resistivity of an electrically homogeneous medium is a true value, but measurements of a layered material, which is the normal occurrence in soil survey, result in a value of apparent resistivity, depending on the number and properties of the layers present.

In resistivity surveys four metal electrodes are driven into the ground in a line. They are then connected to an electrical circuit such that a current is introduced into the ground via the two outer electrodes and the resulting potential difference is measured across the two inner electrodes.

The zone of measurement penetrates the soil to a depth roughly equal to the distance between the outer electrodes. Thus, to measure the apparent resistivity of the top 1 metre of soil, the outer electrodes are placed 1 metre apart. Greater depths are measured by increasing the electrode spacing accordingly. This is called vertical electrical sounding, and it yields a series of apparent resistivity values which can be related to theoretical values from which the true resistivity and thickness of the layers present may be calculated. In order to obtain information on horizontal variations, the elctrodes are moved along a traverse at constant separation, to measure the changes in apparent resistivity at constant depth. This method is called horizontal profiling.

6. APPLICATION OF GEOPHYSICAL TECHNIQUES

6.1 General

The two methods described are the most useful geophysical methods in connection with civil engineering problems. They are complementary to each other as they have differing advantages and limitations. Though both require reasonably flat, level ground with near horizontal subsurface layers, they are capable of giving good results under most conditions of slope and geological structures. Some borehole or trial pit correlation is required in order to relate field results obtained to particular site conditions. The methods have been in use for many years in USA and France as a preliminary survey tool and conference proceedings report many examples of their routine use in soil surveys.[15,16]

6.2 Earthwork costs

The seismic refraction method is especially suited to data required in costing earthworks.[17,18]

In areas of cut, the depth of overburden and the rippability of rock layers are required for earthwork calculations. The chart published by the Caterpillar Company relating shock-wave velocity to rippability with a standard tractor enables estimates of blasting requirements to be made.

In costing earthworks along alternative routes of new construction, the seismic refraction method is speedy and consists of portable equipment well suited to back packing to inaccessible mountain areas. With correlation in similar nearby areas accessible for drilling rigs, reliable cost estimates of earthwork quantities over alternative mountainous routes have been made.

6.3 Planning detailed borehole surveys

More effective use of boreholes required for design purposes can be made when information from a preliminary geophysical survey is available to indicate areas requiring special investigation. In homogeneous areas where subsurface conditions are similar, fewer boreholes are required. Recent work in UK on a proposed road line was utilised in planning the design survey.[19]

6.4 Materials survey and other applications

In areas of construction, the location of borrow areas has an important effect on material costs. The geophysical methods described, together with air photo interpretation, have been used to indicate most suitable areas for further investigation, and also to map the extent of useful deposits in existing borrow areas. The seismic refraction method is particularly suited for early evaluation of quarry sites, especially where it is extremely difficult to place boring machinery in the most suitable places.[20]

Many other subsurface problems in civil engineering have been tackled with geophysics with varying success. Useful application on tunnelling conditions[21,22] landslides[23] and dam sites[24] have been reported, also water-table investigation[25,26] and fault location. Geophysical methods have often been used in an attempt to solve difficult problems of subsurface investigation where other methods have failed. Some success has been achieved in the location of underground caverns and mine shafts, and in these extreme conditions geophysics can usefully supplement normal methods of survey.

6.5 Limitations

Under very poor site conditions, involving steep slopes or a complex geological structure, the interpretation of the geophysical data may be so difficult that the results are of little use in site investigation. An appreciation of the limitations of geophysical techniques assists the choice of the most suitable method for any particular investigation. As different methods measure different subsurface properties, they naturally have differing limitations and advantages. However, they can both be applied to most problems with some degree of success. Particular limitations of the methods are as follow.

6.5.1 Seismic refraction Sometimes velocity contrasts between geologically or mechanically distinct layers may not exist and the whole may appear as one seismic layer. Examples of this phenomenon have been found with hard clays overlying shales and limestone. The general requirements in the seismic refraction technique are that deeper layers have increasingly higher velocities and also increasingly greater thickness. Where a thinner layer occurs at depth it does not show up in the time-distance graph and remains hidden. A blind zone is a layer which has a velocity lower than the layer above it. Such a layer is not detectable by seismic refraction because the refracted ray bends towards the vertical at the velocity inversion and the waves never return to the surface. Lack of awareness of these situations will lead to erroneous calculation of depths and velocities of layers present.

All these drawbacks can be minimised if the seismic survey is supported by a strategic borehole investigation.

6.5.2 Electrical resistivity Electrical resistivity surveys are normally considered to be less accurate than seismic survey although they are quicker to carry out. A frequently quoted accuracy for electrical resistivity surveys is that the interpreted depth is $\pm$ 20 per cent of the true depth. Changes in water-table and the composition of the moisture within the zone of measurement affect the results, so careful interpretation is necessary. As in seismic surveying, many of the problems of interpretation can be reduced by following up with a limited borehole survey.

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8. APPENDIX 1

EQUIPMENT AND FIELD PROCEDURES FOR SEISMIC REFRACTION AND ELECTRICAL RESISTIVITY SURVEYS

8.1 Seismic refraction

8.1.1 Introduction In this method, shock waves are generated near the ground surface; some of these are subsequently refracted at the interfaces of the earth's strata. Sensitive geophones placed at the surface and connected to a recording system measure the arrival time of the wave at each geophone point, the nearer positions recording the direct surface wave as the first arrival and the farther points recording the refracted wave. Formulae (see later) are then used to calculate the wave velocity in each layer, the soil depth to bedrock and the angle of any dipping beds.

8.1.2 Field equipment Several variations of instrument layout are available. They are all capable of producing a time/distance graph of the shock-wave arrivals at different distances from the shock-wave source.

8.1.2.1 Shock-wave source This may consist of a) a hammer, b) a falling weight, or c) an explosive charge.

a) A sledge hammer and ground plate have been used successfully with both single-channel and multi-channel instruments. The hammer head is fitted with a sensitive microswitch which is actuated by the hammer blow so that the instant of impact can be signalled to the timing equipment. The depth of penetration of the shock wave produced varies according to the ground conditions, and is most useful for shallow investigations down to about 10 m.

b) The falling weight method is an extension of the principle of the hammer and incorporates a weight of up to 10 kg falling from a height of about 3 or 4m. Greater depth penetration is possible in many cases, though the control equipment is more complex than the hammer.

c) A small explosive charge buried at 1 - 2 m produces a shock wave capable of detection at considerable geophone distances. A special instantaneous electrical detonator is used with about 1/10 kg of special gelatine. The shot is fired by a circuit connected to the shock-wave timing system so that the instant of detonation can be recorded.

The shot hole is augered to 1 - 2 m depth according to the charge size and the ground conditions. The primed charge is lowered into the auger hole and is well tamped with moist clay stemming. The size of charge is dependent on the overall geophone spread length, the site noise conditions, and the geophone amplication available at the instrument. With explosive, the depth of investigation can be up to 50 - 100 m depending on the soil/rock properties.

8.1.2.2 Seismograph In the single-channel system a single geophone is used, usually with a hammer shock-wave source. The instrument timing system records the time from hammer impact to first shock-wave arrival at the geophone. A series of measurements are made at increasing geophone distances from the hammer.

In the multi-channel apparatus, usually 12 geophones are connected up to the recording system and an explosive charge or hammer blow is used to produce the shock-wave. The recording system produces a record of the arrival time at each geophone simultaneously on the 12 amplifier/galvo channels. The record is usually produced on a dry-write photo-sensitive paper on which the galvo deflections are produced, together with 2 or 10 millisecond timing lines. The shot or hammer instant is recorded

on a further channel so that the travel times may be read off for all geophones to produce the time/distance graph

8.1.3 Site details Straight traverse lines are required and the technique does assume that the layers of rock and soil are homogenous, but this method may be used in areas where dipping strata are present.

Shots on impacts are necessary from both ends of the traverse in order to obtain a true value for the shock-wave velocity in the 2nd and 3rd layers. The geophone separation is dependent on the depth of investigation and will vary from 2 - 4 m for shallow hammer investigation to about 15 m for deep refraction with explosives. Tests are run with the shock-wave source close to each end of the traverse initially and then shots at distances of 1/3 total spread length from end geophones are fired. Further long shots may be required to obtain information in deeper layers. The geophone amplifiers are adjusted according to the ground noise on the site, eg tree movement or traffic, and also the nearness of the geophone to the shot or impact point.

8.1.4 Calculations From the seismic records, the time from detonation at impact to the arrival of the first wave at each geophone position is read off to the nearest millisecond. A graph is then constructed of these times versus geophone distance from the shot-hole. A typical such graph for a double dipping layer is shown in Fig 7. The apparent velocities are calculated from the slopes and the following formulae are used to calculate the true velocity, the angle of dip, and the depths of the layers from the shot position.

Angle of Dip (2nd layer)
$$\phi = \frac{1}{2}\left(\sin^{-1}\frac{V_{1B}}{V_{2B}} - \sin^{-1}\frac{V_{1A}}{V_{2A}}\right)$$

The true velocity (2nd layer)
$$V_2 = 2\cos\phi\left(\frac{(V_{2A})\,(V_{2B})}{V_{2A} + V_{2B}}\right)$$

Depth to 2nd layer at shot-point A
$$D_A = \frac{(X_{1A})\,(V_2)}{2\,V_{2A}\cos\phi}\sqrt{\left(\frac{V_{2A} - V_1}{V_2^2 - V_1^2}\right)}$$

Depth to 2nd layer at shot-point B
$$D_B = \frac{(X_{1B})\,(V_2)}{2\,V_{2B}\cos\phi}\sqrt{\left(\frac{V_{2B} - V_1}{V_2^2 - V_1^2}\right)}$$

The true velocity (of 3rd layer)
$$V_3 = 2\left(\frac{(V_{3A})\,(V_{3B})}{V_{3A} + V_{3B}}\right)$$

The depth to 3rd layer at spread centre
$$D_2 \simeq 0.85\,(D_1) + \frac{X_2}{2}\sqrt{\left(\frac{V_3 - V_2}{V_3 + V_2}\right)}$$

where D_1 = mean of D_A, D_B

X_2 = mean value of break distance = $\frac{X_{2A} + X_{2B}}{2}$

V_{1A}, V_{2A}, etc are velocities derived from slopes in Fig 7

X_{1A}, X_{1B}, etc are break distances read off Fig 7.

8.2 Electrical resistivity

8.2.1 Practical application Several forms of electrode configuration have been used. For practical reasons the Schlumberger arrangement is to be preferred for vertical electrical soundings (V.E.S.) since usually only the two outer electrodes are moved after each measurement. The Wenner configuration, where the electrodes are equidistant, is best suited for horizontal profiling. The layout of the two types is shown in Fig 8.

With V.E.S. using the Schlumberger arrangement, measurements are first taken at close outer electrode distances of about 2 m, and further measurements are then taken at increasing outer electrode distances up to about 300 m. Occasionally the inner electrodes require moving to greater separation in order to obtain satisfactory instrument readings.

To calculate the apparent resistivity from measurements using the Schlumberger arrangement, the geometric proportionality constant K is equal to

$\frac{\Pi(AB^2 - MN^2)}{4\,MN}$ where AB and MN refer to electrode distances in Fig 8.

Therefore, apparent resistivity = KR where R is the resistance measurement from the field instrument.

The interpretation technique to obtain information on the number of layers present consists of plotting apparent resistivity against $\frac{MN}{2}$ on transparent double log paper and relating the resulting field curves to theoretical master curves. General sets of master curves have been published[14] using the Schlumberger arrangement for two, three and four layers with different resistivity and thickness ratios. These theoretical curves are calculated assuming that all the layers are horizontal and that no horizontal changes in resistivity occur.

The interpretation of results from horizontal profiling consists of calculating the apparent resistivity at each station using the formula ρa, the apparent resistivity = $2\Pi a.R$ for the Wenner configuration, where a = electrode spacing and R is the measured resistance.

Significant changes in apparent resistivity indicate a lateral change in soil type or moisture condition.

The results of resistivity surveys require initial correlation with some borehole data to confirm the interpretation under the particular site conditions.

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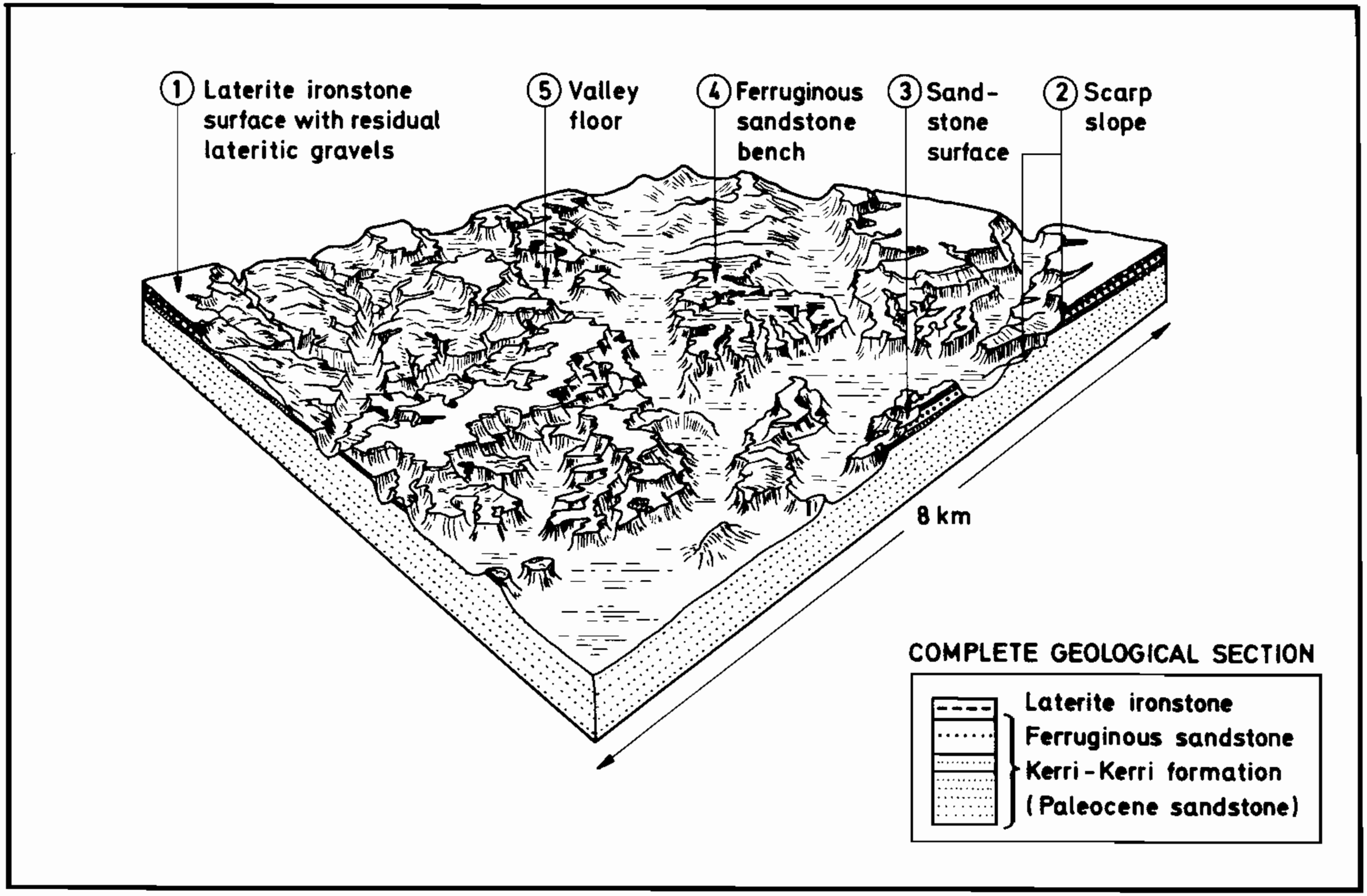


Fig. 1. BLOCK SECTION OF THE DOTO LAND SYSTEM, SHOWING COMPONENT LAND FACETS

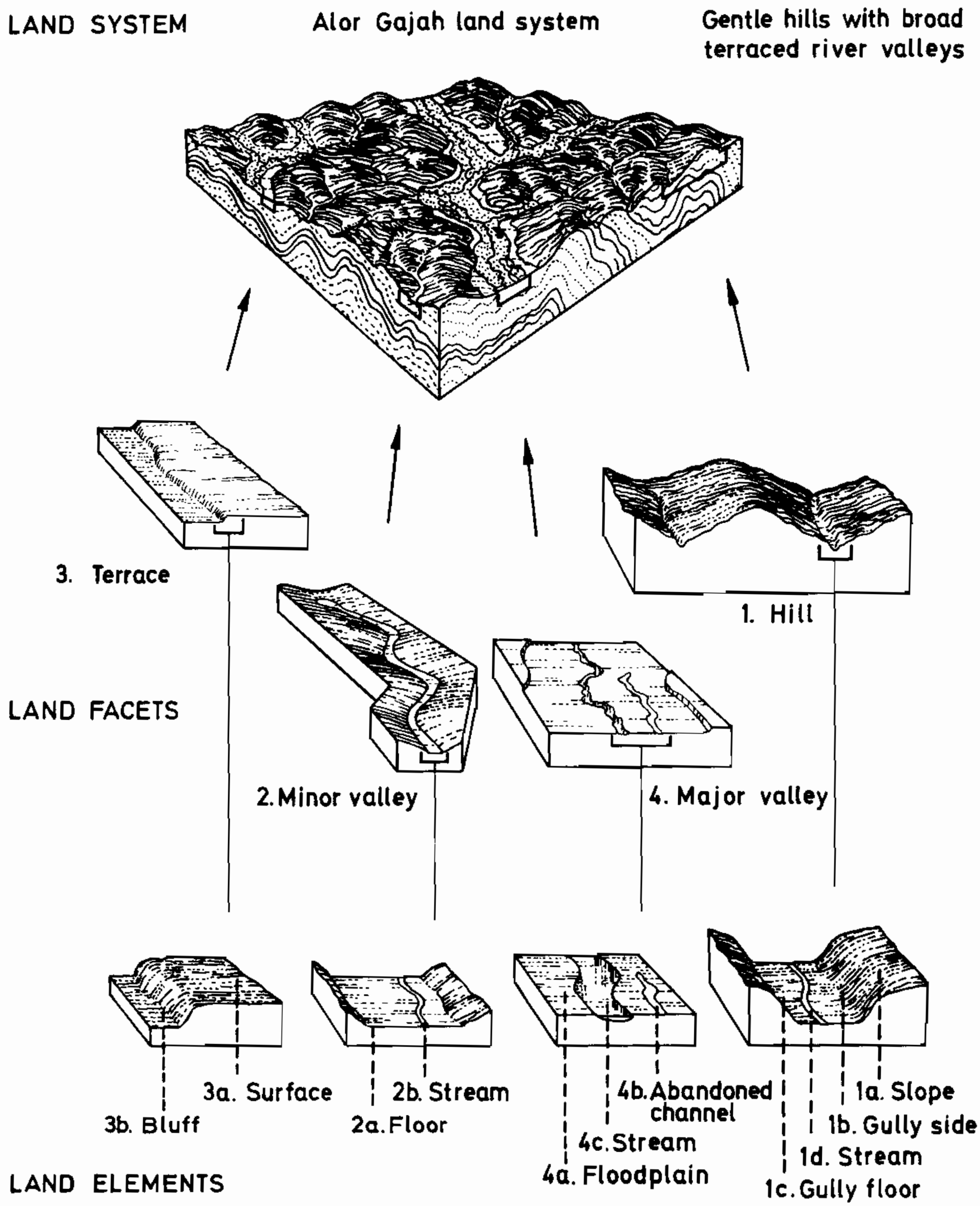


Fig. 2 DIAGRAM TO SHOW THE RELATIONSHIP BETWEEN LAND SYSTEM, LAND FACET AND LAND ELEMENT

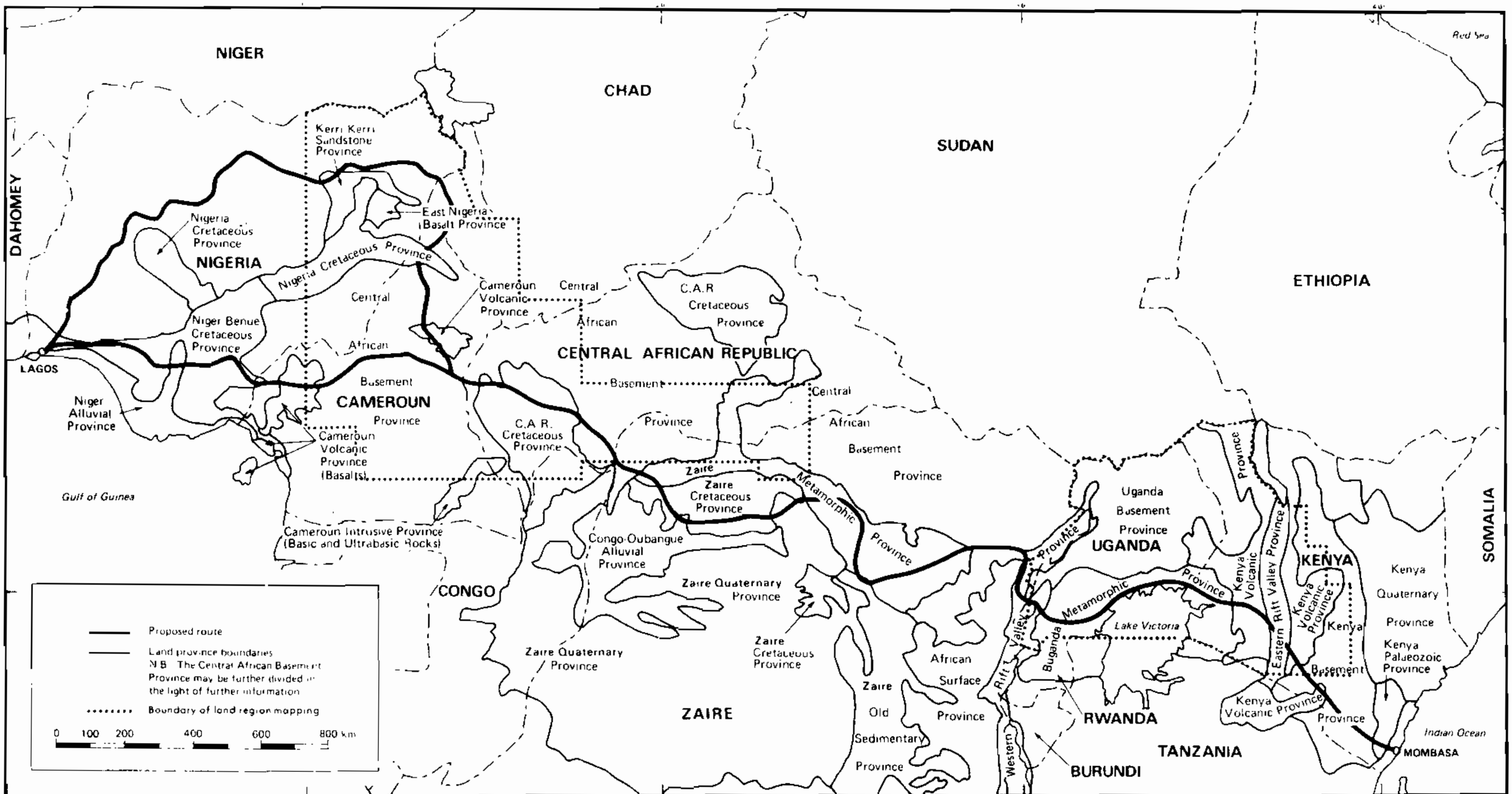


Fig. 3 THE LAND PROVINCES OF THE TRANS-AFRICAN HIGHWAY

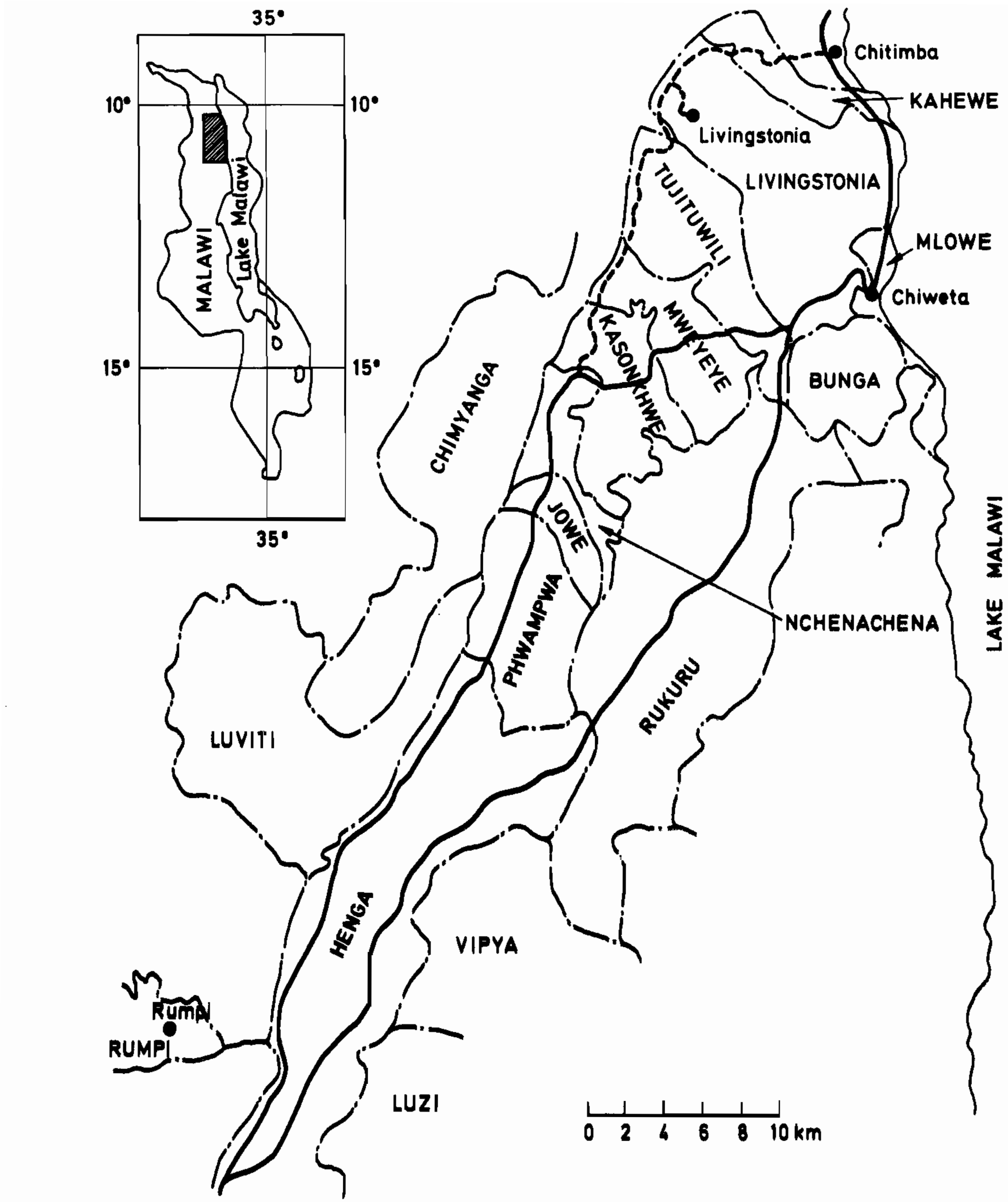


Fig. 4. RUMPI-CHIWETA TRANSPORTATION CORRIDOR LAND SYSTEMS

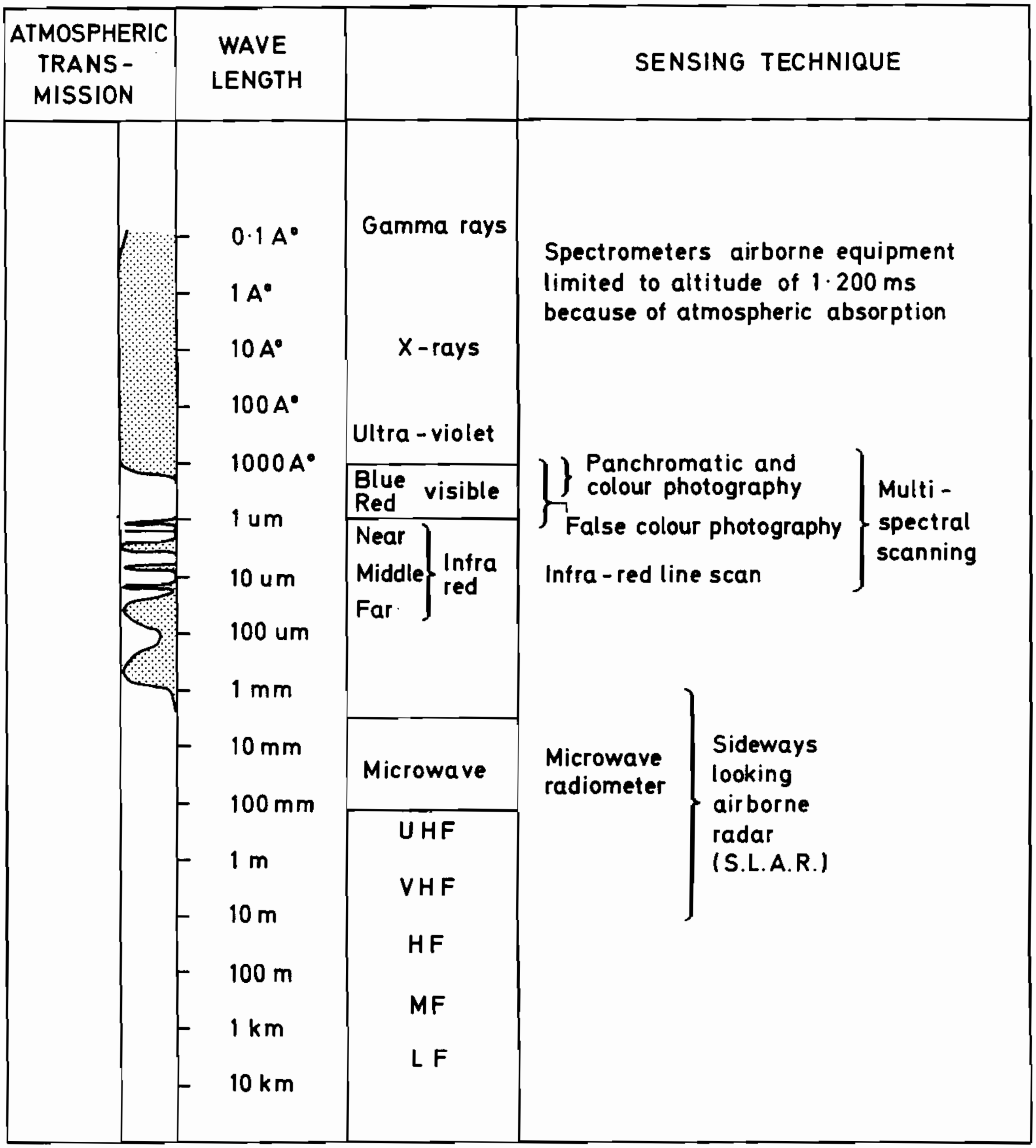


Fig. 5. REMOTE SENSING TECHNIQUES RELATED TO WAVELENGTH OF THE ELECTROMAGNETIC SPECTRUM

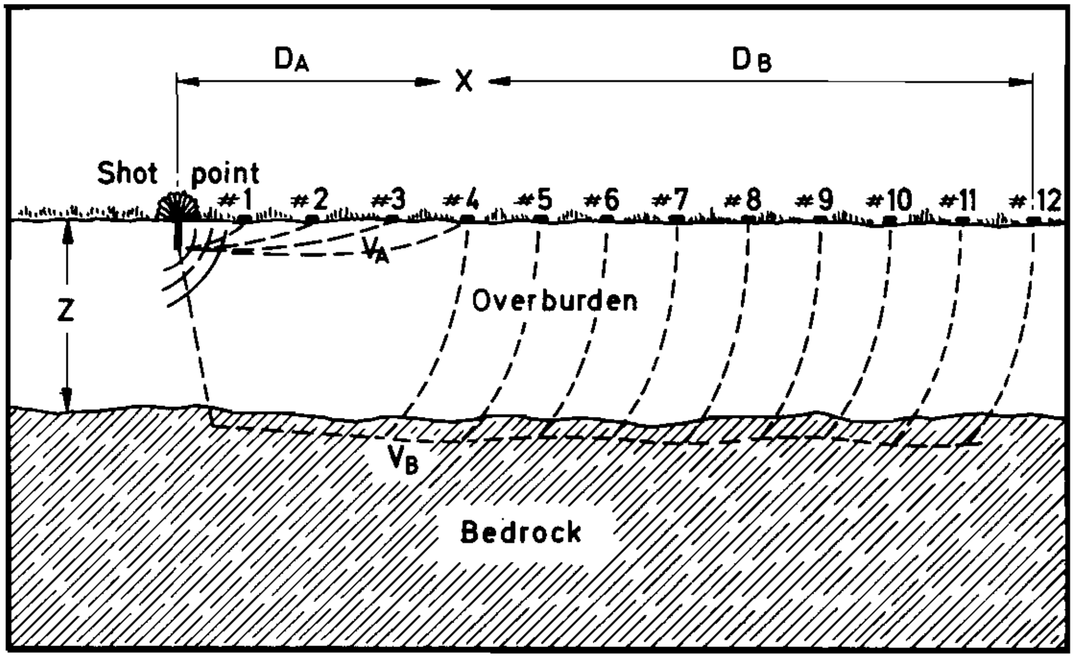
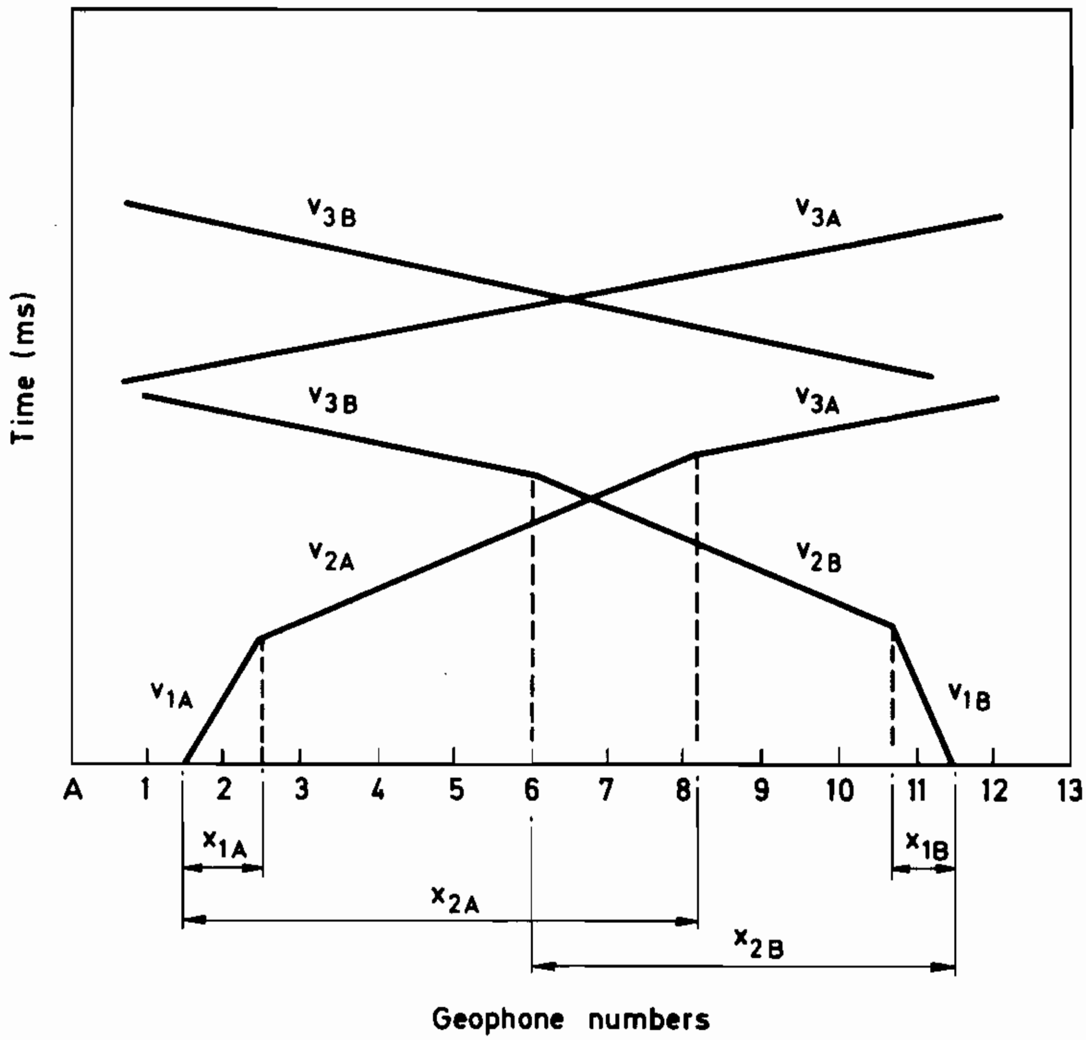


Fig. 6. REFRACTED WAVES OF ENERGY

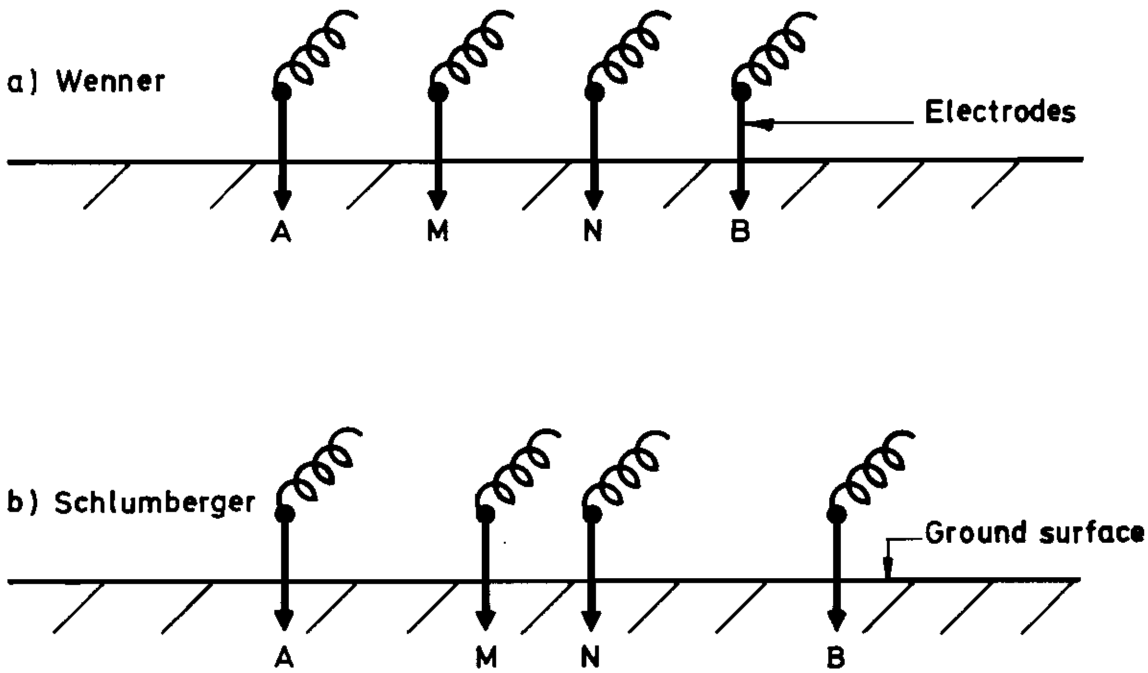


Note

x values are read off in metres according to geophone spacing

v values are the slopes in metres/second

Fig. 7. RELATIONSHIP BETWEEN TIME OF TRAVEL OF THE SHOCK WAVE AND POSITION OF GEOPHONE. TYPICAL EXAMPLE OF DIPPING DOUBLE LAYER SHOWING PARAMETERS USED IN CALCULATIONS



Note: The 2 outer electrodes are the current electrodes (A&B). The potential difference is measured across the 2 inner electrodes (M & N)

Fig.8 LAYOUT OF TWO TYPES OF ELECTRODE CONFIGURATION USED IN ELECTRICAL RESISTIVITY SURVEYS

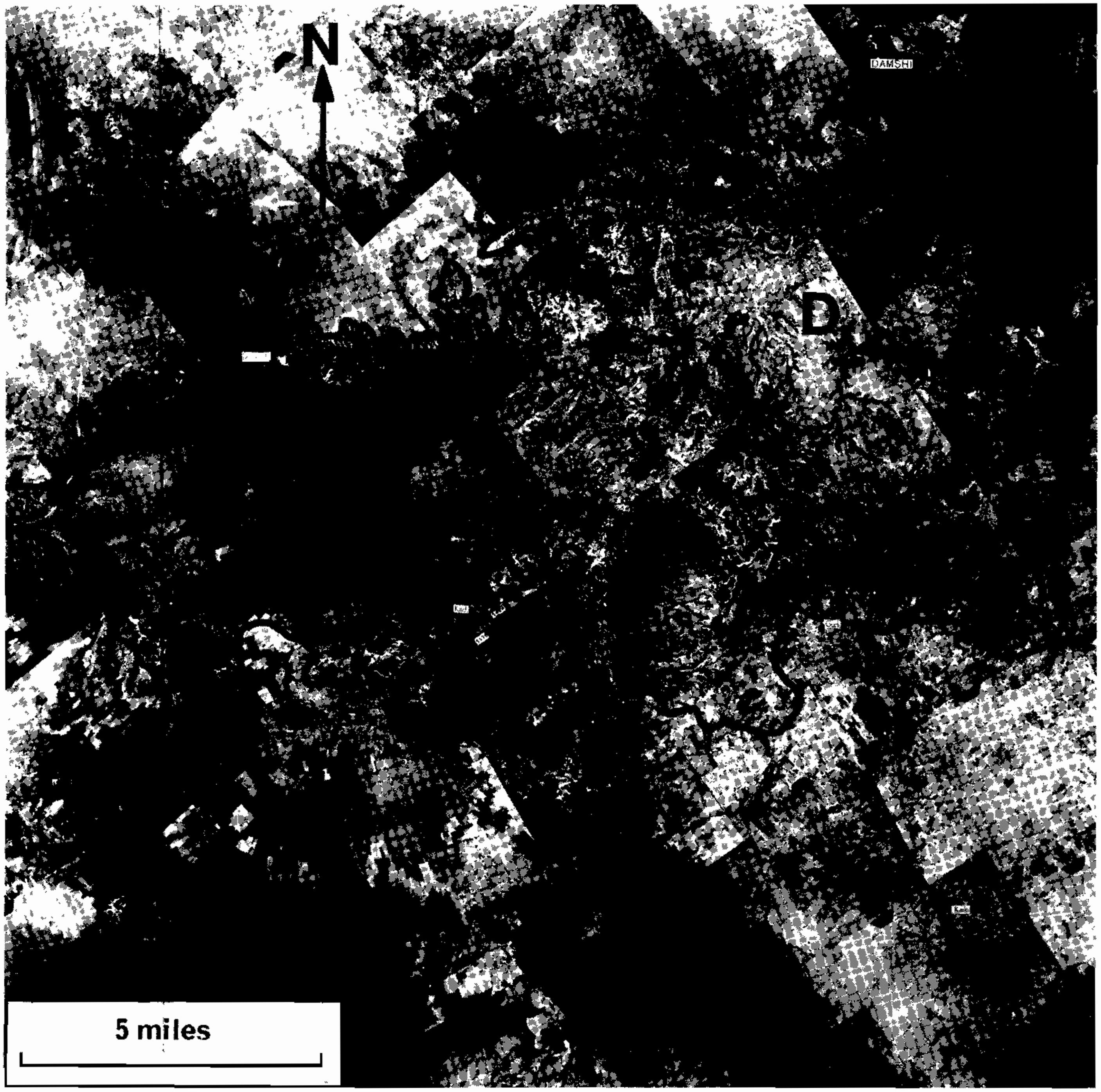


Plate 1 PHOTO-MOSAIC SHOWING THE DISTINCTIVE PATTERN OF THE DOTO LAND SYSTEM (D)

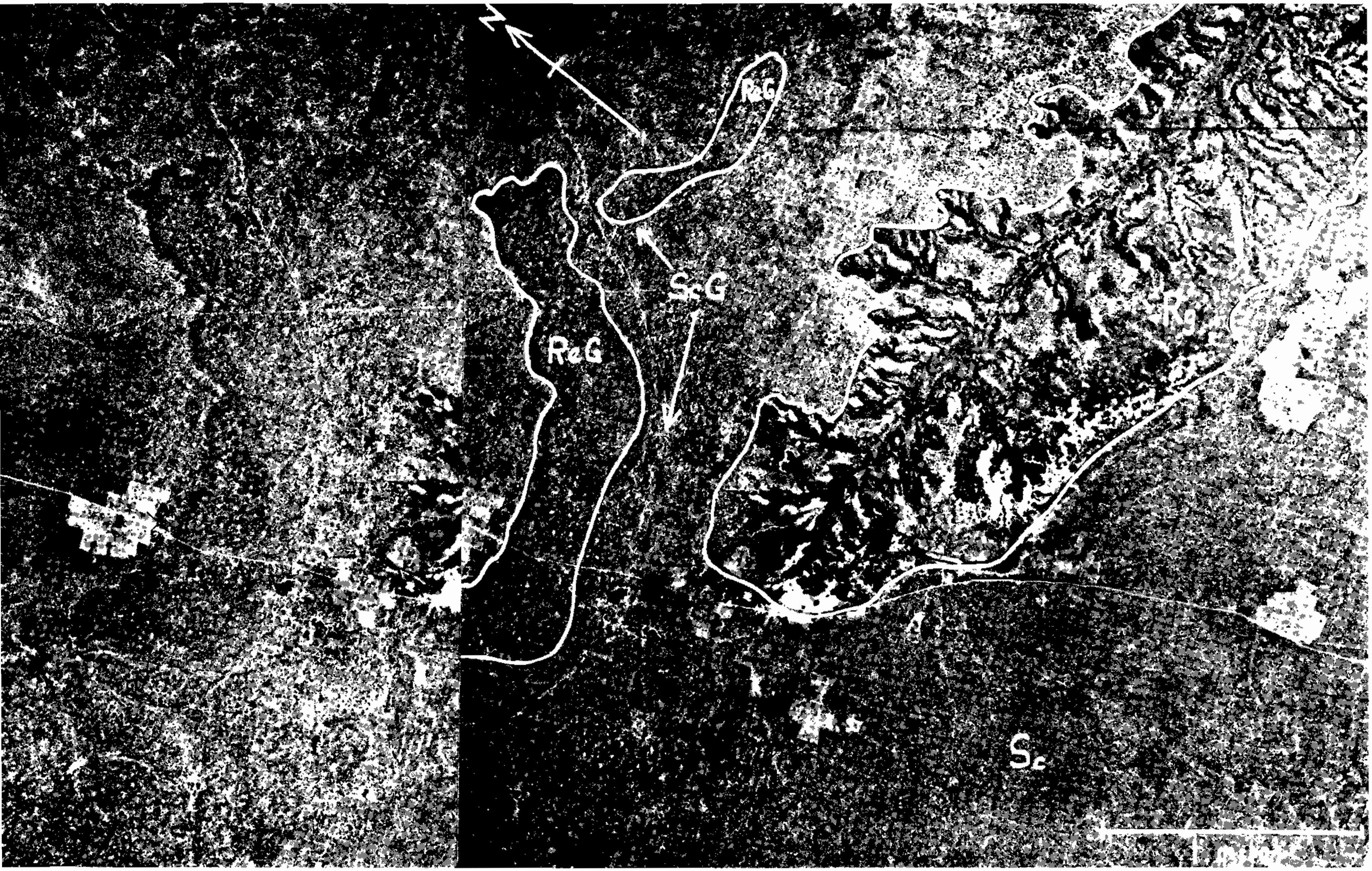


Plate 2 ANNOTATED STEREO PAIR OF AIR PHOTOGRAPHS OF THE DOTO LAND SYSTEM, SHOWING LOCATION OF LATERITE GRAVEL (Re G)

Plate 3 AIR PHOTOGRAPH SHOWING LOCATION OF OLD AND NEW ROAD LINE ON BETTER DRAINED SOILS IN UGANDA (OLD LINE IN WHITE; NEW LINE IN BLACK)