STRUCTURAL APPLICATIONS OF REMOTE SENSING IN THE CAPE PROVINCE, AND A NEW MODEL FOR THE EVOLUTION OF THE CAPE FOLD BELT.

by

A.R. NEWTON, M.Sc.
Dept. of Geology, University of Cape Town

Thesis submitted in fulfillment of the requirements
for the degree of Doctor of Philosophy.

University of Cape Town

September, 1975

postulated "Agulhas triple junction".

A comparison of colour, and low-sun-angle photographs with normal black-and-white photographs in the Laingsburg area, showed that the colour photographs were easier to interpret but contain little or no additional geological information, while the low-sun-angle photography is not suited to this terrain because the relief is too high and the trend of the structures too nearly parallel to the direction of illumination.

An interpretation of the LANDSAT imagery of the western part of the Fold Belt showed that the overall, and in places the detailed, structure of the Fold Belt shows up well, although climatic and land-use patterns are important in determining how much detail is visible. However, not a great deal more information is visible than can be obtained from the 1 : 1 Million published map.

Most published maps of the area studied are 60-70 years old, and it is shown by comparison with recent, unpublished, detailed field sheets that photogeological techniques offer a rapid and accurate method of assisting remapping in such areas.

The second type of terrain chosen was the Precambrian granitic gneiss of Namaqualand. Although lithological interpretation was more difficult than in low-grade metamorphic rocks, it was possible by using well-exposed structures to reconstruct a deformation history consisting of a very early isoclinal phase of folding, a second near-isoclinal phase, a third more open phase producing interference structures, and a fourth phase consisting of open buckle folding. Colour photographs were again found again found easier to interpret, but contain only a small amount of extra geological information compared to black-and-white photographs.

ABSTRACT

Two types of terrain were chosen for this study. The first was the end-Palaeozoic Cape Fold Belt, where sample areas totalling over 8,000 km^2 were selected, and photogeological maps produced. Structures were found to be comparatively simple, consisting of upright to overturned folds, often in en echelon arrangement, with the intensity of folding increasing northwards before dying out rapidly at the tectonic axis of the original trough. Folding is particularly severe just north of the two major strike-faults (the Worcester and Cango Faults), suggesting a genetic relationship between folding and faulting. This implies that the faults are much older structures than had previously been thought. Disharmonic folding is common, and cascade folds are present in places. The predominant direction of overturning is northward. In the NW branch of the Fold Belt the fold structures are more open, and overturning less common. The NW and E-W fold trends converge in a syntaxis, and continue as a single SW trend.

These features suggest a new interpretation of the Cape Fold Belt as a gravity gliding orogen, with deformation being initiated by uplift of the southern flank of the depositional trough along a series of major strike faults, resulting in a stepped slope which formed a décollement surface between the pre-Cape basement and the overlying poorly consolidated Cape-Karroo sequence. Thus the major faults must have had a northward downthrow originally, their present southward downthrow resulting from a later subsiding phase. There is support for this model from other lines of evidence e.g. development of chloritoid adjacent to the décollement surface, despite the lack of any other metamorphic or igneous activity associated with deformation, and lack of involvement of the basement in the deformation.

Consideration of the Cape Fold Belt in its wider, Gondwanide, context, shows that it is unlikely to be related to a subduction zone, since it was of intracratonic origin, and it is suggested that the uplift responsible for gravity gliding may have been due to the rise of an early mantle plume which later subsided, but which determined, through its associated fractures, the future lines along which Africa and South America were to drift apart. The plume-generated fractures form a

postulated.../

Contents

Illustrations

Maps

1. INTRODUCTION

Large areas in southern Africa are still, geologically speaking, little known: they range from areas of "basement" where the high metamorphic grade and complex structures render work very difficult, to the large, comparatively undisturbed areas underlain by Karroo and younger rocks. Until the geological histories and mutual relationships of these areas are better understood, there is little chance of forming an accurate estimate of the country's mineral resources, and with the comparative lack of trained personnel, it is important to develop any technique which will save field time or make fieldwork more efficient. Remote sensing is such a technique, and it is the writer's aim to show how this method can be used to help elucidate the structural pattern and tectonic history in various types of deformed rocks. It is not claimed that interpretation of remote sensing imagery can reveal the complete structural picture - it is merely one tool among many, and operates at its own particular range of scales: it must be supplemented by work on the outcrop scale and on the microscopic scale. What is claimed, however, is that it is an equally unique source of information as the other techniques, that it involves no more interpretation than they do, and that without it the resulting picture is likely to be incomplete or even inaccurate. A thorough study of appropriate imagery prior to fieldwork can save a great deal of time, allowing a concentration of attention on most difficult areas, or those most significant for structural or other reasons.

For the present study, it was decided to concentrate on two types of terrain which were reasonably accessible and which promised useful results - the Cape Fold Belt and the gneisses of Namaqualand. It was hoped to show that remote sensing could play a useful part in elucidating the very different types of structure present in these areas. It was further hoped to make comparative studies of different types of imagery - particularly a comparison of colour and false-colour IR with black-and-white, and areas near Laingsburg and O'okiep were flown for this purpose. Unfortunately the false colour film proved defective, so that only comparison of colour and black-and-white proved possible.

The Cape Fold Belt study began with the area north of Heidelberg (Fig. 1), and this was followed by the area north of Montagu and by the Outeniqua-Kammanassie area N.E. of George which was interpreted as a contribution to the Geodynamics Programme for the Cape Fold Belt. By this time it was clear that full understanding of the Cape Fold Belt would require much more work along many lines, one of which was the structural mapping (or re-mapping on a larger scale) of large areas, and as a first contribution to this the areas around Ceres and Touws River were studied. The total area photogeologically surveyed amounts to just over 8 000 km^2.

As a result of this concentration of attention, the writer evolved certain ideas on the possible evolution of the Cape Fold Belt (Newton, 1973), and a modified and expanded version is included in this thesis. The study is confined, then, to the western part of the Cape Fold Belt, but it is suggested that this limitation is not serious because the western part contains a representative sample of the structures developed in the Belt as a whole, and includes the important syntaxis region in the S.W. Cape.

It is hoped to extend the study to the eastern part of the Cape Fold Belt at a later date.

2. THE ROLE OF REMOTE SENSING IN STRUCTURAL GEOLOGY

The geological information which can be obtained from remote sensing methods falls into two main categories - lithological and structural. It can be defined in terms of the major recognition elements, which are form, colour or tone, texture and pattern. The fundamental element is tone (or colour) since it is variations in this which create the image. The recognition of form is dependant upon delineation of boundaries, which may be lines or linear contacts between different tones, textures or patterns, while the textures and patterns consist of more or less closely spaced rapid alternations of tones or colours, sometimes in a recognisable geometric arrangement.

An extremely important aspect of form is that given stereoscopic imagery it can be studied in three dimensions, which is a tremendous advantage over all two-dimensional presentations because of the increased amount of significant information which becomes available.

What we are studying in remote sensing thus consists of two types of information: one is a record of the amounts of energy reflected (or emitted) from the terrain and recorded in the form of an image - and today the wavelength spectrum which can be utilised ranges from the ultraviolet to microwave - and the second consists of the three dimensional form of the land surface. The latter is controlled by a complex of related factors, of which the main ones are the lithology of the bedrock, its structural and metamorphic history, the type and intensity of processes of disintegration, both chemical and physical, and the rate and manner in which the products of the disintegration process are removed, transported and deposited. In many parts of the world, recent changes in the weathering, erosional and depositional patterns must be recognised and allowed for. The importance of differential erosion to the interpreter can hardly be overestimated, since the etching out of lithological types, planar and linear discontinuities is a major source of interpretation information.

Lithological interpretation is concerned mainly with those elements which reveal the character of the rock-type, i.e. the tonal characteristics of the rock itself and the soil developed on it, aided (or obscured) by the type and amount of natural vegetation present. Structural interpretation although depending to a large extent on the recognition of lithological contacts, is more concerned with the three-dimensional arrangement of rock bodies, planes and lines, for which a stereoscopic view is indispensable if the maximum amount of information is to be obtained.

The question of the scale of image in relation to the scale of the structure is also important (e.g. Hemphill, 1958). Until recently the normal scale range for regional air photo surveys was 1:20 000 to 1:40 000, which gave, on a single stereomodel, a coverage of 20-50 km^2, and on which individual folds of 100-200m wavelength can be seen and detailed joint pattern studies made. With the development of super wide angle lenses, scales of 1:60 000 to 1:80 000 have become common, with corresponding decrease in detail and increase in aerial coverage. The extreme case is represented by satellite imagery, where scales of 1:500 000 and smaller are the norm, and which are only suitable for study of the largest scale structures: however, because of their large coverage these may reveal features not readily detectable on larger scales, and are also convenient for studies of the broad-scale distribution and orientation of structures.

Structural studies may be defined as those concerned with the location, orientation, style and history of folding and fracturing, but it is unusual for any study to be concerned only with structure, except in some dealing with fractures and others with evaluating methods. Thus a history of structural studies would cover much of the same ground as a history of regional studies, and since this is already well-covered in the literature (e.g. Colwell, 1960; Greenwood, 1964; Miller, 1968; Mekel, 1974) it will not be dealt with in detail here. It is necessary, however, to mention a number of publications of special significance to structural interpretation.

One of the fundamental properties of a structural plane, whether bedding, foliation, fault and joint, is its orientation, and much attention has been given to the measurement of dip and strike in a stereomodel. Strike is easy to determine since the orientation of the photograph is usually known to within fairly close limits. Dip can be measured with a parallax bar, by finding the height difference between two points along the line of dip, or by finding the height differences between any three points on a dipping surface. Both methods require some skill with a parallax bar, are fairly laborious, and depend on the presence of a well-exposed dip slope or marker bed crossing a pronounced hill or valley, and hence are not generally used where the intention is to follow photo-interpretation with fieldwork -

dips can be measured much more conveniently in the field. Dips can be estimated in the stereomodel with a fair degree of accuracy given a little practise, but these values, or photo-dips, are not the same as the true dip because of vertical exaggeration. Since this is the ratio of vertical to horizontal scale in the subjective stereomodel, it is not easy to measure: various formulae have been proposed, but as Mekel, Savage and Zorn (1970) show in their review, none is really satisfactory, and they recommend that for each block of photographs, where conditions are constant (e.g. focal length, photo base, image separation) a number of points should be chosen and the estimated dip compared with that obtained by the parallax bar. This will give an average value for vertical exaggeration, which can be applied to all subsequent dip estimates. A simple dipmeter with conversion scales was evolved by them, and results are claimed to be accurate to within a few degrees. Van der Bent (1969) uses a formula by Fichter (1954) to construct a set of wedges representing 5° ranges of dips, which are photographed stereoscopically and the small prints set beside the dip slope to be estimated. He obtained good results in a test. For rapid reconnaissance studies such as the present one, sufficient accuracy is given by classifying dips into broad groups: all true dips of more than about 50° appear near vertical, and these therefore form a "steeply dipping" group; dips below 50° can be subdivided into those which appear to be greater than about 25° and those less than about 25°, called respectively "moderately dipping" and "shallow dipping". These groups can be signified easily on the map by using one, two or three ticks on the symbol with increasing dip.

Another technique involving the measurement or estimation of dip is that of structure contouring. This was developed as a prospecting tool in the oil-producing areas of North America, and involves the use of either elementary photogrammetric techniques (Desjardins, 1950) or a high-order plotter (Shearer, 1957). A related technique is the drawing of isopach maps from aerial photographs using a Kelsh plotter to detect uraniferous channel deposits (Wittkind et al, 1960). If the tracing table of the plotter can be connected to an analogue recorder and digitiser, dips and strikes can be calculated by computer from coordinates of points recorded while tracing the outcrop across the topography (Jackson, 1967).

The application of photogeology to modern methods of structural analysis is rare, but the work of Stephens (1969) is a good example: he studied two small areas in Malawi and Tanzania, measuring dips by means of a slope comparator and conversion chart on a grid system which yielded 80-90 measurements per photo. In the Malawi area, six sub-domains of foliation were then distinguished by eye, and β and π diagrams constructed (Ramsay, 1967). From these he was able to conclude that an original homogeneous set of folds had been affected by a second phase which had affected both the axes and the axial planes of the earlier folds. In the Tanzanian area six domains were again selected, and again it could be demonstrated that the earlier axial planes had been rotated around the later axes.

Even where there are more than two phases of folding involved, it may be possible to disentangle the resulting complex outcrop pattern provided that exposures are good. In Namaqualand (Newton and Joubert, 1973, and Section 3.2.2., this thesis) four successive sets of folds can be distinguished, mainly on the basis of trend, style and mutual relationships. In Greece, Bodechtel and Papadeas (1968) were able to distinguish three phases of folding in metamorphic rocks, and also three ages of faulting from their relationships to each other and to the folding.

In other regions where the superimposition of folding episodes, and related transposition of foliation is more complete, it may be possible to identify areas where a particular fold style and trend is dominant: this led Hepworth (1967) to develop the concept of "photogeological tectonic domains", which "refer to an area in which, as far as can be established by primary photogeological methods, structures formed during a particular tectonism are dominant" (op.cit. p.254). They are characterised by "the attitude of the regional fold axes; trend of the regional strike; lithology and metamorphic grade; structural or tectonic style; tectonic sequence" (op.cit. p.255). He applied this concept to the Karamoja area, Uganda, and to avoid any possible confusion with existing geological nomenclature he called them simply A, B and C. Domain A is gneissic and E-W trending, including granite dykes, strike ridges, fractures and foliation. B, the dominant tectonism, is N-S, with a strong axial plane foliation and prominent cross-jointing. It is later than A, and overprints it locally. The C domain is characterised by close-spaced NW-trending planar structures with near-vertical dips, and are essentially shear zones. In places, C overprints B. Thus not only the distinctive trends and styles, but also the age relationships emerged from the photogeological study, and Hepworth suggests that the concept of tectonic domains is one which is highly suitable for preliminary elucidation of old orogenic belts. The work was later extended over much wider areas on a reconnaissance level, with locally more detailed studies (Hepworth and Kennerly, 1970).

Some of the most prominent features on air photos are the straight or gently curved alignments of topography, vegetation, tonal boundaries and stream courses which mark the trace of rock fractures on the earth's surface. They may represent anything from relatively minor joints to major fault-zones, but unless displacement can be proved it is best to classify them as only fractures. The literature in this field is considerable: comparisons between linear features on air photos and joint sets mapped on the ground usually show close similarity (e.g. Lattman, 1958; Boyer and McQueen, 1964), although in some cases some joints are mapped which cannot be seen on the photos (Brown, 1961), and exceptionally, a trend on the photos corresponds to no major set of fractures on the ground (Lattman and Nickelsen, 1958). An increase in the density of fracture traces in the vicinity of faulted zones was found by Henderson (1960) who measured 3,500 fracture traces in the Mpande area of Tanzania, concluding that some preferred trends were probably related to the directions of Rift faulting. He also found similar patterns in both Bukoban and pre-Bukoban rocks, i.e. the fractures are either post-Bukoban or old basement fractures which were rejuvenated. Renner (1968), working in the eastern Monsech area of Spain, found that in places the fractures related to the main N-S Pyrenean deformation, while elsewhere they were due to a major sinistral wrench fault. A method for using fracture trace data to calculate the three-dimensional parameters of fold structures, originally developed by Permyakov (1949), is discussed by Huntingdon (1969). The basis of the method is a rose-diagram of fracture traces taken from photographs or maps. From this, a parallelogram is constructed from a formula derived by vector analysis, and from measurements on the parallelogram such dimensions as the length and width of the fold and lengths of the limbs can be derived using further formulae. The method is applied to four fold structures from different parts of the world, and a fair measure of agreement between calculated and actual dimensions is demonstrated. Huntingdon emphasizes that considerable further verification and study are required, and that results should be interpreted with caution, but he is confident that the techniques can be applied in the great majority of cases.

It is a common experience that fracture traces are sometimes visible even in heavily forested or jungle-covered areas, presumably because changes in soil moisture content affect the growth of the vegetation, but it is more difficult to explain the presence of visible fracture traces where bedrock is overlain by a considerable thickness of residual or transported overburden. Wobber (1967) reported their presence in glacial soils 50m. thick, and Blanchet (1957) found many similar examples. A thorough study comprising photogeology and fieldwork is that of Norman (1968B): he used mainly coastal regions so that bedrock features exposed on the coast could be correlated with linear features under superficial cover inland. All linear features were included, and of these the proportion of straight lineaments caused by joints and faults was only 30%. The most common other causes were soil boundaries, landslide traces and bedding structures. Of the curvilinear lineations, only 18% were due to faults and joints, while nearly 44% were due to soil boundaries and lithological contacts. The influence of depth of cover on the clarity with which faults could be seen was investigated and found to be negligible, even where the cover was over 50m. deep. Even where the cover consisted of transported rather than residual material, the visibility of the faults was not strongly reduced. These results clearly imply some form of upward propagation of fractures from bedrock through the soil cover, and this may be due to continuous or rhythmic stresses induced by rotation of the earth and earth tides (Blanchet, 1957). Finally a new method of analysing fracture traces using holography is described by Pincus and Dobrin (1966). A transparency of an air photo is made and illuminated by laser light, producing a diffractogram, i.e. each linear element is represented by a pair of dots, so that the diffractogram consists of a dot cluster, which is in effect a kind of rose diagram on which maxima can be seen. By a filtering process, any direction may be removed to study the remainder, and this could be used for example to remove extraneous linear elements, or the regional part of the pattern for easier study of the local part. An example of a well-jointed sandstone is given.

A final aspect which must be considered is the suitability of the various types of imagery for structural studies. The basic tool for most photogeologists has been, and will continue for some time to be, the normal black-and-white print: it is cheap, easily handled and duplicated, easily annotated, and can provide abundant detail. Enlargements and mosaics are relatively cheap and easy to make, and it can be used in the field as well as in the laboratory. It therefore forms the standard against which other imagery types may be judged. Normally, such photography is taken within about two hours of noon so that shadow areas are minimised: in hilly terrain this is clearly essential, but where the topography is gentle there may be great advantages in photographing while the sun angle is low. Hackman (1967) suggested that photography flown at times when the sun elevation is only $20-30^{\circ}$ could show advantages due to accentuation of mild topographic differences by shadowing and this was shown in practise by Howard and Mercado (1970) and Slemmons (1969). Limitations to this technique are that photography is limited to short periods of the day, and the direction of illumination may not be favourably oriented with respect to the trend of the structures.

Colour photography is becoming increasingly available in many parts of the world. It comes in two forms - the reversal transparency and the print from a negative, and their respective advantages and disadvantages are

i) the transparency shows greater detail and more subtle differentiation of colours, but has a lower exposure latitude, is difficult to annotate and expensive to copy. Since one is therefore usually using the original film, special precautions have to be taken to avoid loss or damage, and these restrict its use - in the field, for example.

ii) the colour negative has a wider exposure latitude and any number of prints can be taken from it: these are expensive, however, and often difficult to annotate (but easier than transparencies). Some control of the final product is possible at the printing stage.

iii) in comparison with black-and-white, the main advantage of colour is in the vastly greater range of colours which the human eye can differentiate compared to the number of grey tones: according to Anderson (1964), a factor of 10^3 is involved. This means that in theory more rock units should be discernible. Thus the main advantage is probably in lithological mapping, although there will often be a benefit in structural work due to better outlining of folds, etc. It must be noted, though, that much of the additional information on colour photos is non-geological in origin and hence may be actually distracting to the interpreter. The writer's experience is that although much more geological information is <u>easily</u> seen on colour photos, most of it is actually present on equivalent black-and-white but is more subtly expressed and only noticed by an experienced interpreter. There is, however, usually a small residue of information not present at all on black-and-white, as would be expected.

Newton (1974A) found that in the semi-arid terrain of Witvlei, S.W. Africa, the value of colour photography varied with the time-lag since the last rainfall: photos taken soon after rain showed maximum information and were to be preferred to panchromatic, whereas once the soil and vegetation had dried out the colour range was very limited and the information content less than with panchromatic black-and-white prints.

Finally, as regards cost, it should be noted that in many cases, the extra cost of the colour film is a very small percentage of the total cost of photography, and that savings on print costs can be made by (i) printing in black-and-white only except where colour is particularly advantageous and (ii) using stereopairs consisting of one colour and one black-and-white print, which often does not degrade the colours too seriously and eases the annotation problem since this can be done on the black-and-white print.

Near-infra-red radiation can be recorded on special black-and-white film or special colour film. The latter is called "false-colour/IR" and the three layers of the film are sensitised to green, red and infrared, and a minus-blue filter is used. Thus on the resulting transparency, green is recorded as blue, red as green, and infrared as red. The predominant source of infra-red is that reflected from vegetation, and hence the main advantage in geology is where there is a close correlation between vegetation and rock type. There seems to be little advantage over colour for structural interpretation, although Paarma and Talvitie (in Smith, 1968, p.431) found that lakes and bogs which were controlled by fracture directions showed up particularly well on this type of image. Annotation is a particular problem with false colour, as it is available only in transparency form. It is also difficult to process, has a low exposure latitude, and is liable to deterioration if not carefully stored before use. It has excellent haze-penetration properties, however, since it is used with a minus-blue filter.

Black-and-white infrared photography has not found much application in geology, but Fischer (1963) found that he could detect streaks colinear with fold axes in adjacent areas and interpreted this as due to thinner soil cover over anticlinal axes, resulting in less grass and hence lower IR reflectance. In S.W. Africa, Newton (1974) found that the vegetation became dessicated soon after rain, so that black-and-white IR shows only slight differences to panchromatic film, and suggested that in areas where the ground is light-toned, vegetation alignments on IR would be less distinct than on panchromatic, since the vegetation would also show light tones.

Multiband photography comprises a number of techniques aimed at producing several negatives, each registering a selected part of the visible and near-IR spectrum. These can be viewed separately or made into transparencies which when placed in a special viewer with variable light sources and filters, form a synthetic image showing true colour or a variety of false colour effects. The main object is to enhance the contrast between the "target" information and the "background" to a maximum, and could be useful in structural work by outlining fold structures or enhancing tonal contrasts across faults.

Thermal Infrared is that part of the spectrum lying beyond about 1.5 µm wavelength, and which therefore cannot be recorded photographically. Instead, a line-scanning device is used and the incoming radiation is focussed onto a photo-detector: the resulting electrical output is used to modulate a light source which synchronously scans a photographic film, building up an image which is a representation of the IR emitted from the ground. The IR windows at 3-5µm and 8-13µm are utilised, and flights are made just pre-dawn to minimise insolation effects. Good accounts of the basic principles can be found in Jones (1970) and Matsumo, Hase and Nishimura (1969). Disadvantages of the continuous strip imagery produced are (i) susceptibility to yaw, pitch and roll of the aircraft, (ii) change of scale across the strip, and (iii) lack of stereoscopy. The main application to structural geology lies in the detection of faulting, usually due to groundwater-controlled temperature effects (Sabins, 1967; Strangway and Holmer, 1966; Wallace and Moxham, 1967), but the structure of volcanoes can also be investigated by associated thermal effects (Fischer et al, 1964).

Radar is the only image-producing "active" sensor, i.e. where the source of the radiation is in the instrument package. A pulsed-energy linescan technique is employed to produce a continuous-strip image with similar disadvantages as thermal IR (unless a ground-range presentation is available) except that by flying each strip twice from different sides or at different altitudes, it is possible to produce stereoscopic coverage. It is also possible to obtain a pseudoscopic effect by using the normal and crosspolarised images if these are both recorded (Newton, 1973A). The image quality is low compared to aerial photography. The main advantage in radar lies in its all-weather and night-time capability, and applications so far have mainly been in areas where aerial photography is difficult, such as Panama (Vicksne, Liston and Sapp, 1969; MacDonald, 1969). Structural applications have so far been mainly in the field of lineament analysis (e.g. Kirk, 1970) for which radar is particularly suited because of its small scale, suppression of much irrelevant detail, and strong shadowing (similar to low-sun-angle photography, but with radar the direction of "illumination" is under the operator's control). A major disadvantage is that lineaments perpendicular to the flight line are poorly recorded, thus probably biassing the results. The only remedy is to fly each area at least twice, and preferably four times, giving four orthogonal "look-directions" (MacDonald, 1969). Also to be guarded against are pseudolinears of cultural origin, some of which may give very strong reflections, such as power lines and lines of trees (Wise, 1967). On the credit side, radar can give some penetration of vegetation in the longer wavebands.

Of rapidly increasing importance and availability are the various types of imagery taken from orbital altitudes: these range from the hand-held camera shots of the Gemini and Apollo programmes to the multiband sensors of ERTS (now LANDSAT) and SKYLAB. Imagery has so far been confined to the visible spectrum and near IR, but LANDSAT 3 will have a Thermal IR sensor. Early studies (Hemphill and Danilchick, 1968; Van der Meer Mohr, 1969) showed the potential for recognising both lithological units and structures, while the suitability of orbital photos for fracture analysis was shown by Lowman (1969) and Abdel-Gawad (1969). Stereo pairs or strips were not usually obtained except on an experimental basis. The linescan imagery of the LANDSAT series does not have the definition of comparable photographs, but it does have the advantage of complete coverage in many parts of the world and of being multispectral: four bands which can be combined into a false-colour IR image. Viljoen et al (1975) describe a number of examples showing the amount of structural information (some of it new) that can be obtained from LANDSAT imagery in its composite form, and how it can be mosaiced to provide coverage of areas of almost subcontinental scale. There is no doubt that satellite imagery contributes usefully to mega-tectonics and throws regional relationships into relief, but its main contribution is in relatively poorly known areas.

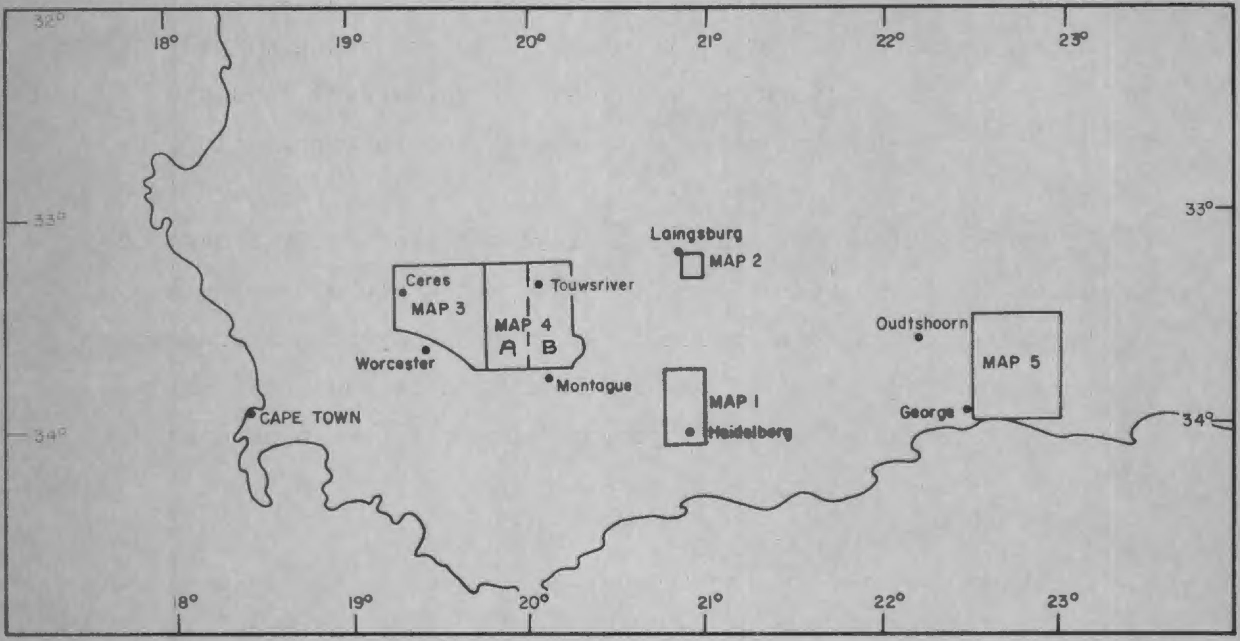


Fig. 1 Areas covered by photo-interpretation maps

3. APPLICATIONS

3.1 The Cape Fold Belt

The areas chosen for study are as follows (see Fig. 1):

1. The Heidelberg-Warmwaterberg area. This was chosen as a fairly typical area of Table Mountain Group and Bokkeveld folding, and because all existing maps show a gap in the continuity of the Worcester fault. It was desired to investigate this, and also the structure and relationships of the Cretaceous outlier. It was subsequently found that part of the area was being mapped in detail by an M.Sc. student of Stellenbosch University, and thus field data would be available for checking the interpretation.

2. The Laingsburg area. This is an area used for student mapping exercises at the University of Cape Town and hence was well-known to the writer. It is a structurally interesting area almost on the northern flank of the Cape Fold Belt, and it was intended to make comparative studies of different imagery types in an area where the geology was known in some detail.

3. The Ceres-Worcester-Touws River-Montagu area contains the important "syntaxis" of the Cape Fold Belt and was expected to throw light on the behaviour of rocks in this area and their relationships to the more general E-W trend of the Cape structures. It was subsequently found that much of the area had recently been mapped on 1:50 000 by the Geological Survey, and thus abundant field data was available for checking the interpretation.

4. The Outeniqua-Kammanassie area comprises the southern part of the "corridor" through the Cape Fold Belt chosen for detailed study as a contribution to the national Geodynamics project. Besides forming a basis for later fieldwork, it was felt that the area had inherent interest and was also an example of interpreting an area where no geological maps on a scale larger than 1:1 million were available.

The method of study was the same for all areas: the central parts only of each photograph were annotated, and as each strip was completed it was compared to adjacent strips and any geological mismatches were investigated and resolved. The geological information was transferred to 1:50 000 topo sheets by sketchmaster. The final map was drawn as an overlay to these sheets.

In the following descriptions the emphasis is on structure, but some discussion of lithology is inevitable as it is sometimes directly relevant to structural interpretation.

3.1.1. The Heidelberg area (Map 1)

The distribution of the main rock types is similar to that on the official map (Cape Geol. Comm. Sheet 2, 1907), with additional information falling under the following headings:

i) more detailed stratigraphy following tracing of marker beds in Table Mountain Group, Bokkeveld and Cretaceous.

ii) delineation of the complex pattern traced by the Worcester and associated faults.

iii) elucidation of the detailed structure pattern within the major folds, and plotting of fracture traces.

iv) delineation of remnants of erosion surfaces.

Lithology and stratigraphy

With such different lithologies as the Table Mountain Group and Bokkeveld, few problems were anticipated in distinguishing these on air photos. The Table Mountain Group forms high ground with poor soils and vegetation, is light-toned in outcrop, well-jointed, and dissected into steep gorges and cliffs. The Bokkeveld forms low ground, has well developed soils on shales (±80% of the sequence) and is consequently highly cultivated. It shows dark tones in outcrop and has rolling topography interrupted by asymmetric ridges where sandstones crop out. It was found that the Cedarberg Formation of the Table Mountain Group was easily identifiable, forming a smooth slope of dark tone and being less resistant than the surrounding quartzites, and tracing this meant that the Group could be subdivided into three - Peninsula Formation, Cedarberg and Pakhuis Formations (not separable) and Nardouw Formation. It became apparent that only the

Nardouw Formation is present in the Warmwaterberg in the north and the Ertjiesvleiberg in the south. le Roux (1974) mapped the Nardouw Formation also on the south flank of the Langeberg, without mentioning the criteria he used to recognise it, and since it is very similar in appearance to the Peninsula Formation, its presence could not be confirmed. It was found possible in the Warmwaterberg to distinguish a more readily eroded zone near the top of the Nardouw Formation. This does not appear to have been recognised or mapped before, but subsequent photo interpretation showed it to be widely traceable in the south-western Cape, therefore although unnamed and undescribed it forms a useful marker.

In the Bokkeveld rocks north of the Langeberg it was found that six sandstone bands could be mapped, thanks to differential erosion of the open, gently plunging folds. In the field, le Roux actually found seven bands, his lowest one not being easily seen on photos. It is now well-known, of course, that the old picture of four sandstones and five shales is oversimplified, and the true picture is much more complex (e.g. Rust, 1973 p.247-276).

Normally, one would expect to be able to differentiate Bokkeveld and Cretaceous easily, but in the Heidelberg area this is not always the case. The surface here approximates to an old erosion level, of probable Tertiary age, dissected but with extensive level interfluves, and sloping gently south. In places low hills rise above the general level, and some of these consist of Cretaceous rocks, especially near Heidelberg. The old surface is often deeply weathered, as is much of the Cretaceous, and cultivation is often intensive, so that rock type differences tend to be obscured. This is probably a case in which colour photography would be helpful, because of the distinctive reddish and yellowish hues of the Cretaceous soils, but was not available. In the event, a few guidelines emerged:

i) the Cretaceous hills showed bedding traces which though mainly discontinuous, in aggregate defined the trend of the bedding over part of the outcrop.

ii) a distinctive horizon high up in the succession outlined the gentle synclinal nature of the structure (not previously described).

iii) the general trend of the contact as given on the Cape Geol.

> Commission map. However, no Cretaceous was shown north of the line of the Worcester fault on this map, whereas this was inferred from the photographs and confirmed on the ground by le Roux.

On le Roux's map the Cretaceous is shown resting with unconformable contact on the Bokkeveld south of the Ertjiesvleiberg; however, the Cretaceous marker horizon referred to above shows that a large part of the sequence is missing here, and hence a fault contact must be inferred, presumably a subsidiary of the Worcester fault. Part of the western contact is also probably faulted: this was not clear from the photos, but fieldwork by the writer showed that the contact runs almost at right angles to strike, and therefore a fault can be inferred here also.

The Worcester Fault

The Worcester fault problem was solved satisfactorily, but only after some initial problems. For example, normally the contact between Table Mountain Group and Bokkeveld or Cretaceous is easy to define due to lithological and structural differences, but in heavily forested terrain these differences are minimised and unless there is a great topographic difference, criteria are few. This is the case in the Grootvadersbos plantation area WNW of Heidelberg, where interpretation was difficult and tentative, eventually resulting in the plotting of a series of bounding faults both parallel and perpendicular to the Worcester fault. It was found that this fault system should be continued along the north side of the Duivenhoks River valley: at first this appeared to be a normal contact, but dips in the Bokkeveld showed a syncline whose axis was so near the northern contact that some of the succession must be cut out, and a strike fault could therefore be inferred. In the field, le Roux confirmed the presence of this fault, calling it the Tradouw Fault.

Whether there is a direct continuation of the Worcester fault is more dubious, in that there is very little photo evidence. As discussed above, Bokkeveld and Cretaceous can be very difficult to distinguish, and soil and agriculture obscure structural evidence. Bedding traces are, however, more common in the Cretaceous than in Bokkeveld, and when all such traces are plotted only a narrow zone is left through which the fault could pass without some visible displacement. This zone lines up with the roughly E-W segment of the course of the West Duivenhoks river, and thence with the

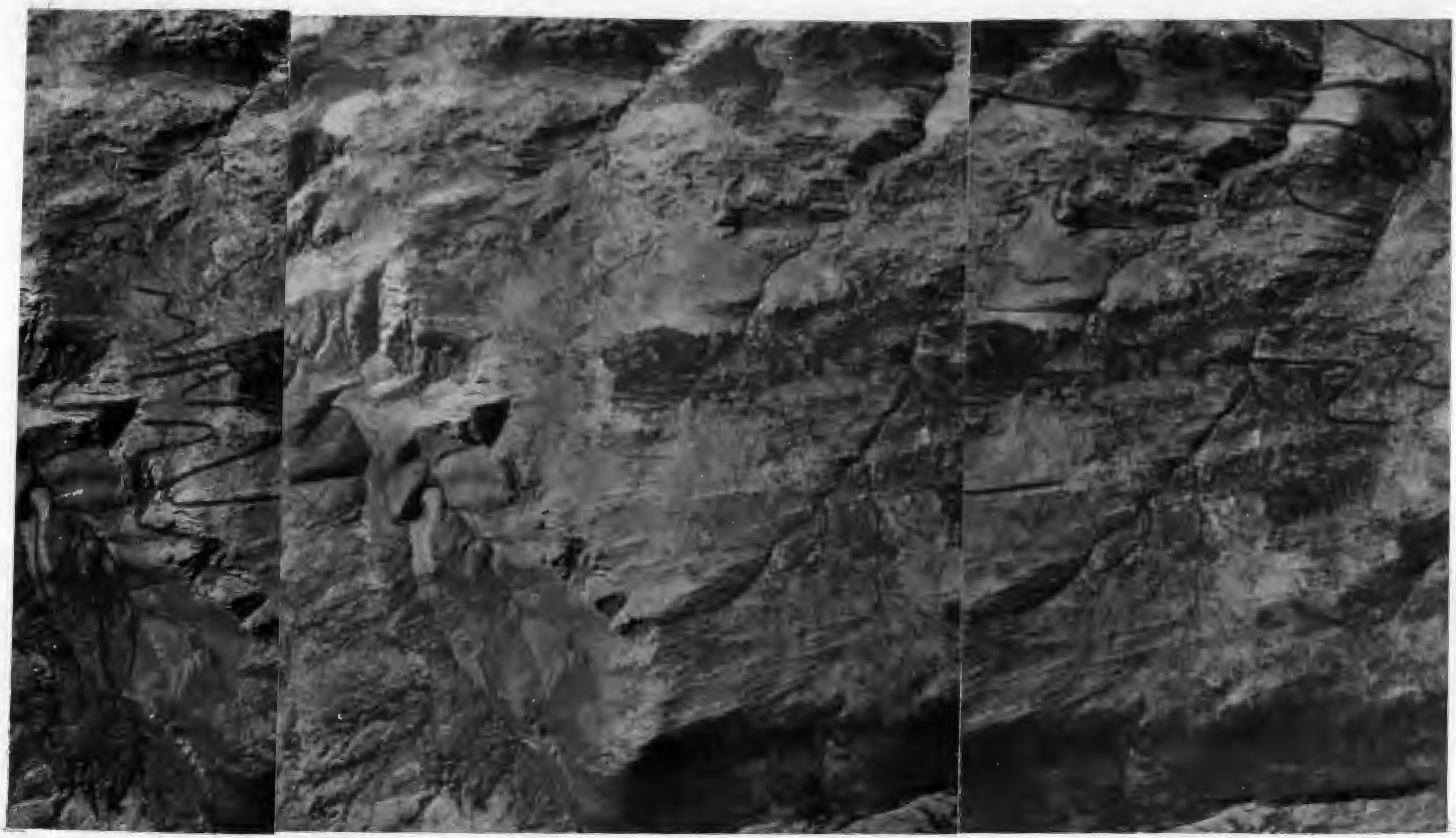


Plate 1 Disharmonic folds in the Table Mountain Group north of Heidelberg

known extension of the fault on the south side of the Ertjiesvleiberg, so a tentative line for the fault can be plotted. On le Roux's map, the Worcester fault is terminated at the western side of the Cretaceous outcrop. If this was intentional, it implies that this segment was inactive in post-Cretaceous times. However, he shows the Tradouw fault as having affected the Cretaceous and he interprets the Worcester fault as being contemporaneous or later than this. One of these alternatives must be wrong, and the preferred explanation is that the Worcester fault does cut the Cretaceous, although the line is obscure.

The Tradouw Fault is unusual in that it is shallow-dipping; on the photos it appears to be parallel to bedding, and this is confirmed by le Roux. He suggests that it may have been a thrust originally, with movement reversed at a later date.

Folding and Faulting

Fold axial traces are shown on the map, and plunge directions inferred from dips and closures. Faults were identified by linear traces and displacements, and strike faults by omission of strata: faults are sometimes marked by quartz veining.

In the Nardouw Formation, a large number of minor folds are present: they are usually fairly open, short, en echelon folds with only locally consistent plunges. They die out downwards so that the Cedarberg Formation is unaffected, and die out much more suddenly at the Bokkeveld contact (Plate 1). In many cases this folding is on too small a scale to be plotted at 1:50 000, and is represented on the map by an undulating dip arrow. The Peninsula Formation shows very much less of this small scale folding. South-dipping axial planes are fairly common, but overturning can rarely be seen. Fold trends vary slightly, from 070^{o} to 090^{o}.

In the Bokkeveld rocks, folds are more open and symmetric: they are only well seen north of the Langeberg. Plunges are very gentle and mainly eastward.

The major faults have been discussed above: apart from these there is the tentative fault mapped along the northern side of the Langeberg, which was postulated mainly on the evidence of the lowest Bokkeveld sandstone, which seemed to abut against the Table Mountain Group in places. The evidence was poor, though, and le Roux was able to show that the contact was normal.

The fault in the Warmwaterberg shown on the Cape Geol. Comm. map was easily extended on the combined evidence of negative weathering and silicification. It seems to die out rapidly within the Bokkeveld.

A feature which may represent a strike fault is present in the eastern part of the Langeberg, about 2km north of the Cedarberg Formation outcrop. It can be traced for nearly 10km E-W; in the east it marks the foot of a slope, and in places is shown by vegetation alignments also. In the west it follows a stream valley. It does not appear on le Roux's map.

Joints are visible only in the Table Mountain Group: the main feature is a strong trend perpendicular to strike. Some streams possibly controlled by master joints, have straight segments up to 2-3km long, on which there is no evidence of movement. On exposed dip surfaces, strike joints are also common.

Overall deformation pattern

The main fold axial trend is just north of east; there is some arcuation on the northern side of the Langeberg - trends become E-W in the east and are oblique to the Bokkeveld contact, which runs ESE here. In the Warmwaterberg and the northern Bokkeveld, plunges are consistently gentle and eastward. In the Langeberg, plunges are predominantly eastward in the east, but more variable in the centre and west. The Ertjiesvleiberg rocks plunge west, as does the Bokkeveld syncline to the north. Axial planes are generally near vertical, sometimes dipping steeply south. Visible overturning is rare. Minor folding is most intensely developed in the Nardouw Formation, not visible in the Cedarberg Formation, and is less well developed in the Peninsula Formation. Folds in the Bokkeveld are mild, but because of the shallow plunge have considerable effect on outcrop form. The reason for the high intensity of folding in the Nardouw Formation is not clear, but may be due to its being more thinly bedded than the Peninsula Formation, with shaly bands, and that it is sandwiched between two incompetent horizons, namely the Cedarberg Formation and the lowest Bokkeveld shales, and was able to deform to some extent independently.

The major faulting is south of the Langeberg and consists of the steeply dipping Worcester fault downthrowing to the south, with a final movement

Plate 2   Dome in Dwyka rocks, Laingsburg Area

in post-Cretaceous time, and the Tradouw fault just to the north, which is a bedding fault in the east but near-vertical in the west, and is probably more or less contemporaneous with the Worcester fault. Both major faults are crossed and possibly offset by small N- and NW-trending faults. The main Cretaceous basin has been warped into a gently eastward plunging syncline.

3.1.2. The Laingsburg area (Map 2)

A considerable body of knowledge of the geology of this area has been built up over the years during student mapping exercises, and a brief account of the lithological and structural features of the area and their identification on air photos was given in an earlier paper (Newton, 1966). The stratigraphy is shown in Table 1. To summarise, the comparatively simple geology and semi-arid climate combine to make this an excellent area for photo-interpretation. Even if lithologies cannot be exactly determined, contacts can be drawn with confidence and several good marker horizons are present. The lowest of these is the prominent white quartzite at the top of the main Witteberg quartzite sequence. This can be followed easily along the Witteberg mountains in the south of the area, and defines a large anticlinorium with a steep, often overturned northern limb and much shallower southern limb i.e. an asymmetric fold with south-dipping axial plane.

The overlying Witteberg shales contain another quartzite - the Floriskraal Formation, which is not particularly prominent in the south, but which clearly outlines another anticline further north: again the fold is asymmetric and northward overturning can be seen. The intervening syncline is of course also asymmetric, but is modified in the west by an additional anticline-syncline pair on the south limb. The core of this syncline contains the lowest Ecca beds, the contact with the Dwyka being clearly delineated by the White Band. In the north the Ecca reappears in a much broader, open syncline, again asymmetric with a shallow-dipping north limb. Beaufort beds may be present in the core of this syncline, but since the position of the contact is not yet finally agreed, and since no clear photogeological criteria are present, no attempt has been made to delineate a contact. The plunges of all the major folds are very gentle, easterly. Minor folds on all scales are present, the larger ones being visible on the photos, e.g. the elongated dome in Dwyka tillite just south of the Buffels River (Plate 2), and various small folds in the Ecca and Witteberg.

Faulting and thrusting are both present and visible on the air photos.

TABLE 1

Stratigraphy in the Laingsburg Area

	Photogeological Legend	Standard Stratigraphy		
E5	Mainly shales with some sandstones	Ecca Group		
E4	Massive sandstones with shales			
E3	Shales with some sandstones			
E2	Sandstones with some shales			
E1	Shales and siltstones			
D3	White Band shales	White Band		Dwyka Group
D2	Black shales	Dwyka shales		
D1	Brown weathering shales			
T7	Fine tillite	Dwyka Tillite		
T6	Coarse tillite			
T5	Fine tillite			
T4	Coarse tillite			
T3	Fine tillite			
T2	Coarse tillite			
T1	Fine tillite			
W5	Shales and siltstones	Buffels River shales	Lake Mentz Shale	Witteberg Group
W4	White quartzite and shales	Floriskraal quartzite		
W3	Shales and siltstones	Leeuwkloof Poort shales		
W2	Main White quartzite	Wittepoort quartzite		
W1	Reddish quartzites and shales	Swartruggens formation		

Plate 3 Faulted syncline in Ecca rocks, Laingsburg Area

In the extreme south, duplication of the white Witteberg marker quartzite occurs in the Buffels River gorge, with the plane of separation dipping south only a little more steeply than bedding (Plate 3). In the northern Witteberg anticline a similar situation occurs although it is not so obvious: the anticline appears normal except that while three quartzites can be seen on the southern side, only two are visible on the northern side. Tracing these horizons eastward, the lower and middle quartzites close round the plunge of the anticline, but the upper quartzite is not affected. It continues as a strike ridge for several miles, with no sign of an equivalent quartzite on the north side of the syncline. A thrust or high angle reverse fault is therefore postulated which must be almost parallel to bedding. In the intervening syncline the White Band east of Floriskraal Dam is seen to be duplicated, again by a south-dipping dislocation with movement up the dip of the plane. Along approximately the same line, but west of the Dam, another slight dislocation is present, but here it has the appearance of a normal fault downthrowing to the south. Only three other small normal faults are present, one a strike fault and two trending northeast.

It was intended to use this area as a test area for comparison of colour, false-colour IR, and low-sun-angle photography with the standard black-and-white photographs. The false colour film unfortunately turned out to be faulty, but the results of the other comparisons follow.

Low-sun-angle Photography

This was flown between 0800 and 0845 hours, with a sun altitude varying from 25°-35°. Due to plane and camera limitations, the scale of photography was restricted to 1:25 000, and this makes comparison with the standard 1:36 000 photos rather difficult, since a mental allowance has to be made for scale differences as well as those due to the low sun angle. A further unavoidable disadvantage was that the sun azimuth was only slightly oblique to strike, so that shadows fell almost along the ridges instead of across them, and consequently any subtle relief features were not accentuated. The net result was that over most of the area the low-sun-angle photos show no advantage over the normal ones (apart from those due to the larger scale). Only in the north, in the broad Ecca syncline, were stratigraphic horizons picked out more clearly in fold closures, since here the strike is nearly perpendicular to the direction of illumination, while the differences in relief are small. Another contributory factor is that this was the first strip flown, and hence the angle of incidence of sunlight was a minimum. From this experiment it would appear that for angles of incidence over 30° there is little advantage to be gained, since the terrain appearance is similar to that for higher angles except for slightly longer shadows. It can be concluded that the Laingsburg area is not a suitable one for application of low-sun-angle techniques, since

i) the structural grain is not in a suitable direction

ii) the relief is too great, so that at the appropriate low sun angles the shadows are too long and dense and the sunlit slopes tend to be overexposed

iii) the general angularity of the slope changes is another adverse factor - in gently rolling topography the subtle relief changes would probably show up better.

Colour Photography

As mentioned above, most of the low-sun-angle photography is little different to the normal Government high-angle photography, and it was decided to use the former for comparison with the colour photography since then scale differences were eliminated. The method used for comparison was to make up stereopairs consisting of one colour print and one black-and-white: by closing alternate eyes, it is then possible to make detailed comparisons between the two.

In the Ecca rocks in the north of the area, it was found that the colour differences between adjacent beds were actually <u>less</u> than the total differences on black-and-white. This is contrary to most previously reported experience (e.g. Minard, 1960; Chaves and Schuster, 1968); it is probable that exposure is a contributory factor here, as this strip is slightly over-exposed and the colours consequently slightly faded, but this is not the whole story, since in the adjacent strip the exposure is accurate but the same effect can be detected. The colours involved are shades of brown and buff for the sandstones and greenish grey for the shales, and it is noticeable that the differentiation of sandstone and shale is very good on the correctly exposed colour film, superior in fact to that on black-and-white, but on the over-exposed colour film the differentiation is poorer than on black-and-white. The question remains as to the cause of the poor differentiation within the sandstones on colour film: exposure is clearly a critical factor, but it may be that in addition there is a difference in the spectral sensitivity of the two film types in the region where brown and buff are recorded.

Over the rest of the area it was found that there was little difference in the amount of geological information recorded on the two film types: colour differences are certainly easier to see than tonal differences, but the latter are always present and are fairly obvious.

To summarise then, the advantages of colour photography in the Laingsburg area are minimal: this may be partly due to the small range of colours in the rock and soil types, and to the fact that surface morphology and texture play just as important a role in photographic recognition as tone or colour. Clearly with colour film exposure is very critical: even slight errors in exposure (or processing) may reduce or eliminate any advantage over black-and-white film. As regards annotation, there is no doubt that colour prints are harder to annotate satisfactorily than black-and-white: the prints are glossy, and coloured pencils and inks do not show up well. Annotating on even a semi-matt overlay means an image degradation which more than annuls any advantage the colour film may show. Probably the best method is to use that adopted for this comparison - stereopairs of one colour and one black-and-white print, with annotation being made on the latter in the normal way. The colours, though fainter, still come through clearly, and emphasize the tonal differences of the black-and-white prints.

Summary and Conclusions

The Laingsburg area is well suited to structural interpretation of air photos: exposure is good, there is little vegetation, and rock-types are distinctive, with several good market horizons. A detailed stratigraphic sequence can be assembled, which helps in elucidation of structure. The picture which emerges is that of a series of major anticlines and synclines trending E-W and plunging gently eastward, with asymmetric profiles and axial planes dipping steeply south. The intensity of folding diminishes from south to north across the area. Minor folds are developed which conform to the major structures. Several small thrusts developed on the shallow limbs of folds, the planes of dislocation dipping slightly more steeply than bedding. Normal faulting is minimal. Fieldwork confirmed these findings and showed that the only important structural feature not visible on the photographs was a zone of intense minor folding and cleavage development in the lower part of the Dwyka shales.

In this area, for structural work, low-sun-angle photography has no advantages, and with colour photography, an advantage of ease of interpretation is liable to be nullified by departures from ideal exposure and problems of annotations.

3.1.3. Ceres - Touws River Area (Maps 3 & 4)

Published geological maps covering this area are: Sheet 1, Cape Geological Commission (1906); Sheet 2, Cape Geol. Comm. (1907); Sheet 4, Cape Geol. Comm. (1906); and Sheet 5, Geological Survey (1915), all on a scale of 3.75 miles to 1 inch. Remapping by the Geological Survey on 1:50 000 scale is in an advanced state, and three-quarters of the area has now been covered, but the field sheets are unlikely to be published. In this study, these field sheets were consulted after the photo-interpretation maps had been prepared and a detailed comparison was made.

3.1.3.1. Map 3 is a quarter degree sheet comprising 1:50 000 sheets Ceres, Worcester, De Doorns and Nuy: the total area of Cape Supergroup rocks is a little less than 2 000km^2.

Lithology and Stratigraphy

In the Table Mountain Group, the Peninsula, Cedarberg and Nardouw Formations can be recognised everywhere. The Piekenier, Graafwater and Pakhuis Formations are thin and not distinguishable on air photos. The Peninsula and Nardouw Formations resemble each other very closely, and in many places it is possible to distinguish them only on the basis of their stratigraphic position relative to the Cedarberg Formation. The latter is always identifiable from its weathering and erosional characteristics, described above. A new feature arising from the present study is the possibility of subdividing the Nardouw Formation on the basis of photogeological criteria. It was noticed that towards the top of this unit there was a band which is more susceptible to weathering and erosion than those above and below, with the result that it forms a slightly negative topographic feature: in some places this is quite pronounced, in others very subtle, but it is almost invariably present. It does not resemble the Cedarberg Formation, but clearly consists of sandstones like those above and below. In the field, it is rather difficult to detect, and was not mapped at all by the officers of the Geological Survey in their recent work in the area. The average bed thickness is less than in the sandstones above and below and it may well be this, combined with some subtle lithological difference, which accounts for its distinctive weathering characteristic. It is not proposed at this stage to designate it as a formal stratigraphic unit; this will require an investigation in detail, but it clearly indicates the possibility of subdividing the Nardouw Formation into members. The unit, referred to informally here as the "soft band", is about 50m thick and occurs about 400m below the top of the Nardouw Formation. Correlation with the subdivision of the Nardouw Formation given by Rust (1967) is not entirely clear: he calls the uppermost unit the Rietvlei member - a 300'-600' thick white orthosandstone, with finer grain size and thinner bedding than the underlying quartzite. There are thus two differences compared to the "soft band" - first, the Rietvlei is apparently of uniform lithology, whereas in the "soft band" the bedding thickness and resistance to weathering increase markedly above the basal 50m; second, the base of the Rietvlei is only 100-200m below the Bokkeveld, compared to some 400m for the "soft band". Clearly, more work needs to be done on the subdivision of the Nardouw Formation: as stated by Rust (1967) the present definitions of member boundaries are vague.

Subdivision of the Bokkeveld Group is not easy using photogeological evidence alone, since the individual sandstones are identical in appearance and in structurally complex and poorly exposed areas it may be impossible to identify an individual sandstone: this is the case in the area NE of Ceres, while in the Hex River valley the sandstones are not visible at all west of De Doorns. No attempt was made to plot the intraformational contacts, which are in any case mostly hidden: instead, the trend and dip of the ridge-forming sandstones are indicated, and where possible numbered, on the map.

The contact between the Bokkeveld and Witteberg Groups has always been difficult to define (Theron, 1970) because of its transitional nature, and without using the heavy mineral suite (Rust, 1973) the boundary is somewhat arbitrary. However, Witteberg is only locally present - in the extreme N and NE of the area covered by Map 3, and more detailed discussion is deferred to the description of Map 4 below.

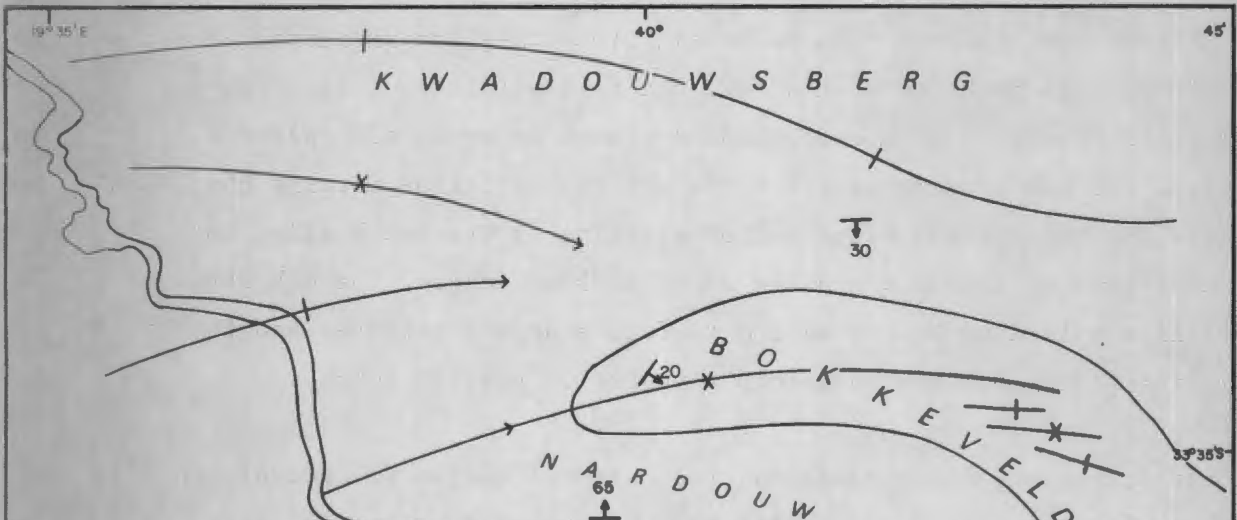


Fig. 2 Relationship between fold axes and trend of major contacts east of Worcester

Structure - Folding

The main feature of the area is the convergence of the northerly Cedarberg fold trend with that of the main easterly trend - the Cape syntaxis. Thus the trend of the fold axes radiates from a point somewhere south of Ceres, from NNW through NE to ESE. A contrast in fold styles is also immediately apparent - in the Table Mountain Group the folds are large and therefore relatively few, while in the Bokkeveld Group they are much smaller and more numerous. In both cases, however, the fold axial trace is often curved, the folds plunge at both ends, and in places an en echelon pattern is evident. The two largest single folds are the anticline forming the Hex River mountains, and the Hex River valley syncline on its south side, both of which extend on to Map 4 and are about 40-50km long. The Hex River mountain anticline splits up at its NE end to form a double closure, and the Hex River syncline widens out eastward into a number of smaller folds.

In the northeast, fold trends and the regional strike are roughly parallel, but as the syntaxis is approached they become oblique to each other, and just east of Ceres the folds are at right-angles to strike. It is noteworthy that the Table Mountain Group/Bokkeveld contact is almost unaffected by the small folds in the latter. In the southeast, a major syncline occurs between the Langeberg and Kwadouwsberg, and it can be seen that the individual fold axes are generally east-west, i.e. oblique to the main trend of the syncline and to the contact between Cape and pre-Cape rocks (Fig. 2). Thus the 1:1 million Geological Survey map, and the LANDSAT imagery, give a false impression of a single large sinuous syncline, which is in fact made up of a number of smaller, oblique folds. The overall southeasterly trend of the Cedarberg Formation is also deflected by these folds, into a series of right-angle bands. The folds die out in the Peninsula Formation, and the basal contact is unaffected by them.

The basal contact has, nevertheless, been affected by other structures, and the photo-interpretation is given in Fig. 2; however, mapping by the Geological Survey has shown that the structures are more complex. Toogood (in press) has described the contact as being isoclinally folded, with axial planes dipping southward. The trend of these folds is parallel to the contact, and at an angle to the E-W folds described above. Because of this difference in both style and trend, it is suggested below (p.46) that they have a different origin, and in fact may be connected to movement on the Worcester fault, which is very close and which makes a sharp change of direction here.

This part of the Langeberg, in the SE corner of Map 3, is the only place where overturning occurs. Elsewhere, axial planes are approximately vertical and dips moderate.

The intense small scale folding in the Nardouw Formation seen in the Heidelberg area is not present here, but in the NE it is involved in the short wavelength folding of the Bokkeveld rocks, whereas in the main outcrop of the Table Mountain Group it reflects only the large scale folding.

Structure - Fractures

It will be immediately apparent from the map how much information on fractures can be obtained from air photos - far more than is usually plotted from a ground survey. The Table Mountain Group is a particularly fruitful unit to study, because of its massive, brittle nature, general lack of too much obscuring soil and vegetation, and presence of vein quartz filling some of the larger fractures. In the highly cultivated Bokkeveld, fractures can normally only be seen by their effect of displacing lithological units, or more rarely by a distinct topographic feature.

The most noticeable feature of the fracture pattern is the very marked WNW trend over the whole area, ranging from joint sets to faults showing displacement. The latter include a series of faults forming an en echelon group trending E-W just north of Ceres, from Groenhof in the west to Bokrivier in the east. These all downthrow to the north except the most easterly one. It is significant that the line of the Ceres earthquake aftershocks also has this trend (Geological Survey Seismological Bulletin No. 4, 1974), which points to the presence of further faults which are not visible on the surface. These faults have an average length of about 15km. A number of other fractures of almost equal length are present, but show little or no displacement. The dip of most fracture planes is very steep, since they show little deflection by topography, but small changes of trend are common, and only the shorter ones could be described as straight.

In the Hex River mountains and Kwadouwsberg, an ENE set of fractures is present: these are generally short and show no displacement.

Of the remaining fractures, three are particularly prominent: the first trends NE from the Hex River valley across the Hex River mountains, and may link up with a fault which displaces the Cedarberg Formation further southwest, in which case its total length would be about 40km. Along most of this great length, however, there is no displacement. This is also the case with the second NE-trending fracture further west, which cuts across the whole outcrop of the Table Mountain Group, but seems to die out rapidly in the underlying Malmesbury and the overlying Bokkeveld. The third fracture intersects the second near its southern termination, and extends NNW about 18km to the Dwars River, and again no displacement can be detected over most of its length.

In summary, it can be said that the fractures show a similar pattern over most of the area, in contrast to the systematic variation shown by the fold trends, and thus it seems likely that the two are not directly related. Further, since displacements are small or lacking, it seems likely that fracturing has contributed only slightly to the overall deformation. Exceptions to this are of course the Worcester fault, just south of the area studied, and the faults of the Groenhof-Bokrivier zone: the latter extend across the adjacent area (Map 4) south of Touws River, and may joint up with the fault south of the Anysberg. This would make them part of the western termination of a major zone of E-W faults of which the Cango fault is the most important member.

Comparison of air photo and field maps

As mentioned above, the 1:50 000 field sheets of the Geological Survey were compared with the photogeological maps, but it was found that this comparison was not always straightforward because of differences in objectives behind the two types of map. The photomaps are largely concerned with structural data, and only the major lithological contacts and marker horizons were plotted: the Survey maps, on the other hand, are primarily lithological, and the amount of structural information is variable: fold axes, for instance, are rarely plotted. However, from the dip and strike symbols and the form of lithological contacts, it was usually possible to determine where fold axes would be.

On the whole, the agreement on the positions of the major contacts was remarkably good, and this is probably a reflection of the considerable lithological differences between the major units. The Bokkeveld/Witteberg contact is the major exception, and here the boundary is rather arbitrary. The "soft band" in the Nardouw Formation had not been mapped by the Survey and this is probably a reflection of how poorly defined it often is on the ground, as compared to its appearance on air photos. Many more fractures are represented on the photo maps, but this may be a matter of field strategy on the part of the Survey, rather than that the fractures are not visible on the ground.

In many cases the differences were connected with faulting; in the northern part of the area the ESE fault and fracture pattern is represented by fewer but more continuous faults on the Survey maps, compared to the shorter, less continuous but more numerous ones on the photo maps. This is probably largely a matter of interpretation, since offsets are small and the visible segments of fractures often short. Whether such segments are joined across areas of no exposure is largely a matter of inference.

In only two cases were folds mapped on the ground but not plotted on the photogeological maps: one is a gentle, doubly-plunging anticline NNE of Ceres (shown in dotted outline on Map 4) and the other is the case of the Malmesbury/Table Mountain Group contact depicted in Fig. 2. In the latter case the relief differences are large, the beds are all steeply dipping and the folds are isoclinal, the three factors combining to make the recognition of these folds impossible on photos, even when it is known that they are there.

A small, infaulted segment of Malmesbury rocks was not identified on the photos on the Dwars River, SW of Ceres.

In summary, the differences between the field and the photo maps, insofar as they recorded similar information, are neither large nor particularly significant; similar differences would probably occur between maps produced by different geologists in the field, or different interpreters in the laboratory. If the photo maps are regarded as a basis for subsequent fieldwork, and this is how they are regarded by the writer, they can clearly save a great deal of field time, and in the case of fractures, probably provide more information.

3.1.3.2. <u>Map 4</u> is comprised of four 1:50 000 sheets, namely Matroosberg, Touws River, Baden and Koo, together with a small portion of the Allemorgens sheet. The total area is about 2 750km^2.

Lithology and Stratigraphy

The area is adjacent to that shown in Map 3, and all the comments regarding the Table Mountain Group and the Bokkeveld Group made above apply also to this area. However, large areas here are underlain by Witteberg rocks and there is also some Karroo, and these deserve some comment.

Witteberg rocks are recognisable on air photos on both lithological and structural grounds: the sequence consists of alternating, thin, whitish quartzites and thick shales forming a large number of fairly small folds: because of this folding, and the similarity between the quartzites, it is difficult to separate one from another or trace any for long distances. Towards the base of the sequence, there is a transition into the Bokkeveld group, the quartzites becoming greyer and the folds larger and more continuous. There is in many places a quartzite which seems to display tectonic characteristics of somewhat intermediate character, and which is traceable for quite long distances: this has been selected somewhat arbitrarily as the boundary, and although it may not always be the same horizon (detailed fieldwork would be required to establish this), it is felt that it is probably close enough to the boundary to be accurate enough for reconnaissance purposes.

At the top of the Witteberg is the Floriskraal quartzite, overlain by shales and followed conformably by the Dwyka tillite (see description of Laingsburg area above). These units are recognisable here in two synclines in the northeastern part of the area. The massive, blocky nature of the Dwyka tillite ridges contrasts strongly with the whitish, bedded Witteberg quartzites, and although the exposure is not as good as in the Laingsburg area, it is possible to draw in the boundary with some confidence. The Floriskraal quartzite forms a sharp anticline separating the two synclines. Stratigraphy within the Dwyka is not too clear, but as at Laingsburg it seems likely that three main tillites are present, forming impersistent ridges, overlain by Dwyka shales, at the top of which is the White Band, present only in the northern syncline, and poorly exposed but marked by whitish scree material. A thin layer of Ecca sediments overlies the White Band and fills the core of this syncline.

Structure - Folding

In this area the structures diverging eastwards from the syntaxis continue to do so, and the fold belt broadens, particularly southward. In addition there is a predominance of easterly plunges, so that higher members of the sequence become more prominent, and the first outliers of Dwyka rocks appear.

In the extreme south is the Langeberg, made up of Table Mountain Group rocks dipping steeply north with, in places, an overturned contact with the underlying Malmesbury Group. In the eastern part of the range, minor folds are strongly developed in the upper part of the Nardouw Formation, strongly resembling those seen in the Heidelberg area (p. 17). They are short and steeply eastward plunging, approximately symmetrical concentric-type folds, although some show asymmetry with steeply southward dipping axial planes. There is strong disharmony between these folds and the overlying Bokkeveld rocks, which appear unaffected. The folding also dies out downwards before the base of the Nardouw Formation is reached.

North of this is the Kooberg syncline, a continuation of one on Map 3, and as in that area, it consists of a series of en echelon fold axes at a slight angle to the trend of the structure as a whole, rather than a single, curving fold axis. Dips on both limbs are moderate, and the axial plane approximately vertical. The plunge reverses so that the structure closes at both ends, but in the east it is merely offset to the south, and then continues in an ESE direction.

The northern flank of this syncline is the southern flank of the next anticline, an extension of the Kwadouwsberg mountains to the west. As can be seen from the map, this is basically a fairly simple anticline in the west, trending SE, though with some flanking folds, but in the east it broadens out into the high massif of the Waboomsberg, where the fold pattern resembles a fist, with the knuckles formed by anticlines plunging eastward, and the thumb by an anticline plunging northeast. Only the Nardouw Formation is present, and structural elucidation is aided by the presence of the "soft band" which forms a prominent marker in most places, although here and there it is obscure. Only in one or two places is there much development of minor folding, and on the whole dips are gentle to moderate, rarely reaching 60°. Synclines of Bokkeveld rocks interdigitate with the anticlines of Table Mountain Group, and in the extreme SE Witteberg rocks appear: these show numerous small open folds trending ENE, and there is clearly some degree of disharmony with the underlying Bokkeveld.

North of the Waboomsberg is the Naugashoogte synclinorium, a large complex

Plate 4 Disharmonic fold in the Bokkeveld Group, south of Matroosberg siding

open fold trending just north of east. Bokkeveld sandstones are widely traceable, and reveal a distinctly disharmonic fold between the first and second sandstones at the western end (Plate 4), where the upper sandstone anticline has been squeezed outwards up the southern flank of the syncline relative to the anticline in the underlying sandstone, which conforms closely to the fold of the Table Mountain Group below. In the second closure, just to the NW, the second sandstone shows a number of minor folds, also not present in the underlying first sandstone.

Witteberg beds come in as this syncline opens out eastward, and their structural style differs considerably from that of the Bokkeveld rocks: fold axes are short (2-4km) and amplitudes small; axial planes are usually near vertical, but some dip steeply north and others south: in a few places limbs are slightly overturned. The synclinorium widens eastward mainly by the addition of further folds on the southern side, so that as the fold axes trend roughly ENE, the southern contact with the Bokkeveld is continually displaced southward, in the same way as the Cedarberg Formation in the SE of the Ceres area. This process is shown diagrammatically in Fig. 3.

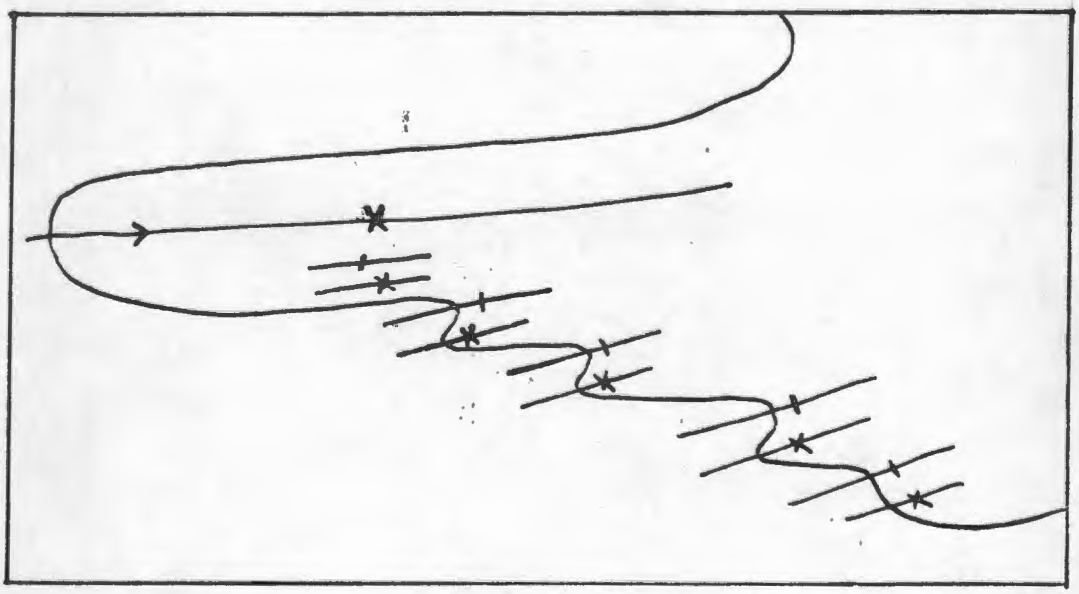


Fig. 3. The Nougashoogte Synclinorium

The Nardouw Formation is brought to the surface in three places north of the Nougashoogte syncline, twice by faulting and once by folding. These can together be regarded as a structural "high" separating the Nougashoogte

Plate 5 Folding in Witteberg rocks southeast of Touws River; shale squeezed out from between two sandstones

synclinorium from another complex synclinorium around Matroosberg siding, this being the extension of the Hex River valley syncline. The latter, which was trending NE on the eastern edge of Map 3, swings to E-W as it passes north of Matroosberg, and like the Nougashoogte structure, widens by addition of further axes on its southern side. These folds vary in trend from ENE to ESE, and form an almost anastomosing pattern, with folds bifurcating in several cases. The plunges of these folds show frequent reversals, but as the amounts are small this fact probably has little structural significance. Dips are gentle to moderate, and axial planes vertical.

The Matroosberg synclinorium passes north into a faulted anticline which is a spur of the Hex River mountains anticline. It too plunges eastward, and the main fold axis is on the downthrown northern side of the fault, so that dips in the Nardouw Formation are southward or eastward.

North of the fault, the Bokkeveld is hardly ever exposed, but the Witteberg is strongly folded. It forms the hills to north and south of Verkeerdevlei, which occupies an eroded anticline in Bokkeveld rocks. Fold axial trends are generally ENE and rather more continuous than those described above. Plunges are generally easterly, towards the two synclinal basins east of Touws River which contain Karroo rocks. These are both broad open structures, but the southern one is very asymmetric, with the axial plane trace very close to the southern limb, which is steep. Separating these synclines is a tight anticline in Floriskraal quartzite, with an axial plane which is vertical in the east but becomes north-dipping as traced westward. To the south of these structures the Witteberg again shows typical folding on short anastomosing axes. An unusual feature is that in one fold the shale has been squeezed out completely from between two sandstones, which are in contact as a result (Plate 5). Further south is an example of disharmonic folding also due to mobility in the shales (Plate 6).

Structure - Fractures

The most important fault in the area is that south of Touws River: in the west it has a considerable downthrow to the north (bringing Witteberg rocks against Table Mountain Group) and is one of the few large faults with this sense of movement in the Cape Fold Belt. It is itself displaced by a small later fault with a southerly downthrow. Traced eastwards its continuation

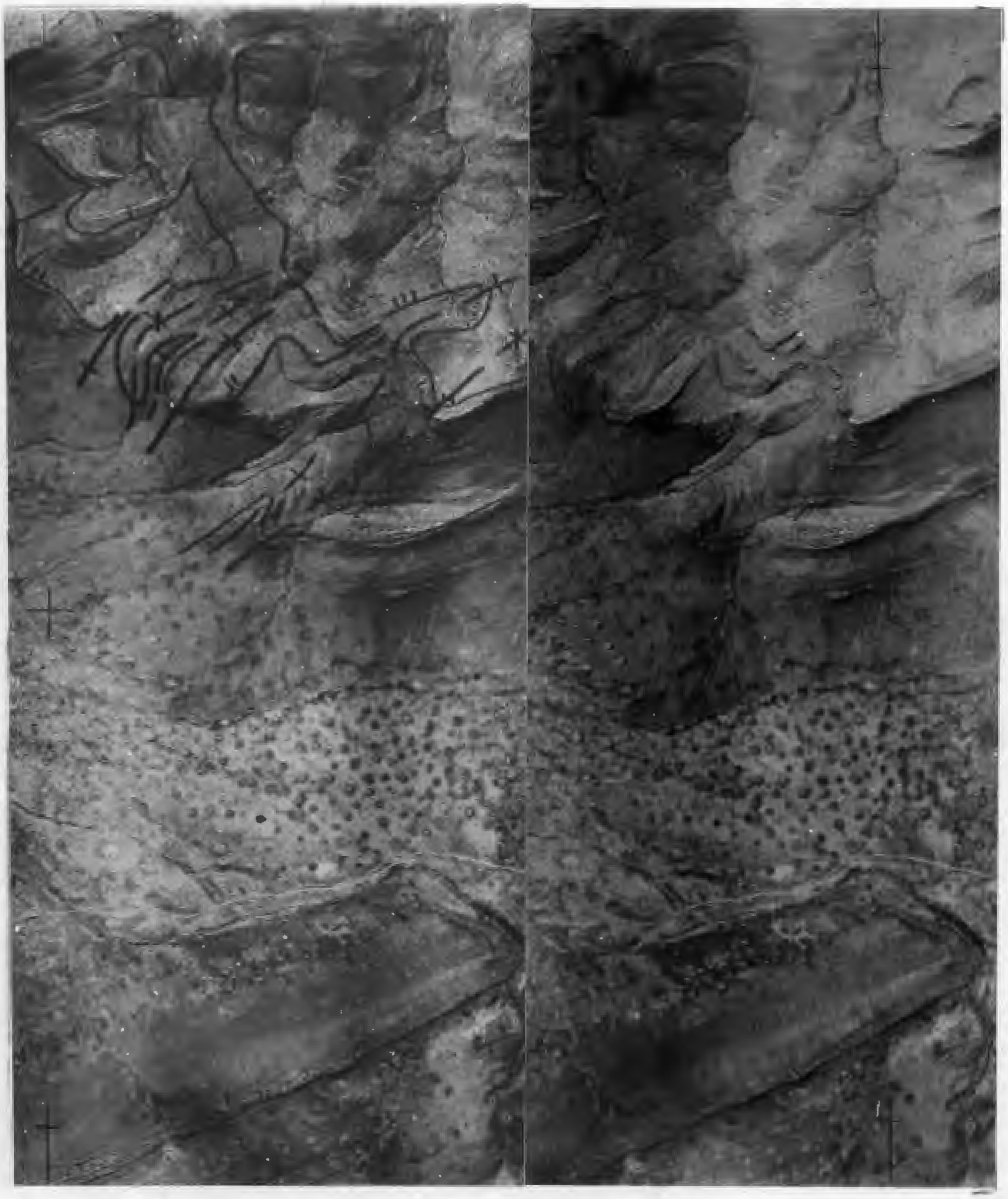


Plate 6 Disharmonic folding within the Witteberg Group

is not clear, but it may well follow, and even be partly responsible for, the southeast trending Touws River valley: it seems to die out before reaching the eastern boundary of the area, but only a few kilometres further east may reappear as the fault forming the southern boundary of the Anysberg.

South of this fault, on the western side, are a series of faults and fractures with a WNW trend, a continuation of the trend described on Map 3, and responsible for some small displacements of Bokkeveld strata in the Matroosberg siding area. Two of the more southerly of these faults trend nearer E-W and are responsible for outcrops of Table Mountain Group: they define a small graben with the Table Mountain Group on the uplifted northern and southern flanks.

The other area where faults are prominent is the Waboomsberg in the southeast. They are mostly associated with the eastward plunging anticlines on the flank of this massif. The main trend is again WNW, and both northward- and southward-downthrowing faults are present, with throws up to several hundred metres. Faulting dies out at or below the contact with the Witteberg Group.

Minor fracture patterns are not so well developed as in the Ceres area, but sets with WNW and ENE trends are present in the Table Mountain Group.

To summarise, the structure of this area shows most of the elements common in the Cape Fold Belt.

i) Large amplitude, long wavelength folds in the Table Mountain Group, with some overturning in the Langeberg.

ii) Synclinoria of Bokkeveld and Witteberg rocks, with the latter showing much smaller scale folding than the former.

iii) Disharmonic folding on various scales and at several levels in the stratigraphic sequence.

Important but more local features are:

i) the unusual Waboomsberg "fist fold", whose significance is not fully understood, but it clearly plays an important role in the eastward widening of the Cape Fold Belt which occurs in this area.

ii) the WNW fracture pattern, which is typical for the south-western Cape.

Comparison of air photo and field maps

Geological Survey 1:50 000 maps were only available for the western half of the area: for the rest, only limited field data is available. Most of the general points mentioned in connection with the comparison of Map 3 also apply to this area, e.g. recognition of the "soft band" in the Nardouw Formation and plotting of fractures, but again the overall agreement is very close, and the main differences concern the continuity and extensions of faults and are relatively minor.

3.1.4. The Kammanassie - Outeniquaberg Area (Map 5)

This area comprises most of 1:50 000 sheets Stomptdrif, Buffelsdrif, Wilderness and Karatara, with the Cape rocks underlying about 2 000km^2, a strip of pre-Cape rocks along the coast, and small area of Cretaceous in the north and extreme SE. The area forms the southern part of the geotraverse through the Cape Fold Belt which is being studied as part of the National Geodynamics Project, mainly by workers from Stellenbosch University, and the present photo-interpretation was done partly to aid future work in the area. No published maps are available other than the 1:1 million Geological Survey map of the whole country (1970), except for a study of the pre-Cape rocks by Potgieter (1950).

Lithology and Stratigraphy

The areas of pre-Cape rocks have to be left almost blank on a photogeological map: the reasons for this are (a) the depth of weathering, resulting in good soils which are either cultivated or heavily covered with natural vegetation, and (b) the lack of differential erosion of different rock types, due to an erosion surface of probable Tertiary age which bevelled the area, and which is not yet sufficiently dissected for the etching out of different lithologies to have occurred.

The Table Mountain Group occupies the high ground of the Outeniqua and Kammanassie mountains, and also the low ranges of hills separating these two massifs. Exposure is generally quite good, with the exception of the south-

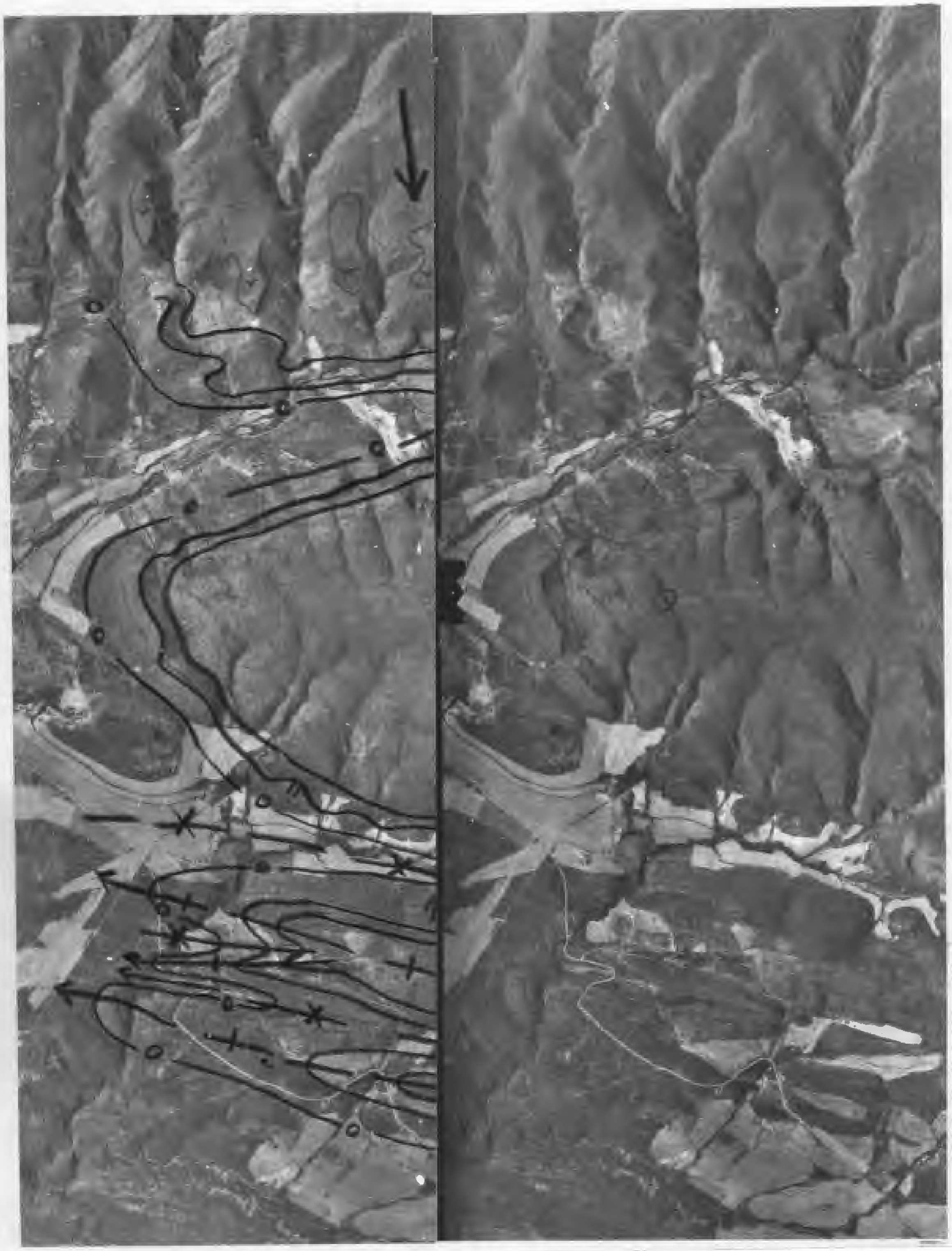


Plate 7 Small scale folding of the Table Mountain/Bokkeveld Group contact, south side of the Kammanassieberg.

facing slopes of the Outeniquaberg, where there are extensive forest plantations: in these areas, normal indications of bedding and dip are virtually absent, and very little information can be gleaned from the air photos.

Over most of the area it was again easy to recognise the Cedarberg Formation, and hence to subdivide the Group into three units corresponding to the Peninsula, Cedarberg and Nardouw Formations, in spite of the great distance from the type areas. The "soft band" within the Nardouw Formation is also unmistakably present (Plate 7), but is in places only visible over limited distances, and on the overturned limb of the Outeniquaberg anticline is rarely visible at all. It is possible that this is due to a slight change in the lithological character of the band resulting in a greater similarity to the adjacent rocks, particularly those above, since its base is often better defined than its top. On the steeper slopes, usually corresponding to overturned dips, it is obscured by talus.

The outcrop of the Peninsula Formation is comparatively small, being restricted to the cores of the Outeniqua and Kammanassie anticlines. Apart from rather more massive bedding and less minor folding, it is difficult to distinguish from the Nardouw Formation on lithological grounds.

Bokkeveld Group rocks occupy the low ground between the Kammanassie and Outeniquaberg, but are very poorly exposed. Individual sandstone bands can only be traced for short distances, cultivation is fairly intensive, and large remnants of an old erosion surface obscure some parts. It is therefore not clear how much of the sequence is present. North of the Kammanassie mountains, however, the situation is very different: largely for climatic reasons the soils are thinner and outcrops better, so that the stratigraphic sequence is well displayed. Three major sandstone units can be identified, and above these is a fourth, less well-marked unit: these are numbered from the base upwards on the map. Each sandstone unit shows internal bedding and certainly includes some shales, but the intervening major shale units are uniform and characterless, and invariably occupy valleys.

Cretaceous rocks occur in the extreme north, and are photogeologically distinguishable from the underlying Bokkeveld in most places by distinctive topographic and tonal characteristics. At the base of the sequence indications of bedding are scarce, and the terrain consists of small irregular hills and fairly fine textured and somewhat irregularly dendritic drainage pattern. Near the top of this unit is a light-toned band which wedges out westwards. Above this is a well-banded, light-toned unit, forming generally low ground with some minor ridges, which gives way northward to an escarpment formed by an overlying resistant unit forming the local top of the sequence. The basal unit is undoubtedly Enon conglomerate, and the overlying units presumably include the equivalents of the Variegated Marls and Wood Beds. Whether Sundays River Beds are present as well cannot be stated at this stage.

The strike of the Cretaceous is closely parallel to that of the underlying Bokkeveld, and the unconformity between them is expressed only by the shallower dip of the Cretaceous. The Bokkeveld sequence seems to be virtually complete, i.e. pre-Cretaceous erosion had only just reached the base of the Witteberg sequence.

Erosion surface remnants are present along the Kammanassie River valley and along the north flank of the Kammanassieberg, and scattered occurrences are also present along the north flank of the Outeniquaberg. They are clearly related to the valleys as seen today, and presumably represent earlier valley floors now being dissected. Along each valley these terraces slope inwards, and are fairly abruptly terminated against the rocky slopes of the Table Mountain Group forming the valley sides. The average height decreases westward in each valley, and overall the height is lower in successive valleys going southward. Only thin gravelly deposits are present on the surfaces, but weathering of bedrock is usually deep.

Structure - Folding

The structure of the area is dominated by the two complex anticlines forming the Outeniqua and Kammanassie mountains. The Outeniqua is the simpler structure, consisting basically of an asymmetric anticline with a shallow-dipping south limb and a steep, generally overturned north limb. The south limb shows a number of gentle east-west flexures, approximately symmetric about upright axial planes, but on the north limb there is only one subsidiary pair of folds which plunge eastward.

The Kammanassie structure is more complex, but is basically as shown in Fig. 4. It consists of a double anticline with an intervening syncline,

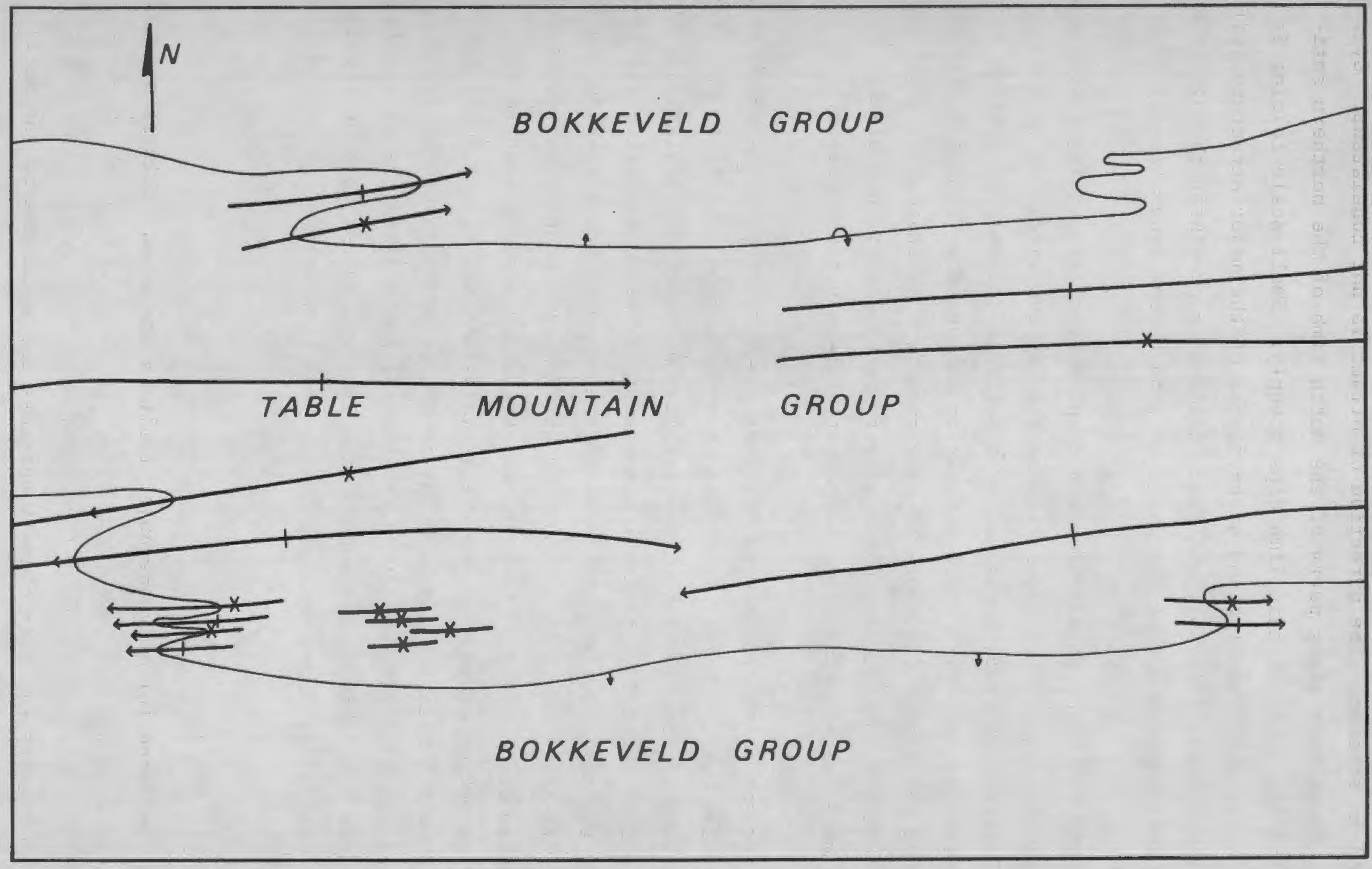


Fig. 4 Structure of the Kammanassieberg

but none of the folds is continuous across the area; each is offset and continued en echelon. The direction of offset is not consistent. Overturning occurs only along parts of the north limb of the northern anticline, but the whole of this limb dips steeply. Small-scale folding is prominent on both the north and south flanks of the major structure, with gentle E-W plunges (Fig. 4), and minor folding is prominent throughout the Nardouw Formation on scales too small to show except schematically.

Between the two major anticlines is a complex syncline running across the centre of the area. This consists basically of two synclines in which Bokkeveld rocks outcrop, separated by a series of closely en echelon anticlines bringing Nardouw Formation rocks to the surface. These anticlines vary along their axes from more or less symmetric to asymmetric with steep northern limbs: overturning seems only to be present in one place. Minor folding on a variety of scales is present, but is not ubiquitous.

In the extreme north of the area the Cretaceous rocks form the southern part of a shallow basin, dipping gently in an arc swinging from NE to NW. This shape may be similar to that of the original basin of deposition, but it is probable that there is a tectonic component to these dips, since (i) if this were not the case, the younger parts of the sequence would overlap the older, and (ii) in other areas (e.g. south of Heidelberg), gentle post-Cretaceous folding can be observed. The swing of strike can also be seen in the underlying Bokkeveld rocks, and here it is associated with a domal structure in the NW which brings up Table Mountain Groups rocks SW of the Stomptdrif dam: the cause of this structure is obscure, since its style is completely at variance with that of the rest of the area and indeed nothing similar is known to the writer from the rest of the Cape Fold Belt.

Structure - Fractures

There is evidence for only one major fault in the area: this is at the contact of Cape and pre-Cape rocks on the southern side of the Outeniqua mountains. One of the main lines of evidence for this fault concerns the Cedarberg Formation: this clearly outlines the anticline to the north, and is last seen dipping south on the south side of this structure. The rocks south of this must therefore all belong to the Nardouw Formation, and this implies that a major portion of the Table Mountain Group is cut out along the contact with the pre-Cape. It was mentioned above that photogeologic evidence is scarce in many places along the southern slopes of the Outeniqua

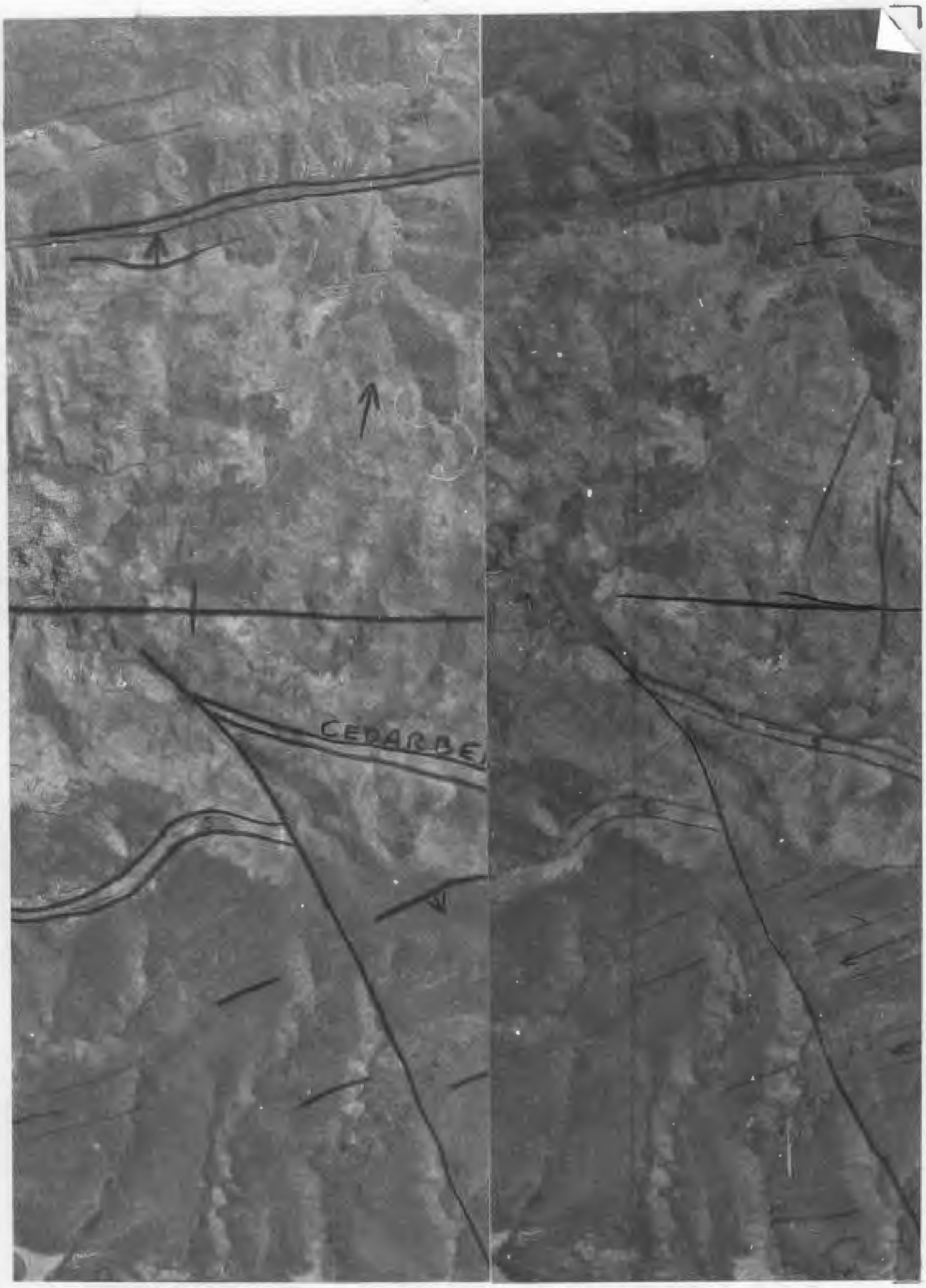


Plate 8 Displacement of the Cedarberg Formation by a small fault in the Kammanassieberg.

due to forestry plantations, and a field check was therefore carried out. Almost continuous exposure was found along the Vanrooyenskraal River north of Bergplaas, but no trace of the Cedarberg Formation was seen and the dips were all southward and gentle. The contact itself is obscured by extremely thick bush and very poorly exposed, but was described by Potgieter (1950) as a broad zone of crushed and brecciated fragments of both Cape and pre-Cape rocks, with abundant slickensides: however, for some reason he inferred only a small northward downthrow, whereas the present evidence suggests that the throw must be several kilometers.

Many fractures are present within and at the upper contact of the Table Mountain Group, but only a few show any displacement, e.g. offset of the Cedarberg Formation in the Kammanassieberg (Plate 8). Most fractures have an orientation between NE and NW, with NNW being the commonest trend. North-south fractures tend to be few but form prominent valley features, and are particularly obvious.

Summary

The folding in the area is on the whole fairly typical of the Cape Fold Belt, i.e. large asymmetric folds with south dipping axial planes, parasitic folds on a variety of mesoscopic scales, and en echelon arrangement of fold axes. The exception is the small dome in the NW of the area. Minor folds are well developed in the Nardouw Formation and in the lower part of the Bokkeveld, but these die out both upwards and downwards so that neither the upper Bokkeveld sandstones, nor the Cedarberg Formation are much affected.

There is good evidence for postulating a major fault bounding the Cape sequence on the southern side, but otherwise faulting is minor. Fracturing is mainly approximately normal to strike, but there is sufficient spread for an interpretation of them as shear fractures in response to a N-S stress to be feasible.

3.1.5. LANDSAT imagery of the Cape Fold Belt

The aim of this part of the study was to assess the amount of geological information present on the LANDSAT (formerly ERTS) imagery, compare it with that available on maps of comparable scale, and evaluate the usefulness of the regional view provided by this type of imagery.

The imagery available consists of black-and-white prints of individual channels recorded by multi-spectral scanner in the satellite: Band 4 (0,5 to 0,6μm), Band 5 (0,6 to 0,7μm), Band 6 (0,7 to 0,8μm), and Band 7 (0,8 to 1,1μm) on a scale of 1:1 million, and a set of false colour composite prints on a scale of 1:500 000.

There are considerable differences between the imagery on different bands, and not all are equally useful geologically. Band 4 is least satisfactory. The contrast is poor, and image "hazy", probably due to scattering of the short wavelengths, but it has the maximum penetration of water and shows shallow submerged sandbars etc. Band 5 has better definition of geological features and the maximum clarity in agricultural land use patterns. This is because vegetation has little reflectivity in this part of the spectrum (red), and hence images in dark tones. Bands 6 and 7 are very similar, with subdued land use patterns and geological information at a maximum. Bodies of water are sharply defined, and drainage patterns show up well. Both are in the near IR, and vegetation therefore images in light tones, and is much less prominent than in Band 5. In the Cape Fold Belt this is advantageous as vegetation patterns are usually distracting rather than helpful. In other areas where vegetation patterns are closely tied to geology, Band 5 might be preferable. Haze penetration is at a maximum in the IR band and hence clarity is good.

Interpretation has to be done mainly monoscopically, since the overlap on prints is only about 10%, but sidelap often amounts to 20%, so that some stereoscopic inspection is possible. More than this is possible with some of the false colour images, since the best of several different coverages were selected, and the image centres varied somewhat, so that combining images from different dates in places provides fairly large overlaps. There can be no doubt that for detailed study stereoscopic cover is a major advantage, just as it is with normal air photos, and enables structural features to be seen more accurately and conveniently traced: fractures for instance usually follow a topographic feature, and dip and plunge directions can be seen. Tracing of drainage is also much easier. The long linear ridges of the Cape mountains give the images a resemblance to some of the models used by Hackman (1967) in his study of varying angles of illumination, which demonstrated the superiority of low sun angles in this type of situation. The sun elevation for the LANDSAT images is 43^{o}, i.e. lower than for normal aerial photography, and this results in distinct shadows on the southern and eastern sides of ridges. This makes even the lower ridges easily traceable monoscopically, and were it not for this factor the advantages of stereoscopy would be even greater.

The same overlaps are, of course, present in the false-colour-composite imagery, but two factors detract from the quality of the stereomodel - one is the enlargement to 1:500 000 scale, and the other is the printing process used to generate the colour prints: this involves screening, and the picture elements become obvious if any further magnification (e.g. a lens stereoscope) is employed. Naked-eye stereoscopy is probably the best in this case. On this imagery the red colours represent IR reflected radiation, i.e. predominantly vegetation. Thus river courses tend to be picked out strongly, but the amount of geologically useful information given by vegetation distribution is small in the Cape Fold Belt.

Stratigraphic analysis

In the Malmesbury Group, very little differentiation of units is possible: the Porseleinberg Formation (Hartnady, Newton and Theron, 1974) forms a line of small dark patches due to remnant natural vegetation on hilltops, and define an approximately NNW trend, but other signs of this, the predominant trend, are few. The pre-Cape granites are not distinct from the metasediments except where they are hill-forming as in the Pardeberg and Paarl masses. The recent sands can be approximately delimited by lack of cultivation patterns, but otherwise the latter is ubiquitous and almost completely uniform, and is identical to the pattern on the Bokkeveld rocks of the south coast wheatlands.

The Table Mountain Group is distinctive, since it forms the highest and most dissected terrain, and appears generally massive. Dip slopes can, however, be observed in places, and the Cedarberg Formation can be followed for quite long distances in places.

The Bokkeveld Group is normally identifiable only north of the Worcester fault, where its outcrop is not obscured by cultivation patterns. Differential erosion of sandstones and shales shows its lithology: long, dark, smooth ridges alternate with soil or alluvium-covered valleys. East of the Cedarberg, the Bokkeveld is confined to a narrow valley and not easily recognised without prior knowledge of the stratigraphic sequence.

The Witteberg Group resembles the Table Mountain Group to some extent, but since it has a much higher proportion of shales, and is folded on a smaller scale, more structural and stratigraphic control of the drainage is present, so that the drainage pattern is usually diagnostic, being finer textured and showing a more trellised pattern.

The Dwyka Group can usually be recognised by the combination of generally dark tones or colours, capped by the White Band, which can be frequently detected in the Karoo.

The Ecca Group is usually recognisable from its distinct layering, its position above the White Band, and where flat lying, by its fine dendritic drainage pattern.

Structural Analysis

The key to the elucidation of folds is determination of dip, either directly by observing dip slopes or the trace of bedding across topography, or indirectly from the stratigraphic sequence. On the LANDSAT images dips can often be obtained in all these ways in rocks of both Cape and Karoo Supergroups, the results being particularly reliable in areas where stereoscopic study is possible. This means that fold axes can usually be plotted with confidence, and the result of such a plot can be seen in Map 6. For comparative purposes, another map was made from the 1:1 million Geological Survey map (1970), by tracing off the faults and by interpreting the dips and contact relationships so as to plot fold axes and plunges (Map 7).

Comparison of these two maps shows clearly that the overall pattern of deformation is similar on both, and that the differences are mainly in emphasis and degree: the main differences can be summarised as follows:

i) Many more fractures are visible on the LANDSAT imagery of the NW branch of the Cape Fold Belt than are shown on the map.

ii) Fractures in the pre-Cape rocks are not visible on the imagery, although many are shown on the map.

iii) More fold detail is visible on the imagery in places, since the map only shows folds which affect the contact between adjacent Groups, whereas intraformational folds show up prominently in places in, for example, the Bokkeveld Group.

iv) In the cultivated area south of the Langeberg, rather more structural information can be gleaned from the map than from the imagery, although the quantity is small in both cases.

The result of this comparison, then, is that where a good quality 1:1 million map is available, which is a compilation from larger scales, the amount of additional information obtainable from LANDSAT imagery is likely to be fairly small.

Significant points to emerge from the present study were:

i) The fact that the NNW-trending Cedarberg folds and the E-W folds of the main part of the belt, converge on each other and swing jointly into a SW direction; they do not swing from NW to E-W, nor is there any sign of superimposition of one fold trend on the other (these features were established independently by de Villiers (1956)).

ii) There is some discontinuity between structures north and south of the Worcester fault in the vicinity of Worcester itself: to the west the Cedarberg folds continue uninterruptedly, but near Worcester the generally E-W trend north of the fault contrasts strongly with the NE trend south of the fault.

iii) Further south, the main Riviersonderendberg anticline trends E-W, but both north and south of it are subsidiary folds trending NE-SW. The Riviersonderendberg fold itself swings round to SW at its western end.

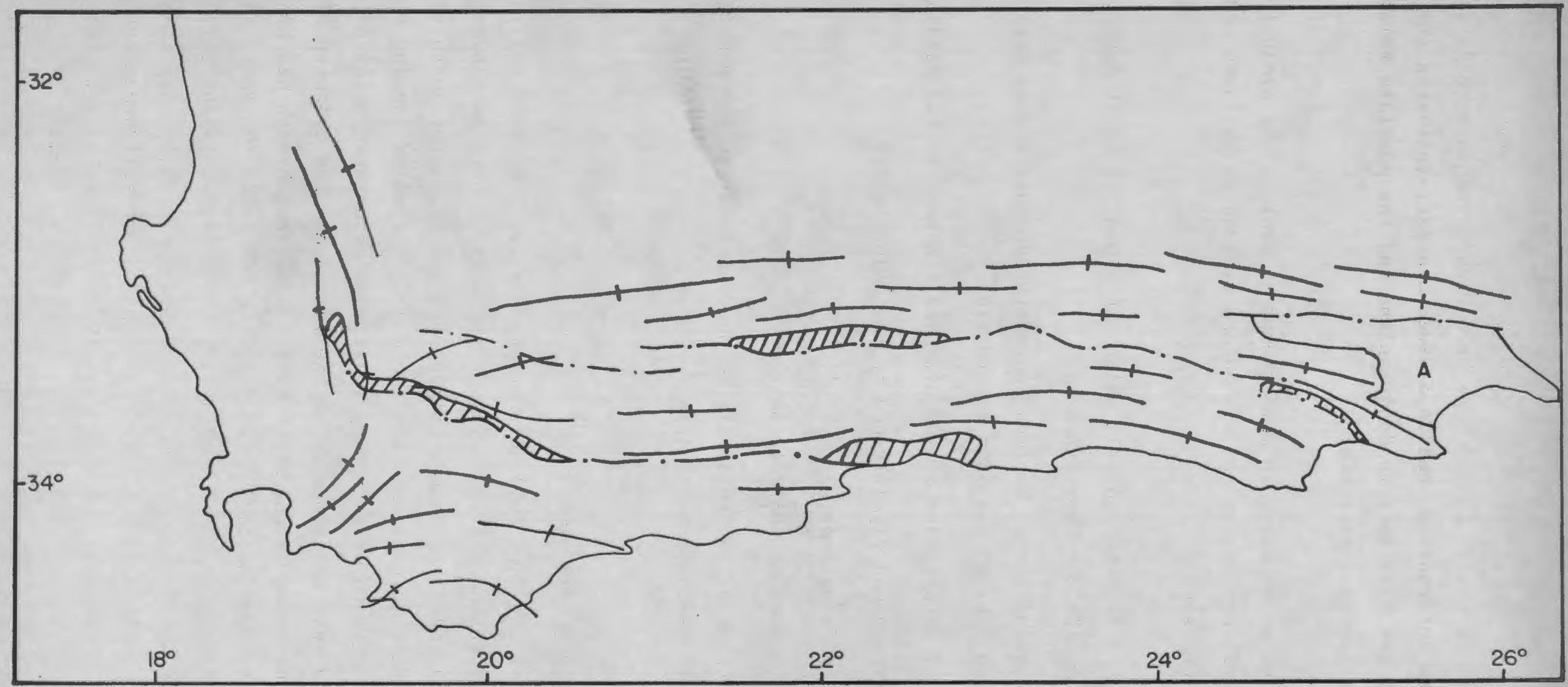
iv) The intensive fracturing of the NW trending Cedarberg ranges.

The possible significance of these features will be discussed below.

3.1.6. A Model for the Evolution of the Cape Fold Belt

The previous sections have described the structure of several areas which can be regarded as representative of the western half of the Cape Fold Belt. The study of these areas, coupled with fieldwork, and an examination of published literature and maps relevant to the Cape Fold Belt as a whole, led to the recognition of various problems concerning previous ideas on the evolution of the Fold Belt, and the development of an hypothesis which might

Fig. 5



The structure of the Cape Fold Belt

solve some of these problems. The basic concepts put forward in an earlier publication (Newton, 1973B) are here considered in more detail in the light of new information, and in a wider context, including the relationship of the Fold Belt to Gondwanaland and the possible relevance of the Plate Tectonics hypothesis.

The main problems encountered in any attempt to explain the evolution of the Cape Fold Belt are listed below, and are treated in the same order in the discussion which follows.

1. The two trends of the Fold Belt which are almost at right angles, and which meet in the Cape syntaxis.
2. The lack of significant regional metamorphism and igneous activity prior to, and during, the main deformation.
3. The extent of involvement of the pre-Cape basement in the folding.
4. The age, history and significance of the major faults.
5. The mode of deformation.
6. The deep structure of the Fold Belt.
7. The relationship of the Fold Belt to Gondwanaland and the possible role of plate tectonic mechanisms.

3.1.6.1. The Two Trends

The major part of the Cape Fold Belt has an average E-W trend and extends from Port Alfred in the east to Ceres in the west. There it converges with the NNW-trending Cedarberg ranges forming a syntaxis on the north side of the Worcester fault (Fig. 5 and Maps 6 and 7). Detailed mapping has shown no interference effects or refolding relationships between folds of the two trends, and they must therefore be of the same age. The overstep of the base of the Dwyka rocks in the north of the Cedarberg branch has been invoked as evidence of an earlier age for the NNW folds (Dμ Toit, 1939), but it can equally be regarded as due to a continuation of the tilting and subsidence which characterised the early development of the Cape trough (Newton, 1973B). Also evident from Fig. 5 is the overall arcuation of the main part of the Fold Belt, within which there are smaller arcs, as at Cape Agulhas and in the Longkloof area, all of which are convex northward. South of the Worcester fault the dominant trend is southwesterly, and is the result of the convergence of the NNW and E-W trends: however, the main axis of convergence appears to be offset along the Worcester fault, having been shifted eastward on the southern side (Fig. 5). It will be described below how all these patterns could be explained on the gravity-sliding model proposed by Newton 1973B) and further elaborated here.

3.1.6.2. Metamorphism and Igneous activity

The overall lack of igneous and metamorphic activity in the Fold Belt is well known and needs no further emphasis. Recently, Elliott and Watts (1974) and Martini (1974), following earlier work by Fuller (1970) in the Beaufort and younger strata, have shown that some sandstones and mudstones of Dwyka, Ecca and Beaufort age contain some volcanic detritus, and that some cherts could be regarded as reworked tuffs. However, the proportion of volcanic material is small, and it is mainly fine-grained, so that Martini (op.cit) is of the opinion that the source area was several hundred kilometres away, and suggests the granitic basement of Patagonia as a source area. The possibility of contemporaneous igneous activity led to the dating of some granitic pebbles from the Katberg (Beaufort) sandstone (Elliott and Johnson, 1972). The ages obtained ranged from 390 to 210my, but argon loss cannot be excluded and the ages must therefore be interpreted with caution.

Not much is known about metamorphism in the Cape Fold Belt, but the regional grade is certainly very low, and there is no evidence that it anywhere reaches biotite grade. The biotite found by Martini (1974) in the ash beds, he regards as detrital. Chloritoid appears in places along the Cape/pre-Cape contact, and its significance is discussed in the next section.

3.1.6.3. Extent of basement involvement

An essential corollary of the gravity model (Newton, 1973B) is that the pre-Cape rocks should not be involved in the Cape folding, and the evidence for and against this must therefore be summarised. Stocken (1954) attributed the "shear cleavage" in the Cango rocks to the effects of the Cape folding, and Potgieter (1950) suggested that the pre-Cape rocks of the George district deformed during the Cape folding by slip along existing shear surfaces, but neither quoted convincing evidence in support of his statement. De Swardt et al (1974) interpret the main cleavage of the pre-Cape rocks at George as a result of the Cape folding, due to a parallelism with a foliation in the

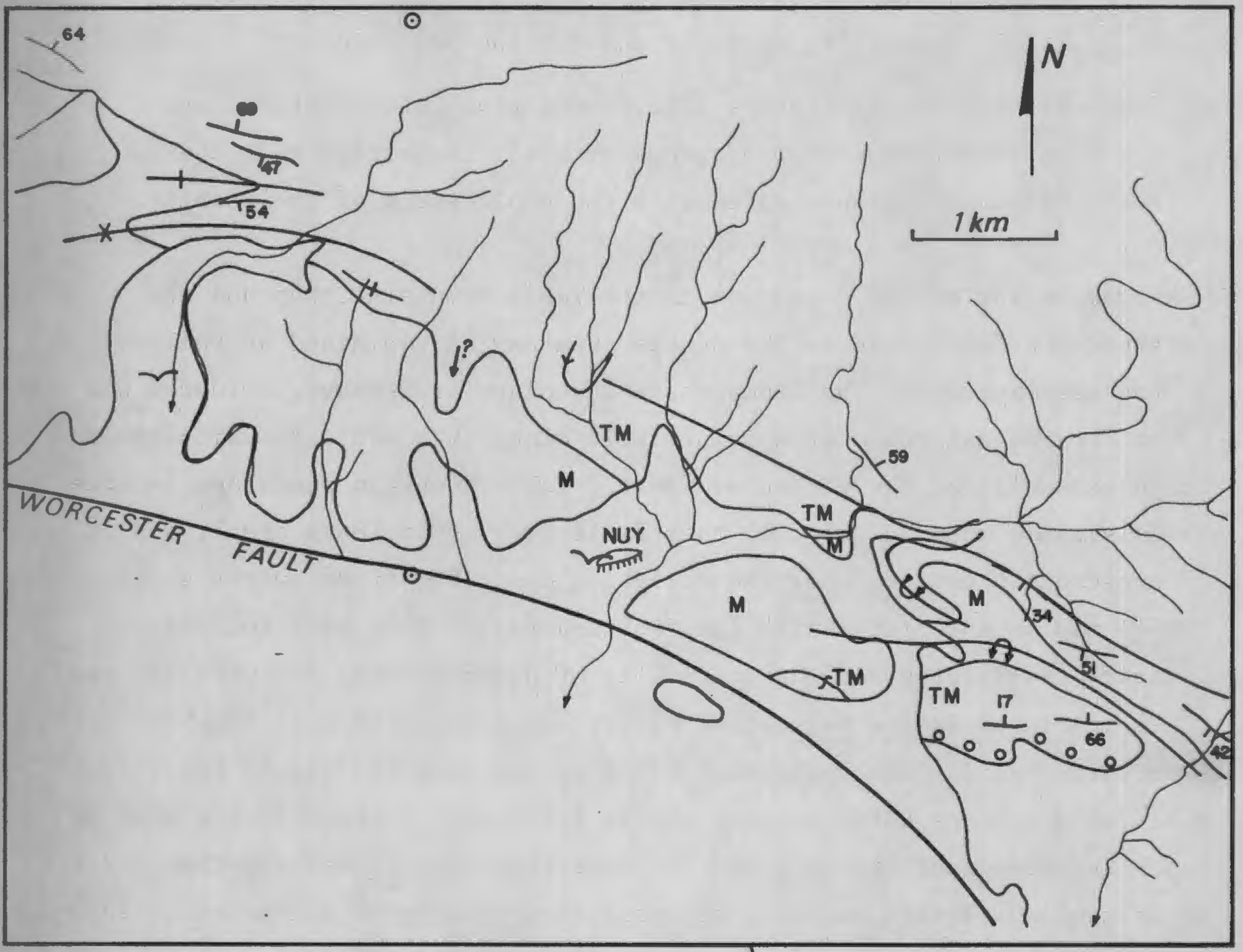


Fig. 6 The area of isoclinal folds of the Cape/pre-Cape contact east of Worcester

Table Mountain Group. There are a number of objections to this interpretation:

i) There is no such parallelism in the southwestern Cape.

ii) Pegmatites are intruded along this foliation in the George granite, and the later aplites are unsheared (Potgieter, 1950), indicating an early age for the foliation.

iii) Biotite in the granite lies in the plane of foliation, and is therefore contemporaneous with it, indicating that the foliation is associated with the emplacement of the granite.

The parallelism of the foliation in the Table Mountain Group and the adjacent pre-Cape rocks in the George area may be explained as follows: in the description of the Kammanassie-Outeniqua area above, evidence was given for the existence of a major fault along this contact, which could be an extension of the Worcester fault. Table Mountain sandstone is often well-foliated when adjacent to this fault (e.g. Heidelberg area), and it is suggested therefore that the foliation described by De Swardt et al (1974) may be associated with the faulting rather than with folding. Hartnady (1969) stressed the difficulty of disentangling pre-Cape and post-Cape structures in the Malmesbury Group, but considered that only the latest structures could possibly be attributed to the Cape folding in the Worcester area and these are both rare and weakly developed. There is one area in which it seems that the Cape and pre-Cape rocks are folded together; this is east of Worcester, and has been described by Toogood (in press). The Table Mountain Group and Malmesbury rocks are involved in several overturned isoclinal folds which strike southeast, parallel to the Worcester fault, and have southward-dipping axial planes (Fig. 6). The rest of the Cape folding in this area (Map 3) consists of open, upright folds with an east-west trend, and the contrast in both style and orientation with the isoclinal folds strongly suggests that the latter have a different origin. Their proximity to and parallelism with the Worcester fault, and the fact that there is often a strong foliation parallel to the fault, suggest a possible explanation. On the gravity hypothesis (Newton, 1973B) the major faults are postulated to have originated as steep normal or reverse faults downthrowing to the north: if in this area the fault did have a reverse movement, it is possible that quite severe compressive stresses acted in the adjacent rocks, resulting in the development of both folding and foliation. Additional local stresses might have been induced by the curvature of the fault in this area. It is possible that similar effects are present adjacent to this and other faults elsewhere, but unless the Table Mountain Group is involved it might be very difficult to differentiate such deformation from earlier, often very complex phases in the pre-Cape rocks.

Another interesting aspect of the Cape/pre-Cape contact is the development of chloritoid (ottrelite) and the possible extent of shearing on and parallel to the contact. Originally recorded by Schwarz (1905), the distribution of ottrelite in the Swellendam area was described by Scholtz (1946): the ottrelite is found in shaly basal members of the Table Mountain Group, and in the Malmesbury, and grades downwards into a chlorite zone. The same distribution was found in the pre-Cape near Worcester by Hartnady (1966), and Potgieter (1950) also mentions the presence of this mineral in a broad zone beneath the Cape/pre-Cape contact. Scholtz (1946) also describes the occurrence of shearing for several hundred feet below the contact, but this is not present in the Worcester area, where quite delicate structures in the Malmesbury are preserved which would have been destroyed by such shearing.

The stability field of ottrelite is not yet well-established, particularly as regards its lower limits. From experimental work, Hoschek (1969) suggests that a typical genesis is from reaction between chlorite and kaolinite or pyrophyllite at between 400^{o} and 425^{o}. Whether such temperatures were attained in the vicinity of the Cape/pre-Cape contact may be doubted, but it does seem inescapable that large quantities of heat must have been evolved there, and sustained for a considerable time to enable the ottrelite porphyroblasts to form. This heat can only have come from friction, since the restriction of the presence of ottrelite to the vicinity of the contact precludes an origin by regional or thermal metamorphism. It seems that, at least in some places, large amounts of slip must have occurred on this contact, and a possible explanation for this involving an association with the major faults is given in the next section.

3.1.6.4. The major faults

These have been traditionally regarded as mid-Cretaceous structures (De Villiers, 1956), i.e. initiated only after the folding, and associated with the uplift of the Cape Ranges and formation of valleys in which the Cretaceous rocks accumulated. Evidence of activity at this time comes from the occurrence

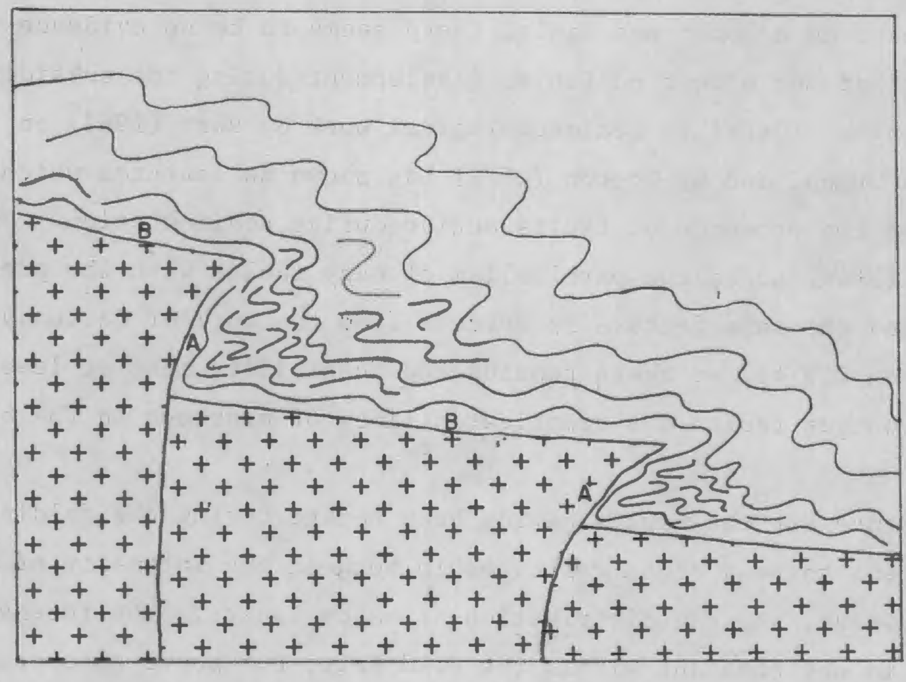


Fig. 7 Proposed mechanism for the formation of cascade folds and overturned basement contacts

of Enon conglomerates banked up against fault planes, and the inversion of stratigraphy represented by pebble types, demonstrating continuous uplift and erosion to successively deeper levels. There is considerable evidence, some of which was given above, that movement continued into post-Cretaceous time also.

What has not previously been investigated is the possibility of an earlier history for the faults, and it is this aspect which is dealt with here.

With regard to a lower age limit, there seems to be no evidence that faulting had any effect on facies development during the subsidence of the Cape trough. Detailed sedimentological work by Rust (1967) on the Table Mountain Group, and by Theron (1972) has shown no features which could be due to the presence of faults active during sedimentation. However, Scholtz (1946) noted the parallelism of many faults with the pre-Cape shear zones, and the same feature is evident from the work of Hartnady, Newton and Theron (1974), so there remains the possibility that at least some of the younger faults are reactivated lines of weakness in the basement.

The evidence for the faults having been active during the folding is that there seems to be a close relationship between the intensity of folding and thrusting, and the distribution of major faults. The intensity of folding is not constant within the Fold Belt, but shows an overall increase from south to north. There are, in addition, zones of high intensity which occur just north of the faults, e.g. the Langeberg and Swartberg mountain ranges. The only major thrust in the Fold Belt (at Baviaanskloof, Theron 1969) occurs in a similar position with respect to major faulting. These factors imply a close genetic connection between folding, faulting and thrusting (see also Sohnge, 1934) and I have suggested (Newton, 1973B, and see below) that a mechanism involving gravitational gliding tectonics would best explain such a connection. The slope on which gliding would have taken place was the southern flank of the Cape trough, but instead of a smooth northward slope it it suggested that differential uplift along faults created a series of steps (Fig. 7). Following the concept of Beloussov (1963), the weight of the raised blocks and the superincumbent load would result in a lateral spreading which causes the faults to become inclined, while the steep slopes on the step risers will give intense folding. This concept then explains

i) the overturning in many places of the Cape/pre-Cape contact;

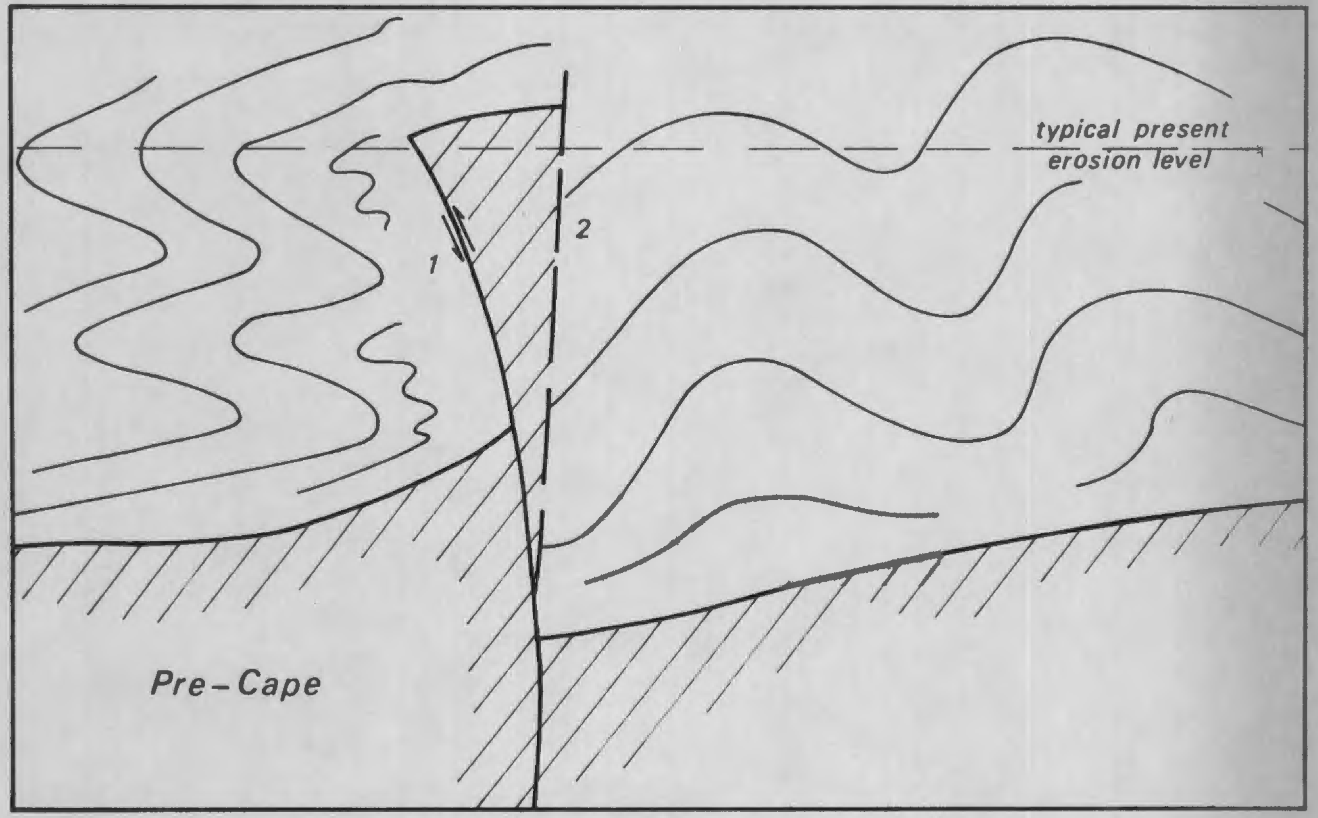


Fig. 8 Schematic representation of suggested relationships along the Cango and Worcester faults

ii) the localisation of intense folding on the northern side of major faults;

iii) the presence of cascade folds with approximately horizontal axial planes;

iv) the development of ottrelite due to intense differential slip between basement and cover rocks.

The occurrence of thrusting can be attributed to more brittle deformation of the competent members in the later stages as they became cemented due to migration of pore fluids through them during folding. Important implications of this model are:

i) The "unconformity" at the base of the Cape sequence may in places actually be a fault surface (region A in Fig. 7) or a surface of decollement (region B in Fig. 7).

ii) The outcrops of pre-Cape rocks on the northern sides of faults are in fact remnant slices which were on the southern sides of the original faults (Fig. 8).

iii) The present displacements on the major faults are in the reverse sense to the original movements, and involve the initiation of new segments (section (2) in Fig. 8). This would take place during a subsequent phase of subsidence and tension accompanying the breakup of this part of Gondwanaland. It is possible that many additional faults were initiated at this stage, and not all of these need have been southward downthrowing - as described above, there are numerous small faults in the Cape Fold Belt, and the directions of throw are often alternate, giving minor horst and graben tectonics: the largest of the northward downthrowing faults are the Touws River fault (Map 4) and the postulated fault south of the Outeniqua Mountains (Map 5).

3.1.6.5. Mode of deformation

Not many suggestions have been put forward for the origin of the stresses responsible for the formation of the Cape Fold Belt. First to consider this in detail was De Villiers (1944, 1956), who invoked a mechanism proposed by Lawson (1927) for part of the Rocky Mountains. This involved horizontal "collapse" of the crust as a result of primary, pervasive compressive stress and a thinning of the crust beneath the trough. This thinning was thought to be the result of flow which transferred crustal material from beneath the subsidiary trough to adjacent areas where uplift and erosion were supplying sediment to the trough. De Villiers (op.cit) suggested that a combination of rock flow away from the trough, and an overall compressive stress, would form a vertical couple which was responsible for the asymmetry and overfolding observed in the Cape Fold Belt, while a northeasterly stress direction would give rise to both the Cedarberg and the main east-west folds, the third southwesterly trend being the result of compression from the south against a rigid buttress.

De Swardt et al (1974) suggest that the Fold Belt can be fitted into an Alpinotype model, "doppel orogen" with gravity sliding away from a central uplift, and at deeper levels heavy involvement of both basement and cover in cleavage folding. The evidence against cleavage in the pre-Cape rocks being of post-Cape age was summarised above, and other objections are as follows:

i) The cleavage is regarded by De Swardt et al as a "regional plane of transport along which the sedimentary pile as a whole has moved forward", i.e. the mechanism is one of simple shear. However, many studies (e.g. Cloos, 1944; Ramsay and Graham, 1970) have shown that cleavage represents the plane normal to the maximum compressive strain (the XY plane of the strain ellipsoid) and Ramsay (1967, p.403-4) shows that this plane does not in general coincide with any direction or phane of transport. Their model may therefore lead to a rather oversimplified picture of the deformation.

parallel

ii) In many parts of the Cape Fold Belt cleavage is absent or is approximately vertical, so that there would be no overall horizontal direction of transport.

iii) The northward sense of regional tectonic transport invoked for the George area cannot be applied to the Cedarberg folds.

iv) Metamorphism is of too low a grade for deformation to have taken place in the "deeper parts of alpinotype orogenic belts" (De Swardt et al, 1974, p.56), and the examples cited by them from the Precambrian all involve rocks of high metamorphic grade.

v) The parallelism of pre-Cape and post-Cape foliations does not extend to the southwestern Cape, where the relationship may be anything from parallel to orthogonal.

In contrast to the above models, the writer's study of the Cape Fold Belt has led to the conclusion that many of its important features can best be explained by a gravity gliding mechanism: the main lines of evidence are as follows:

i) Northward vergence of folds. The attitudes of axial planes vary from steeply north to shallow south-dipping with south-dipping examples being in the majority, and predominating in the northern parts of the Fold Belt. At Schoorsteenberg an isoclinal fold has been proved by drilling (Haughton et al, 1953) on the north margin of the fold belt, and since this appeared to be a gentle anticline on the surface, it is interesting to speculate that many similar isoclines may underlie other simple surface structures. Overall, the degree of overturning appears to increase northward, with the qualification discussed below.

ii) Folding dies out rapidly, almost abruptly, along a line which corresponds quite closely with the axis of maximum subsidence of the Cape-Karoo trough: i.e. the folding is largely confined to the southern and western slopes of the trough. Across the trough axis, folds are scarce, but axial planes generally dip northwards (De Villiers, 1944).

iii) The increase in intensity of folding northwards is not uniform, but has maxima on the northern sides of the two major fault systems, the Worcester and Cango faults. As discussed above, this suggests that the faults were active at the time of folding, and that the intense folding is related to a sharp change in level in the basement brought about by faulting.

iv) The existence of two fold trends almost at right angles implies the existence of two stress fields also at right angles, and problems arise in most hypotheses as to how these could be generated. On the gravity-gliding hypothesis, however, the direction of slope is the controlling factor, and the varying slope directions around a trough would be expected to initiate folds with different trends.

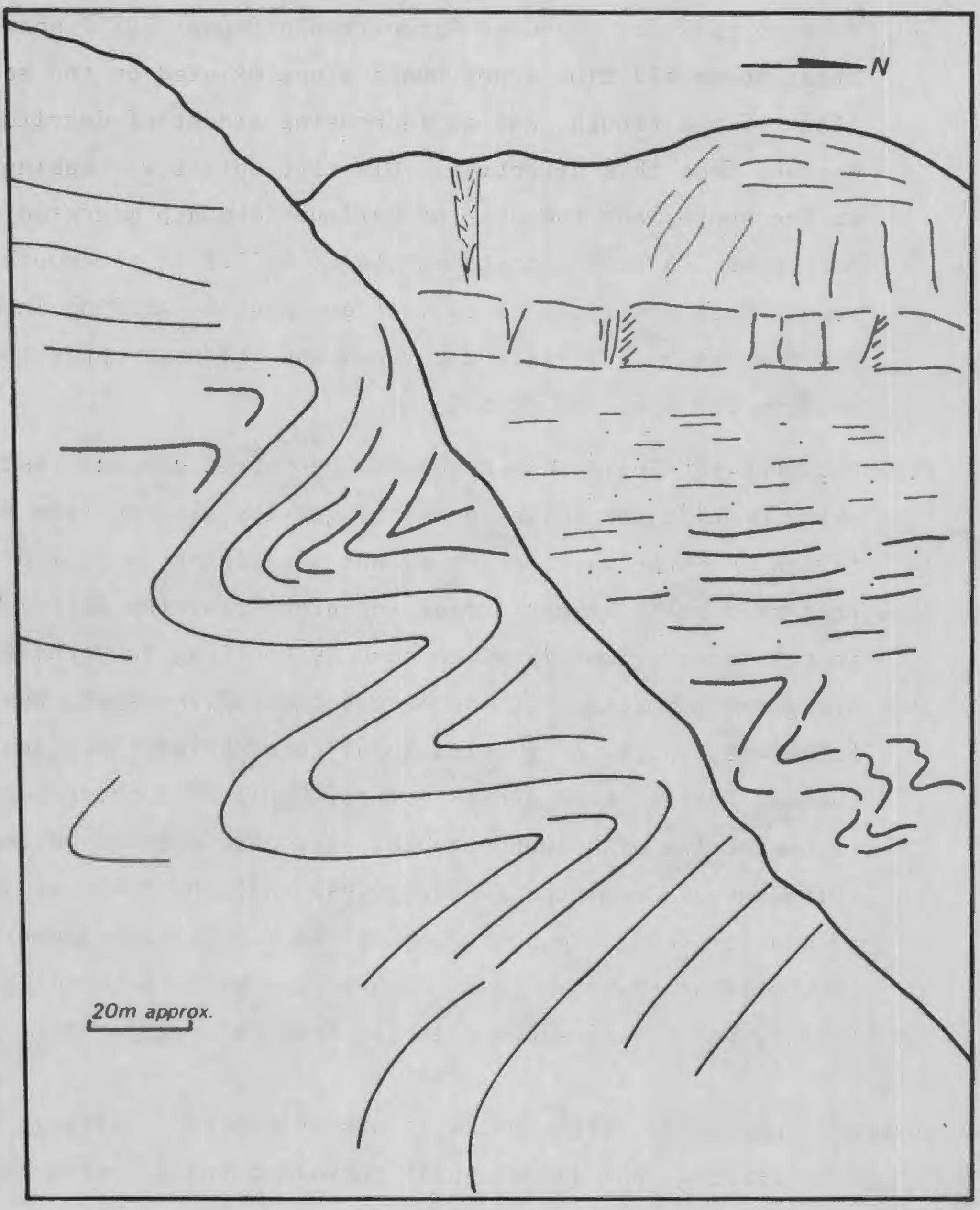


Fig. 9 Cascade folds, Meirings Poort
(drawn from photograph)

v) Isopach maps for the Cape-Karoo trough (Rust, 1973) show that after Bokkeveld time a northward slope existed on the south flank of the trough, and an increasing amount of detritus was derived from this direction. Clearly, uplift was taking place to the south, and the axis of maximum downwarp migrated slowly northward. A simple continuation of uplift to the south would be all that was required to initiate gravity gliding in late Beaufort times. Similar arguments and evidence apply to the western flank of the basin.

vi) Fold style. There seem to be few geometric characteristics which distinguish folds formed by gravity gliding from those formed in other ways, which is not surprising in view of the fact that at low temperatures and pressures, the deformation is in all cases primarily a response by buckling to stresses acting along the layering. It has been suggested, however, that cascade folds are typical of gravitational deformation (Harrison and Falcon, 1934): they consist of thick piles of chevron or rounded folds with subhorizontal axes, and conform to the criterion of De Sitter (1956, p.289) that the inverted limbs of gravity folds are not thinned. Such folds are common in the highly deformed rocks just north of the Worcester and Cango faults, and Fig. 9 shows examples from Meiringspoort.

The northward convex arcuation which occurs on several scales in the Fold Belt also suggests gliding, the differential forward movement being controlled by local variations in slope and in frictional resistance.

Although not confined to a gravity-gliding environment, disharmonic folding is an essential characteristic of it, and is abundant in the Cape Fold Belt; numerous examples were described above (Sections 3.1.1. to 3.1.4). Clearly, there is no extremely weak evaporite layer at the base of the sequence, such as is found in the Jura and Zagros mountains (and this may explain the generation of heat at the Cape/pre-Cape contact which produced ottrelite), but the disharmony is visualised as having been distributed over a number of slightly weaker zones at various stratigraphic levels, such as the Cedarberg Formation and the Bokkeveld, Witteberg and Dwyka shales.

A final important aspect of the style of deformation is the plastic behaviour of rocks which would be expected to be most competent. Sandstones in the Table Mountain Group and Witteberg are folded extremely sharply, but

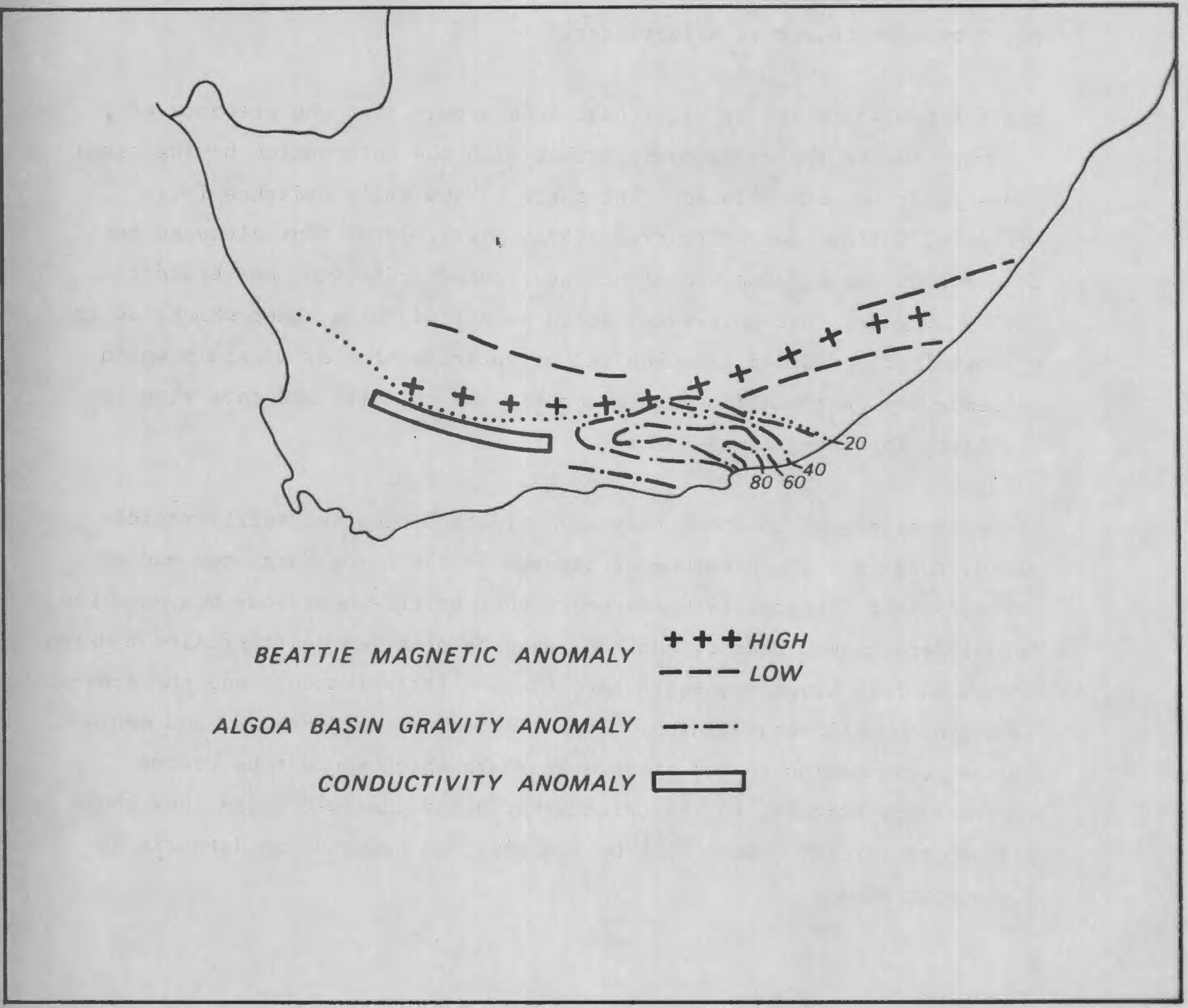


Fig. 10 Geophysical anomalies in the Cape Fold Belt

with only a few radial quartz-filled veins as evidence of brittle behaviour. The Dwyka tillite, also, in the Schoorsteenberg structure, is folded extremely tightly. This evidence suggests a large degree of intergranular movement without cataclasis, i.e. the degree of cementation at the time deformation began must have been small, and abundant pore-fluid present to act as a lubricant.

Until a few years ago it might have been argued that the presence of cleavage in the shales is incompatible with the deformation having taken place prior to consolidation, but there is now ample evidence (e.g. Williams, Collins and Wiltshire, 1969; Clark, 1970) that cleavage can form during the deformation of unconsolidated sediments, and Braddock (1970) suggests that pore-water acted as a fluidising agent which, as it was expelled, produced a mechanical orientation of clay minerals which subsequently recrystallised to muscovite and chlorite and gave rise to fissility in fine-grained rocks.

There is evidence, however, that consolidation occurred fairly rapidly during folding: the presence of thrusts in the Laingsburg area and at Baviaanskloof (Theron, 1969) suggests that brittle behaviour was possible before deformation ceased, and the presence of a few quartz-filled tension gashes in fold hinges suggests late stage brittle fracture and the presence of migrating siliceous fluids. These fluids are evidence of, and would induce, cementation in the arenaceous rocks which would thus become increasingly brittle, to the extent that after the fold phase they could respond to further stress only by faulting, as happened in Jurassic and Cretaceous times.

3.1.6.6. The Deep Structure of the Fold Belt

Our knowledge of the deep structure is very incomplete, due to a paucity of published results. Hales and Gough (1960) reported a -80 mgal gravity anomaly beneath the Algoa basin (Fig. 10) and suggested that it was caused by a relict root, or thickening of the crust, which has provided Airy type compensation for a mountain range since eroded away. Subsequently (Gough, 1973), magnetic evidence suggested a new interpretation: a magnetometer array revealed the existence of an electromagnetic induction anomaly which was interpreted as a ridge of highly conductive mantle material under the west central part of the Cape Fold Belt at a depth of not more than 50km. It could represent a line of ascending mantle material, and the gravity anomaly could mark the eastward extension of this line. The absence of the gravity anomaly in the west would be interpreted as due to uplift (isostatic compensation) having already occurred there. However, the southern side of the magnetic anomaly has not yet been fixed, nor its eastern and western terminations and important remaining questions are

i) How far does it extend in these directions?

ii) Does it continue into the Algoa basin, or north of it, where maximum relative uplift has already occurred?

iii) Why has the Algoa basin not been uplifted isostatically?

De Beer, van Zijl and Bahnemann (1974) discuss the same data, and also the Beattie magnetic anomaly (Fig. 10) which consists of a linear maximum flanked over most of its length by linear minima. The authors state that unpublished deep geo-electrical soundings show that the body causing the anomaly is in the basement beneath the Karroo sediments, most likely in the middle or lower crust, and that it cannot be explained in terms of the mantle upwelling model of Gough (1973). They propose an explanation for the anomaly in terms of Plate Tectonics, which will be discussed in the next section.

The evidence so far collected, then, demonstrates the presence of several interesting structures at depth beneath the Cape Fold Belt, but so far there is not enough data for an unambiguous model to be proposed.

3.1.6.7. Gondwanaland and Plate Tectonics

It has long been recognised that the Cape Fold Belt is part of a much more extensive zone of deformation, possibly extending as far as the sub-Andean ranges to the west and the Hunter-Bowen orogeny in Australia to the east. This was called the Gondwanide orogeny by Du Toit (1937). A good review of the multiple orogens making up this belt is by Craddock (1974), who distinguishes early Palaeozoic orogens (Adelaidean in Australia and Ross orogen in Antartica), middle Palaeozoic orogens (Tasman in Australia, Borchgrevink in Antartica, and an "Acadian" orogeny (Harrington, 1962) in South America), and Permo-Triassic orogens (Hunter-Bowen in Australia, Ellsworth in Antartica, the Cape Fold Belt, and the Sierra de la Ventana and sub-Andean zone in South America). Attention will be confined here to the Permo-Triassic components of this belt, and to "West Gondwanaland",

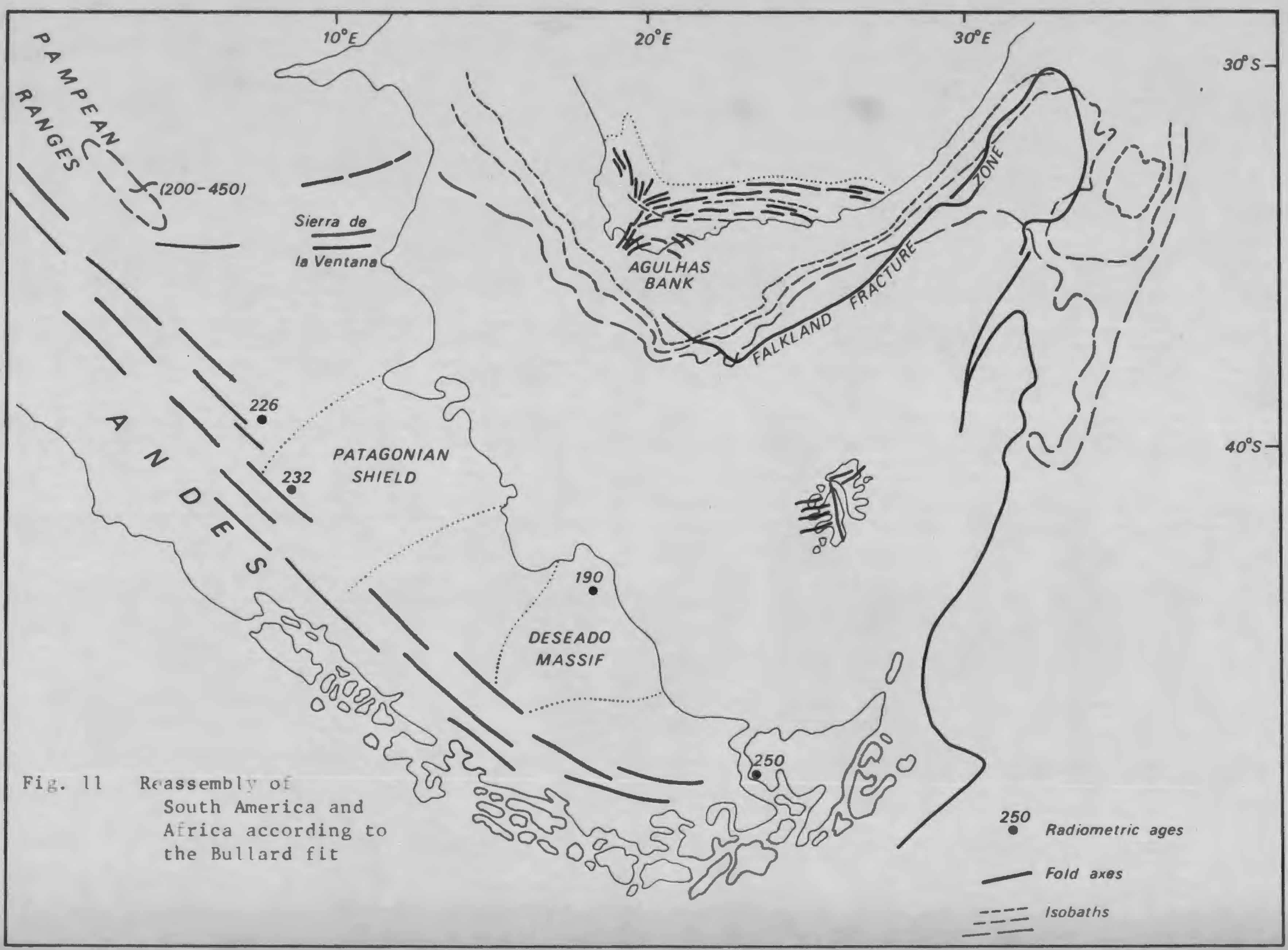


Fig. 11 Reassembly of South America and Africa according to the Bullard fit

since the Africa-Antartica fit is still somewhat ambiguous (Smith and Hallam, 1970). The fit of South America against Africa produced by Bullard, Everett and Smith (1965) was used as a basis for this study, and I am grateful to Mr. C.J. Hartnady for programming and operating the computer which produced the accompanying map (Fig. 11). The outline of the Falkland Plateau is approximately the 2000m isobath, which clearly delimits the Falkland fracture zone on the northern side: the corresponding Agulhas fracture zone is indicated by the isobaths marking the edge of the Agulhas Shelf. It is clear that the Bullard reconstruction does not restore these two fractures quite accurately, but a small westward shift of South America would produce an almost perfect fit, and in addition the eastern end of the Falkland plateau fits into the distal Natal Valley, between the Natal continental margin and the southern Mozambique ridge. The stratigraphic similarities between South America and South Africa have been ably summarised by Du Toit (1937) and Martin (1961), and here attention will be concentrated on tectonic aspects.

The Sierra de la Ventana, or Southern Hills of Buenos Aires, have for long been considered the equivalent of the Cape Fold Belt (Du Toit, 1937). According to Harrington (1956) they are formed of 5000m of marine lower Palaeozoic and continental Permian rocks, and are intensely folded with sinuous but generally northwesterly trending fold axes. Zambrano and Urien (1974) state that these structures can be traced out on to the continental shelf, and may also continue into the Parana basin to the NW, and that there is no evidence for a subduction zone or significant crustal shortening. The Patagonian basins, which also contain Palaeozoic sediments, are unfolded (op.cit).

The extension of the fold belt northwestwards appears more dubious: in the Pampean ranges, the continental Upper Palaeozoic and upper Triassic are almost devoid of folding, and in the sub-Andean ranges, the folding is of Pliocene age (Harrington, 1956). However, the Pampean Ranges have recently yielded radiometric dates of 200-450my, and a series of ages from southern Argentina range from 190 to 250my (Halpern, 1968 and Zambrano and Urien, 1970)(see Fig. 11). There is some evidence, therefore, that igneous and metamorphic activity occurred in various parts of Argentina in the Triassic, and Martini (1974) has suggested that this area may have been the source of fine volcaniclastic material in the Cape-Karroo sequence.

The position of the Falkland Islands can be seen (Fig. 11) to be some 700km.

south of the South African coastline on the Bullard reconstruction. Since there is no evidence that any part of the Falkland Plateau has moved independently of South America, the suggested positions for the Falkland Islands at the western end of the Cape Fold Belt (Du Toit, 1937) and the eastern end of the Cape Fold Belt (Adie, 1952) cannot be accepted. The stratigraphic sequence in the Falkland Islands can be closely correlated with that of the Cape Fold Belt, representatives of all units from the Table Mountain Group to the Ecca Group being present (e.g. Du Toit, 1937). The following account of the structure is taken from a recent photogeological and literature survey (Greenway, 1972).

There are two main structural trends: the first swings slightly from WNW in the west to E-W in the east, and consists mainly of folds, but with some faults and, in the SW, a number of dolerite dykes. In the west, the folds are gentle structures, with dips generally less than 25°, but on East Falkland they are much tighter, with dips of 60° being recorded in places. The second trend is northeasterly, the main fold being a major asymmetric anticline on the west coast of Falkland Sound. Faults with this trend are common on East Falkland, and on West Falkland numerous dolerite dykes also trend NE.

There seems to be a close correlation of folding, faulting and dyke emplacement in both trends, and Greenway (1972) suggests that the fundamental control may be basement faulting. She points out that similar fold and fault trends are found in southern Argentina, but that these did not originate until Upper Jurassic or early Cretaceous. Therefore, either the Falklands deformation would have to be precursory to that in Argentina, or the Falkland rocks remained undeformed until late Jurassic time. This latter is an interesting possibility, since it would relate the Falkland deformation to the opening of the South Atlantic rather than to the Triassic deformation of the Cape Fold Belt, and as Greenway points out, the Falkland fracture zone is itself an almost east-west feature initiated at this time. The presence of dolerites supports this idea, since no dolerites are present in the Cape Fold Belt, their appearance being restricted to the cratonic area to the north. To test this hypothesis it would be necessary to date the dolerite dykes: a Triassic or early Jurassic age would mean that the deformation was probably contemporaneous with the Cape Fold Belt, while a late Jurassic or Cretaceous age would imply that deformation accompanied the breakup of Gondwanaland. Until this is done, the age of the Falkland deformation will remain ambiguous.

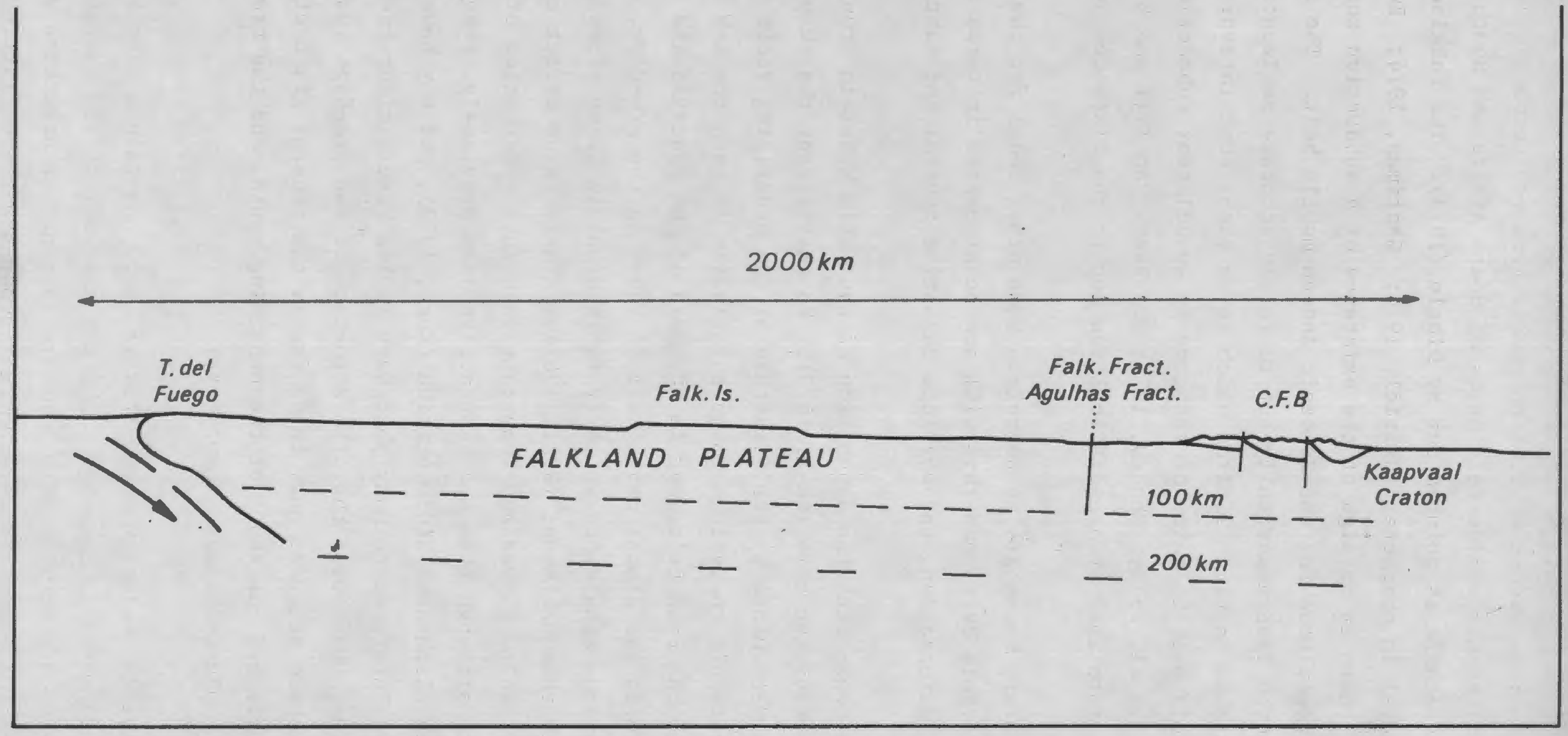


Fig. 12 Schematic cross section from Tierra del Fuego to the Kaap-Vaal craton

Probably the most important fact to emerge from the reconstruction (Fig. 11) is that the Gondwanide fold belts of South Africa and South America were intracratonic as pointed out by Dingle (1973). The Falkland Plateau is continental in character (Dalziel, 1974; Geotimes, 1974; Ewing et al, 1971), and there is no sign of the existence of a subduction zone nearer than that postulated for the Mesozoic Andean mobile belt. The situation is represented diagrammatically but to fairly accurate horizontal and vertical scales in Fig. 12, from which it is clear that interpretation of the Cape Fold Belt in terms of response to an adjacent subduction zone (De Swardt et al, 1974; Rhodes, 1974; De Beer, van Zijl and Bahnemann, 1974) runs into insuperable difficulties due to the distances involved.

It is therefore necessary to postulate some other model for the evolution of the Cape Fold Belt, and this will now be attempted in terms of sedimentation, deformation, and possible causative crustal and mantle processes.

Subsidence began with the deposition of the Table Mountain Group, probably in early Ordovician time (Rust, 1973). To what extent the shape of the trough was determined by the structure of the underlying rocks is not yet clear: certainly there is a rough parallelism in both the E-W and NW branches of the Fold Belt, but in the area of the syntaxis the trends of the Cape folds are almost orthogonal to those in the pre-Cape, and the axis of maximum subsidence in early Table Mountain Group times was east-west rather than northwest (Rust, 1967). There is no direct evidence that Malmesbury faults played any important role in the formation of the early Cape basin, although they had been active just previously, probably controlling Klipheuwel sedimentation (Rust, 1973), and may have been rejuvenated later, since many post-Cape faults have similar trends. It is suggested, therefore, that the structure of the pre-Cape rocks affected the Cape-Karroo sequence only in so far as the general grain of the country may have affected the shape of the subsiding basin, and the trend of subsequently exploited lines of weakness.

Sedimentological evidence shows that in Table Mountain and Bokkeveld Group times, there was a landmass to the north and west of the trough (Rust, 1973; Theron, 1970) but no sign of a southern margin. In Argentina and the Falkland Islands, similar lithologies and faunas are found (Martin, 1961; Greenway, 1972), indicating similar depositional conditions, but derived in these cases probably from the Patagonian craton. Less is known about the Witteberg, but the isopachs for this unit show signs of closing on the south side, although there is apparently no sign of a source area in this direction (Rust, 1973). However, in the Dwyka, Stratton (1970) invokes a southerly source for some of the glacial material. The Dwyka rocks of the Falkland Islands and Sierra de la Ventana (Argentina) have been studied by Crowell and Frakes (1968) who suggest a westerly source direction for the Falklands and a SW source for Argentina, again implying derivation from Patagonia. Discussing the Ecca Period, Ryan (1969) showed that there is a southern Ecca facies deriving mainly "from a geanticlinal ridge bordering the southern margins of the Cape-Karroo geosyncline" (op.cit, p.953), and the axis of the depositional trough appears to have migrated northwards with time. Fine volcaniclastic material also arrived in the basin from some distant source (Fuller, 1970; Elliott and Watts, 1974; Martini, 1974), probably to the south.

The evidence, then, suggests that as the Cape trough subsided, its southern shoreline gradually migrated northward until the sedimentological effects of a southern source area became very marked in the part of the trough available for study today. Thus the southern slope of the trough gradually increased due to a combination of subsidence in the trough and uplift south of it. In the NW arm of the trough, isopachs and palaeogeographic reconstructions clearly show a subsiding embayment at first, surrounded by highlands to NE, N, and NW, becoming less marked in the Witteberg (Rust, 1973), and absent in the Dwyka, when regression resulted in the deposition of continental tillite unconformably over Cape sediments and basement alike.

Sedimentation continued to the end of the Permian (Lower Beaufort rocks are the youngest to be folded) and over 10 000m of sediment accumulated in the zone of maximum subsidence, which although it varied with time, ran roughly along a line from Clanwilliam to East London.

There is insufficient data yet to construct a detailed palaeogeographic map for this time period for south western Gondwanaland, but the Bullard reconstruction allows one to suggest the general picture (Fig. 13). The major positive areas were the Patagonian, Brazilian, and Kaap-Vaal cratons, which were all both sources of sediment and shallow repositories at different times. The main subsiding trough was in the southern Cape, while the Sierra de la Ventana and Falkland areas were undergoing a similar sedimentary history but with lesser subsidence and possibly only intermittent direct connection with the Cape trough. The Andean trough bordered

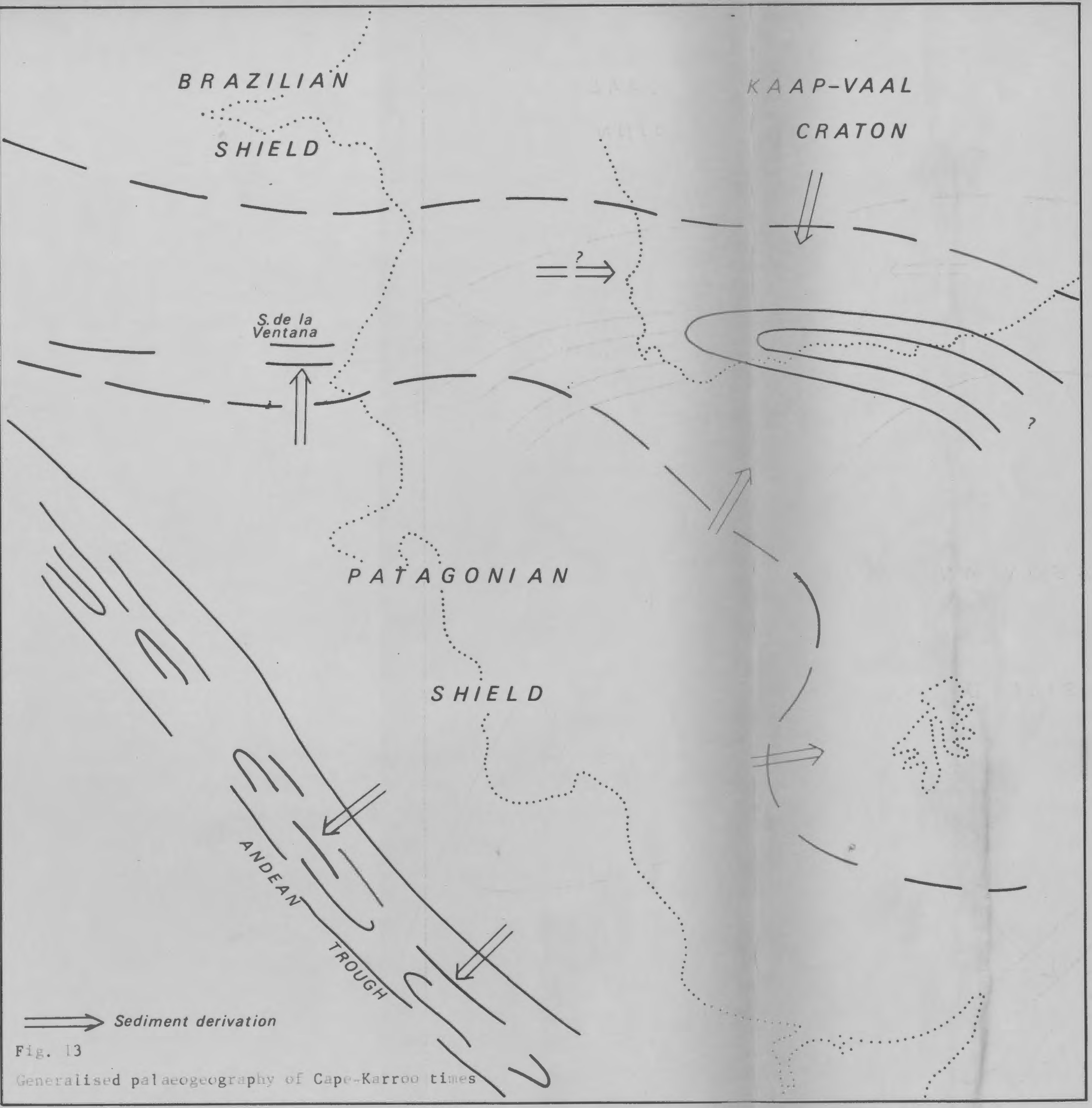


Fig. 13

Generalised palaeogeography of Cape-Karroo times

Gondwanaland to the west.

At the end of Permian time, if the southern shoreline of the Cape trough was still 300km from its axis, the southern slope would have been about 2°. Today, basement occurs within 25km of the axis, giving a nominal slope of 22°. Clearly, extensive uplift occurred to increase this slope, and it is suggested that the uplift was the cause of the deformation through the mechanism of gravitational gliding. The degree of slope necessary to initiate gliding would depend on a number of factors, one of the most important being the pore-fluid pressure in the sediments, since it has been shown (Hubbert and Rubey, 1959) that given high pore-fluid pressures, movement can be initiated on slopes of only a few degrees. That pore-pressure were high cannot now be proved, but impermeable layers to hinder the escape of such fluids were present at many levels in the form of shales, and if, as suggested above, the formation of cleavage was an expression of dewatering, then the presence of fluids under high pressure seems distinctly likely. Folding would begin as soon as the downslope component of gravity exceeded the frictional resistance plus the buckling strength of the rocks, and this may not have been at the same instant for all units - the abundance of disharmonic folding suggests the possibility of some units moving to some extent independently of others. The wavelength of folding seems to have been controlled by the thickness of the dominant competent members: a relationship found to hold for examples spanning several orders of magnitude by Currie, Patnode and Trump (1962). The photogeological maps produced during this study strongly suggest that major fold wavelength is controlled by the Table Mountain sandstones, and probably by the Peninsula Formation alone, since the Nardouw Formation often shows abundant smaller folds related to its different lithology. Bokkeveld rocks show a generally higher density of fold axes than the Table Mountain Group, while the Witteberg, with its thin sandstones, shows a preponderance of comparatively small folds (e.g. Map 4).

Overall, the folding becomes more intense, more asymmetric, and eventually overturned, from south to north, but with local maxima of intensity just north of the major faults, and dies out rapidly and completely along the axis of the trough. It is suggested that the only model compatible with these facts is that of uplift of basement along a series of strike faults, giving an overall northward slope on which sliding took place, but with a series of steps due to these faults (Fig. 7), and a cessation of folding where the slope reversed across the axis of the trough. Friction-generated heat at the base of the sequence was responsible for the growth of ottrelite in the pre-Cape and basal Table Mountain Group. During the formation of cleavages, the rocks would become rapidly dewatered and cemented and much more brittle, so that in the final stages of deformation some thrusting occurred along planes usually only slightly oblique to bedding.

In the northwestern branch of the Fold Belt, deformation is much less intense and asymmetry rather rare, so that it is not certain how much sliding occurred: it is quite possible that the folding here is wholly or partly in response to block adjustment in the basement by faulting.

Folding in the Sierra de la Ventana seems to resemble that of the E-W part of the Cape Belt (Harrington, 1956; Coates, 1969), with cleavage folding and south-dipping axial planes, while the Falkland Islands folds resemble the Cedarberg-type structures, and may also be fault-controlled (Greenway, 1972).

Finally, it is necessary to consider the possible cause of the proposed uplift, and although highly speculative, it is possible to suggest a mechanism which is compatible with certain aspects of the plate tectonic hypothesis and with the history of breakup of this part of Gondwanaland.

Major uplift of the kind proposed here must have its origin at depth - probably in the upper mantle. Gough (1973) has interpreted magnetic evidence in terms of a linear mantle "plume" underlying part of the Cape Fold Belt, and its possible significance has already been commented on (Newton, 1974 B). However, this evidence is as yet incomplete, and it is more profitable to examine a different hypothesis, that of the association between plumes and triple junctions as envisaged by Burke and Dewey (1973). The relevance of triple junctions may not be immediately obvious, but when the relationship of the African and South American plates is examined, one of the striking features is the angularity of the SW corner of Africa, and the corresponding change of direction where the South American shelf meets the northern edge of the Falkland Plateau (Fig. 11). Burke and Dewey (1973) suggest that bends in continental margins commonly mark the sites of triple junctions, and hence plume sites, so the Africa/South America example was studied with this in mind. The north-south trending margins clearly mark the site of original splitting along the mid-Atlantic ridge, and can therefore be regarded as marking a rift. The Falkland

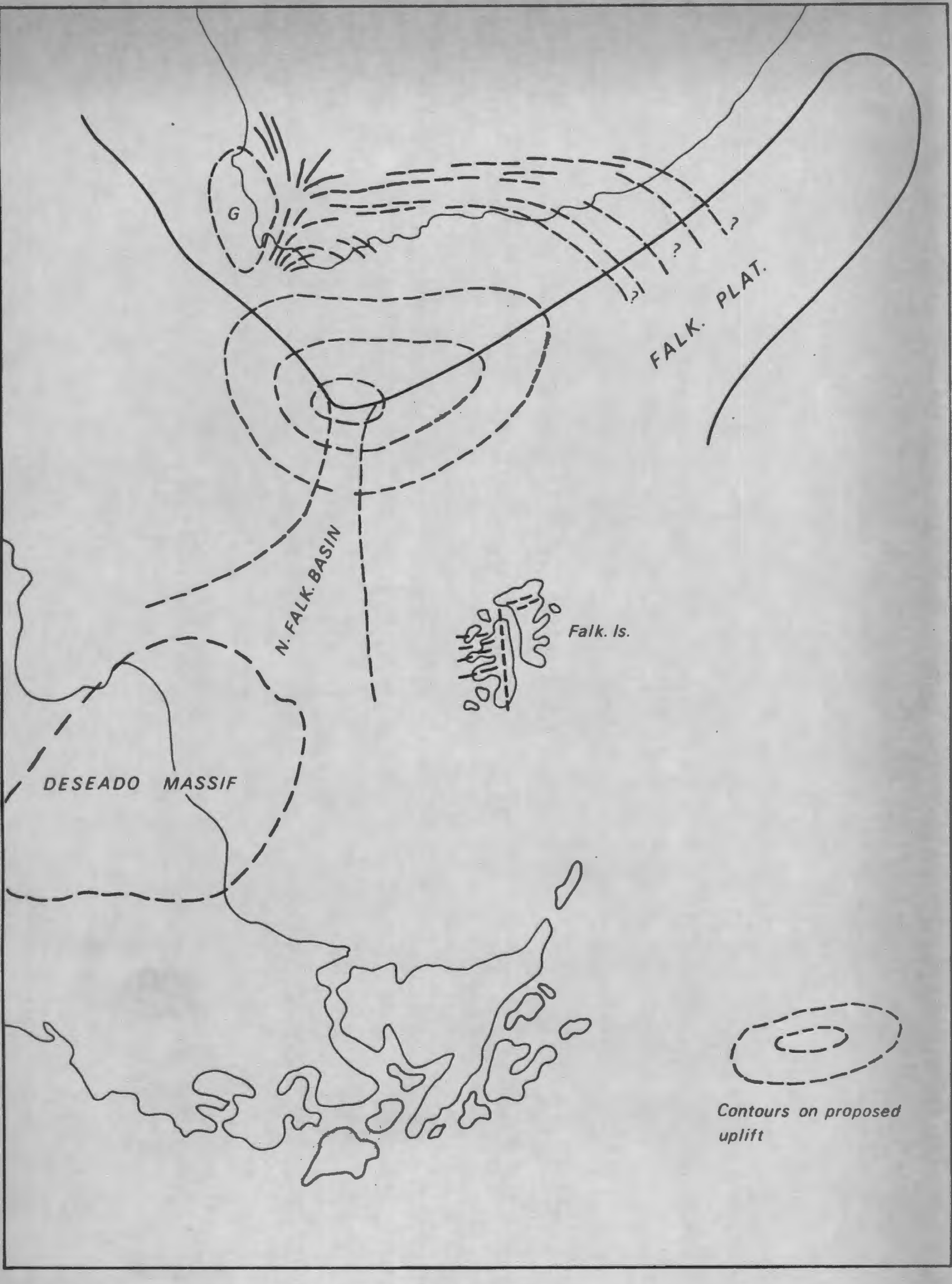
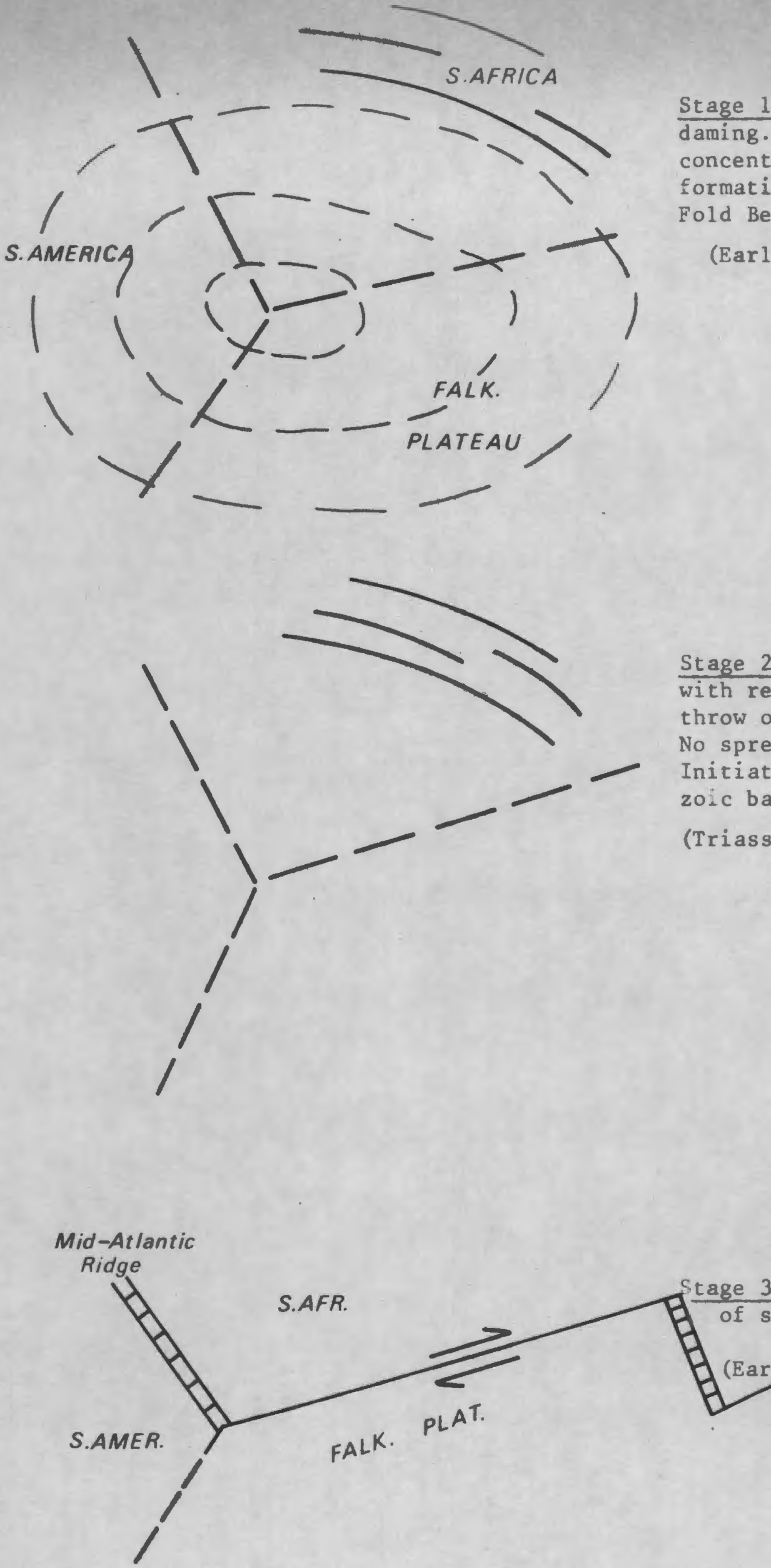


Fig. 14 The postulated Agulhas triple junction

fracture and Agulhas fracture clearly form a transform direction along which lateral movement has taken place (Scrutton and du Plessis, 1973). The presence and nature of the third arm is not so easy to establish, since it must lie on the Falkland plateau, about which very little is known: there is, however, evidence of a trough almost bisecting the angle made by the other two fractures, and meeting them at a common point. This is the North Falkland Basin, whose present day trend is northeastward, and lies to the northwest of the Falkland Islands. According to Zambrano and Urien (1970) this contains up to 2km of sediments, mainly of Upper Cretaceous age. It is therefore possible to postulate a triple junction consisting of one arm which became an active spreading ridge trending north, one arm which apparently remained fairly dormant until Upper Cretaceous, and one arm which became an active transform fault (Fig. 14). Burke and Dewey (1973) cite a similar case at the north end of the Red Sea, where the Dead Sea arm is the transform, the Red Sea is the rift, and the Gulf of Suez is the ridge which did not develop to the spreading stage. The significance for the Cape Fold Belt of identifying this triple junction lies in the uplift which is postulated to accompany and cause the formation of its component fractures. As Fig. 14 shows, uplift centred approximately on such a triple junction would form a large dome, to which the Cape trends are approximately concentric (the continuation of the Cape trends eastward and their arcuation there is based on the suggestion by Dingle (1973), confirmed by information gathered by Soekor (S. du Toit, pers.comm.)). Such an uplift would not only provide the slope down which gravity sliding could take place, but might also have volcanic activity associated with it (Burke and Dewey, 1973) which could have been the source of the volcaniclastic material in the Ecca. The sequence of events visualised for this triple junction is shown diagrammatically in Fig. 15. Stage 1 consists of upwelling and doming in the Upper Permian and Lower Trias (235-200 my B.P.), and formation of concentric and radial lines of failure accompanied by deformation of the Cape Fold Belt. The Cape syntaxis would be the result of the impinging of the northward sliding mass on a relatively rigid basement stiffened by the pre-Cape granites of the SW Cape, which may already have been trending to rise isostatically (Dingle and Scrutton, 1974), and which protected the overlying Table Mountain rocks from deformation (de Villiers, 1956). The upwelling must have been followed by subsidence since no spreading occurred at this stage, and this would lead to a reversal of displacements on the main faults in the Cape Fold Belt, and also to the initiation of the Mesozoic basins of the South African continental shelf and coastal areas which contain sediments as old as Triassic (Dingle and Scrutton, 1974). Stage 3 represents the initiation



Stage 1. Uplift and daming. radial and concentric fractures; formation of Cape Fold Belt.

(Early Triassic)

Stage 2. Subsidence with reversal of throw on Cape faults. No spreading. Initiation of Mesozoic basins.

(Triassic to Jurassic)

Stage 3. Initiation of separation

(Early Cretaceous)

Fig. 15. Schematic representation of the proposed evolution of the Agulhas triple junction.

of the Africa/South America separation in early Cretaceous time (125-130my B.P.; Larsen and Ladd, 1973); the north-trending fracture became a spreading ridge, the east trending fracture became a transform fault, and the third fracture remained dormant until Upper Cretaceous, when it subsided as a trough to receive 2km of Upper Cretaceous sediments. Thus it is suggested that the lines along which this part of Gondwanaland was to fracture may have been determined at an earlier stage, and be associated with the processes responsible for the formation of the Cape Fold Belt.

3.2. Namaqualand

Large areas of southern Africa are underlain by strongly folded and highly metamorphosed rocks, generally termed "basement" though it may consist of rocks of a variety of ages. Elucidating the geological history of such areas requires much detailed field mapping and laboratory work, and *a priori* it seems unlikely that as much of this history will be discernible from interpretation of air photos as is the case for an area such as the Cape Fold Belt. Published studies assessing the amount of information obtainable from air photos in basement terrains are, however, rather few: the most important work is that by Hepworth (e.g. 1967). Apart from this work not many studies can be cited (see Section 2 above), and it was therefore thought worthwhile to investigate parts of Namaqualand where the geology was known from fieldwork, to assess the usefulness of air photo-interpretation in this type of terrain. Two areas were therefore chosen, the first of which had been mapped over many years by the O'okiep Copper Company, and the second was an area newly mapped and described by Joubert (1971). In the latter area structural interpretation was the aspect concentrated on, while in the O'okiep area lithology was treated as well. The O'okiep area also provided an opportunity for the comparison of different film types.

3.2.1. The O'okiep Area (Map 8)

This project was originally visualised as a four-way comparative study involving the existing black-and-white 1:12 500 airphotos and newly-taken colour, infrared/false colour, and low sun angle black-and-white photography. The false colour emulsion is, however, rather unstable, and unfortunately it deteriorated during the flying mission and on processing turned out to be quite useless. The colour and black-and-white imagery is excellent, though.

The area covered is bounded approximately by latitudes 29°28'S and 29°38'S, and longitudes 17°45'E and 17°55'E, and the photographs were taken in five East-West strips of ten photos each, on a scale of about 1:25 000. The camera was a Nistri 54/A of 151.11 mm focal length, and the films Kodak 2402 panchromatic and Kodak 2448 colour negative.

3.2.1.1. Method of Work

A large number of factors determine the amount of geological information obtainable from aerial photographs: these include geological factors such as lithologies present, structural complexity, extent of differential erosion, amount of superficial cover, etc.; vegetation factors - type and amount, and to what extent it is controlled or influenced by the geology; and photographic factors - film and paper types used, processing techniques, sun angle and exposure given, scale and so on. Ideally, for a comparative study, all variables except one should be kept constant, so that the effect of the single variable can be accurately evaluated. This is normally quite impractical, and the aim must be to eliminate as many variables as possible so that the final results will have some meaning. Clearly the geological factors will be a constant in the present study, and to a large extent the vegetation also, although some considerable changes were visible when comparing the old 1:12 500 prints with the new ones.

This leaves the photographic factors, which were the main area of study, and one of the main problems here was the difference in scale and print quality between the 1953 1:12 500 prints and the 1973 1:25 000. In spite of the poor quality of the old photographs, the very much larger scale meant that in general much more detail was visible, so that it was decided to use these as the standard of reference with which the other types would be compared. These were therefore interpreted as fully as possible with the help of the only geological map available - that of Benedict et al (1964), and general observations made as to the extent to which individual lithological units could be distinguished and the general structure elucidated. Comparisons were then made with the 1:12 500 low sun angle and colour prints: this was a laborious procedure because the 1:12 500 flight lines run NE, i.e. across the E-W flight lines of the later photography.

Finally, on a visit to Nababeep, the interpretations were compared with the

1:12 500 field sheets and some of the findings were checked in the field.

3.2.1.2. Interpretation of 1:12 500 black-and-white photographs

(a) Lithology

An attempt was made to differentiate and map the units shown on the geological map of Benedict et al (1964)(Map 8), and the following conclusions were reached regarding the recognition of lithological types.

Modderfontein granite, Brandberg gneiss and Springbok granulite

It is not possible to differentiate these units consistently from one another, since they show overlapping characteristics. The two main modes of outcropping are, first, well-joined, blocky, medium to dark toned with a mottled texture, and second, clean whaleback-type outcrops of generally light tone and almost devoid of vegetation. Both types are seen in association with all three units. Visible banding is scarce in all units, but somewhat less so in the granulites than in the other two.

It is sometimes possible to observe on the photographs the features where the map contacts have been drawn, but on a purely photogeological study these would probably have been drawn in as layering within a single fairly homogeneous unit.

Springbok schist and quartzite. These units are so closely interbanded that for the present purpose they must be regarded as one. They certainly form the most easily recognisable horizon in the whole sequence: slopes underlain by schist are characteristically smooth and often show a tracery of fine lines representing the foliation, while the thin, light-toned outcrops of quartzite can often be traced over quite long distances and are quite unmistakable. The photo characteristics of the Ratelpoort schists and quartzites are identical to those of the Springbok schists and quartzites.

Nababeep gneiss. This can usually be identified because of the fairly consistent presence of coarse lithological banding and the strong topographic expression. The Springbok Upper granulite is usually unbanded and less resistant, typically forming the smoother lower slopes of the Nababeep gneiss hills. The use of visible banding as a criterion means that the contact with the *Transition Stage* is difficult to identify precisely, since the main characteristic of this unit is also its banding, and the difference is mainly one of increased numbers of schist intercalations in the Transition Stage. It must be noted too that the Wolfram Schist outcrops are not distinguishable from the other schist bands on aerial photographs. The *Hornblende gneiss* horizon within the Nababeep gneiss is easily mappable on the photos by the smooth slopes and dark tone of the outcrop, but its precise lithology cannot, of course, be determined.

The Concordia granite gneiss can often be recognised because of its homogeneity and lack of structure (except jointing) over large areas, and the prominent bare whaleback exposures with characteristic light tones. Even where whalebacks are not developed, the particularly good development of several sets of joints, and the resulting rounded boulders, are often characteristic. The contact with the Transition Stage can be drawn consistently but not very accurately, since the main criterion is the upper limit of the banding typical of the Transition rocks. Other units with a very close resemblance to the Concordia are the *Augen gneiss*, the *Red granulite* and the *Rietberg granite*: these show some banding in places, but are not mappable as separate units on the photographs.

The Grey granulite is in many places reasonably distinct as a unit by virtue of distinct banding, often showing minor folding, and close association with bands and lenses of *Shonkinite*, which resembles schist on the photographs. Elsewhere it is indistinguishable from Red granulite and Augen gneiss. On the other hand, the well-banded grey granulite in places resembles the quartzite-schist sequences, and only the fairly subtle difference between quartzite and gneiss bands allows them to be separated.

The Noritoids are a very varied suite of rocks, and show corresponding variability in their topographic and tonal expressions. For the purpose of this study, it is sufficient to divide them into a dioritic and an anorthositic group. The *dioritic type* tend to be darker than their country rocks, and frequently more susceptible to weathering, so that typically they form outcrops of smooth or negative relief, with dark soil tones that can in places be seen even where cultivation has occurred. In some cases, the "diorite" is more resistant than the surrounding rocks and appears as a small, dark-toned hillock, in which case it is easily identified. Comparison with the detailed field maps showed that some "diorites" had been mapped which were not detected on the black-and-white 1:12 500 photographs at all: the reason for this is not known, but may be that in these cases there is a minimum of lithological difference between the "diorite" and its country rock.

The anorthosite type is more varied and usually more difficult to detect than the dioritic type. Some show darker tones and some lighter than the surrounding rocks, but unfortunately the majority have tonal expressions very similar to the rocks in which they occur. Their resistance to weathering also spans quite a wide range, and again many show little difference to their country rocks in this respect. Thus while those bodies with marked tonal and erosional difference to their surroundings can usually be identified fairly easily on aerial photographs, those showing minimal difference in these respects usually cannot.

A third criterion applicable to noritoids in general is shape: in general this is highly irregular and frequently cross-cutting, and is an important supplementary factor in identifying these bodies, usually serving to differentiate them from schist and shonkinite bodies with which they can, in places, be confused.

(b) Folding.

It is in structural geology that photo interpretation usually shows to best advantage: given reasonable exposures and a degree of differential weathering, lithological units can be traced over long distances, outlining the outcrop geometry of folds which can then be reliably interpreted in terms of their profile geometry, plunge, etc., and in favourable cases this can extend to the detection of multiple phases of folding and their probably chronological sequence (Newton and Joubert, 1974). In Namaqualand, Joubert (1971) has presented a convincing case for a very complex structural history involving a number of phases of folding, shearing and fracturing, and logically one would expect to find evidence of these events in the O'okiep area. However, over large parts of the area the structures appear very simple: dips, except in the extreme north, are moderate to gentle as shown by the dip of layering within units and of the contacts between them,and the major structures seem to be gentle, open anticlines and synclines with moderate plunges.

There are, nevertheless, some significant indications of greater structural complexity: first, the well known isoclinal folds near the abattoir, clearly visible on the air photographs, show much too extreme a degree of folding for them to be "drag" folds associated with such a gentle structure as the Springbok dome, and they must therefore be older, a fact recognised by Benedict et al (1964, p.258-9). Second, study of the aerial photographs suggests that the Ratelpoort "syncline" may not be as simple a structure as it appears. Just north of Rietberg the lithological banding appears to swing continuously from NE round to WNW, and on the field maps a prominent foliation is shown which would be axial planar to such a fold. Around Rietberg itself, the picture is complicated by intrusive Concordia granite, but the biotite granulite, for instance, seems to outline the complementary part of the fold where the trend swings from SW round to east. If this is accepted, the structure can be presented diagrammatically as in Fig. 16, taking into account the mapping of Benedict et al (1964) to the east.

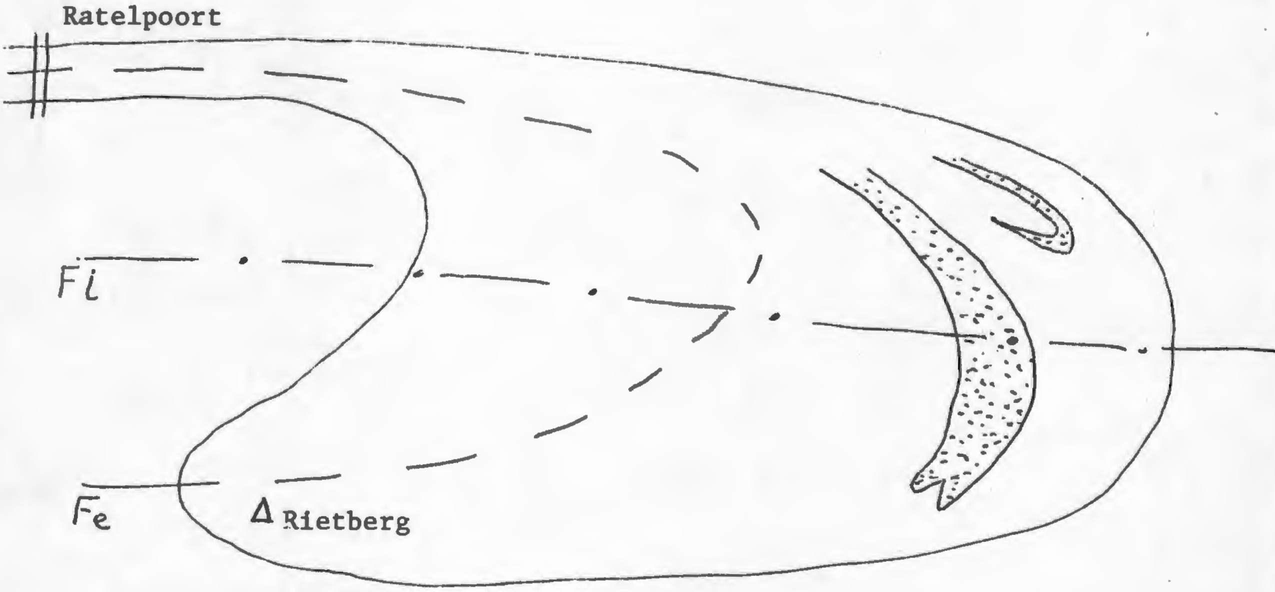


Fig. 16. The Ratelpoort Fold

This represents the folding of an early major structure (axial plane Fe) around a later axial plane Fl. In Joubert's nomenclature, Fe would be F_2 and Fl would be F_3. This interpretation is supported by the quartzite outcrops in the eastern closure mapped by Benedict et al, which strongly suggests the refolding of earlier folds.

The quartzites are undoubtedly the most rewarding from the structural point of view, and the unique view provided by aerial photographs is often an advantage: for instance, just NW of Jan Coetzee a synformal closure was interpreted with some confidence, which was not recorded on the field sheets, although the same structure had been mapped a little further west. This was probably due to poor exposure on the ground being compensated by the overall view provided by the photographs. In the same area, trends of quartzites were often visible on the air photos where no strikes and dips are recorded on the field sheets.

The unusual near-isoclinal and doubly-plunging folds known as "steep structures" (Benedict et al, 1964) are not usually visible on the 1:12 500 photographs: this is attributable to

(i) homogeneity from the weathering point of view of the rocks composing the structures and their surroundings

(ii) the generally small scale of these structures in plan.

(c) Faulting and fracturing.

These are the features best displayed by the photographs, the amount of detail being far more than could readily be produced by field mapping. The scales range from joints up to major deeply eroded lineaments, but it is noteworthy that there is no direct correlation between the length and prominence of a fracture trace and the amount of displacement on it - some of the biggest show little displacement. Joubert (1971) has shown that shearing and fracturing has occurred a number of times during the tectonic history of the area, probably extending up to post-Karroo times, and that many fracture zones show evidence of more than one phase of movement, so that structural interpretation of the fracture pattern would form a complex problem. However, it is felt that a fracture trace analysis might be rewarding, especially in view of the possible association between the steep structures and an episode of fracturing.

3.2.1.3. Comparison of 1:25 000 colour photographs with 1:12 500 black-and-white photographs.

The difference in scale made detailed comparison difficult, but since the low-sun-angle photographs were not suitable for comparison for various reasons (see below) there was no alternative, and several results did in fact emerge.

(i) The schist/quartzite sequences are more distinctive on colour film because of the light to medium brown hue on the schists which contrasts well with the grey to off-white colour of most of the gneisses. Some caution is necessary, however, because similar browns can be observed in transported detritus derived from many rock types, and in many cultivated patches, and other criteria such as lateral continuity and association with quartzites must also be used.

(ii) The quartzites themselves - both Ratelpoort and Springbok - are also very distinctive, and often have a characteristic bluish-grey hue. They are easier to distinguish from gneiss on colour film, when both are interbanded with schist as in the Ratelpoort area.

(iii) Great variation occurs in the colours of soils and other superficial deposits, and although in this area the development of residual soils is rare except on the schists, there might be useful relationships between soil and bedrock in areas where residual soils are more common, such as Bushmanland.

(iv) It was anticipated that colour might make possible the differentiation of gneisses which appear identical in black-and-white photography, but it seems this is not the case. The mineral composition of most of the gneisses and granulites is probably sufficiently similar so that the spectral reflectivity characteristics are very close. All these rocks show up as almost pure white on fresh, clean exposures, and their range of characteristics when weathered appear similar.

(v) The schist bands in the Transition Stage, and the Wolfram schist, have a similar appearance to the other schists described above, and are more clearly visible than on black-and-white.

(vi) Generalisations about the noritoids are difficult because of the variation in the rocks. The more basic ones, with darker colours, show up better than on black-and-white: the large body at Rondegas North, for example, only just discernible in black-and-white, is clear in colour. In some cases, too, dark patches on black-and-white photographs which appear noritoidlike can be dismissed if the colour print shows no distinct colour change. On the other hand, noritoids known from field mapping which are not visible on black-and-white photographs are rarely visible on colour prints either: these are mainly the anorthositic type.

Finally it may be concluded that the colour photographs are very much easier to interpret, particularly for those relatively inexperienced in the work: tonal differences are reinforced by colour contrasts, and these in turn emphasize any banding present and thus aid structural interpretation. Detailed comparison shows, however, that the amount of geologically significant extra information in the colour photographs of this area is relatively small.

3.2.1.4. Low-sun-angle black-and-white photographs

This study stemmed from a model investigation by Hackman (1967) into the influence of shadows and angle of illumination on interpretation, which suggested that low angles might be an advantage in some cases; no tests of this idea have been published, and the opportunity was therefore taken in this case. The photographs were taken over a period of approximately 0830 to 0900 hours, during which time the sun angle changed from 22^{o} to 34^{o}. The first strip taken was the most southerly one.

The area is not ideal for such a test for two reasons: first, the relief is considerable, and in theory one would expect the maximum benefits from this technique in low relief areas such as Bushmanland. Second, the general trend of the strike is approximately E-W, so that the illumination falls at a fairly small angle to strike, whereas the maximum benefit could be expected with the illumination at right angles to strike.

The disadvantage of pronounced relief is that the proportion of the terrain under shadow tends to be larger than is desirable for most interpretation investigations, while steep slopes facing the sun tend to be overexposed, resulting in a very high contrast image. Both these effects are well demonstrated in the photographs. It seems that the angle of incidence (i.e. angle between the ground surface and the incident light) is very critical and that useful extra evidence due to microrelief is obtained only if the angle of incidence is within a few degrees of the grazing angle. For flat and gently undulating terrain, any photographs taken more than about half an hour after sunrise will look similar to those taken at later times. In hilly country, slopes oriented so that the critical angle is achieved (i.e. those sloping away from the sun at less than the sun's elevation angle) will show the maximum amount of detail, but this will often not be traceable very far because of either deep shadow or burnt-out highlight in the photograph, unless film type and processing are chosen to minimise these successfully.

There is also an effect on the visibility of fractures: those oblique or normal to the sun direction will throw shadows provided they are topographically expressed, whereas those parallel to the sun's rays will be minimised and may be overlooked. Fracture analysis should therefore not be undertaken on such photography unless two sets of photographs with widely different sun-directions are available.

3.2.1.5. Conclusions

The aim of this study was to evaluate as objectively as possible the different types of imagery in the particular terrain covered. The conclusions therefore must be taken to apply only to that area, and would probably not be applicable to nearby areas where the geology or the physical terrain are somewhat different. With this proviso in mind, the conclusions are as follows:

1. There is little difference between the black-and-white and colour photos as regards lithological differentiation - the large scale of the black-and-white photographs is largely compensated by the accentuated visual clues provided by colour film. In neither case can all the rock-types recognised on the ground be differentiated, but with care the following categories can be mapped

    (i) Nababeep Gneiss
    (ii) Hornblende Gneiss
    (iii) Transition Stage
    (iv) Concordia, Augen Gneiss, Red granulite and Rietberg granite. These can be differentiated only on the basis of stratigraphic position in most cases.
    (v) Schists. Can only be differentiated on stratigraphic position.
    (vi) Quartzites.
    (vii) Modderfontein granite. Brandberg gneiss and Springbok granulites. Can only be differentiated on the basis of stratigraphic position.
    (viii) Noritoids. Only those showing darker tones than their country

rocks can normally be detected.

Locally, a finer subdivision may well be possible: the above conclusions refer to the possibility of consistent results over the whole area.

The main reason for the comparatively poor results is the high metamorphic grade in the area: this has resulted in a convergence of mineralogy and texture between rocks with probably much greater differences originally, which in turn means that differences in weathering and susceptibility to erosion are minimal, these being the main factors enabling rocks to be differentiated on air photographs.

2. Because of the high metamorphic grade, foliation is not always well developed, and this hampers structural interpretation. The main aids to evaluation are the schist/quartzite horizons. The unique viewpoint offered by aerial photographs provides information which supplements that from fieldwork, and may suggest new interpretations based on a broader view.

3. The fracture pattern is particularly well displayed on aerial photographs, and a detailed fracture trace analysis might well be worthwhile. The larger scale black-and-white photographs, supplemented by a mosaic and the satellite photographs, would be the best material to use.

4. On comparing the colour and the black-and-white photography, there is no doubt that the colour has the greater immediate impact, is the easier to interpret (particularly for the non-specialist), and potentially contains more information. In the area studied, however, colour variations in bedrock are often small, and for detailed interpretation the scale of photography is more important. However, it must be mentioned that the 1:25 000 colour prints were considered to be as good as the 1:12 500 black-and-white prints from most points of view, and in some cases are to be preferred.

5. Low-sun-angle photography cannot be considered to be a useful technique in the area studied.

3.2.2. Springbok-Bitterfontein Area

The results of this work were incorporated in a joint publication with Dr. P. Joubert, and since no further work has been done in this area, this section is presented in the form of the original paper.

Since this is a joint publication, it is appropriate to point out the relative responsibilities and contributions of the two authors, as follows.

From his knowledge of the field area and aerial photographs, P. Joubert chose the examples. These photographs were then studied by the writer, and an overlay and interpretation put forward, which were then compared with the geology as mapped in the field by Joubert. Generally, the agreement was good, with the exception of the Banke structure, which is fully described in the text. The paper was written by A.R. Newton, with the exception of the section on general geology.

PHOTOGEOLOGY IN A GRANITIC GNEISS TERRAIN: NAMAQUALAND, SOUTH AFRICA

by

A. R. NEWTON AND P. JOUBERT

ABSTRACT

The purpose of the paper is to examine, in a particular instance, the extent to which photo-interpretation can be used as an aid to mapping in areas where the tectonic history has been long and complex. The area chosen is in Namaqualand, northwestern Cape Province, where the tectonic and metamorphic history has been worked out in some detail (Joubert, 1971). The rocks are high-grade gneisses and other metasediments which, on the whole, are not easy to differentiate from each other on air photos except where differences in composition are considerable. The first deformational event consists of four periods of folding, with some accompanying shearing; the first episode (F_1) resulted in penetrative isoclinal folding, which is responsible for the layering most prominent now, and only relict fold closures show its tectonic origin: these can occasionally be seen on the photographs. The second episode (F_2) also consisted of tight, penetrative folds which are deformed by the more gentle, open structures of F_3. Interference patterns produced by these two phases are clearly seen on air photos. The fourth phase (F_4) consists of broad open folds which have a different trend from, and deflect, the F_3 folds, and can easily be recognised on air photos. The second deformational event consisted mainly of episodes of shearing and fracturing, and although these structures are in general clearly visible on the photos, their age relationships are difficult to determine. It is concluded that, given good exposures, photo-interpretation may be of more use in areas of complex structure than has hitherto been realised.

CONTENTS

I. INTRODUCTION

The examples on which this study is based were taken from an extensive area mapped by one of us (P.J.) and a full description of the geology can be found elsewhere (Joubert, 1971). The area mapped is shown in Figure 1, and the location of the photographs used here is shown in Figure 2. The purpose of the study was to examine the extent to which the known complexity of the structures in the area could be discerned from purely photographic evidence, since few previous studies have dealt with photo-interpretation in areas with such a complex structural history. We hope that our results will be useful to workers in complex "basement" terrains in other parts of the world.

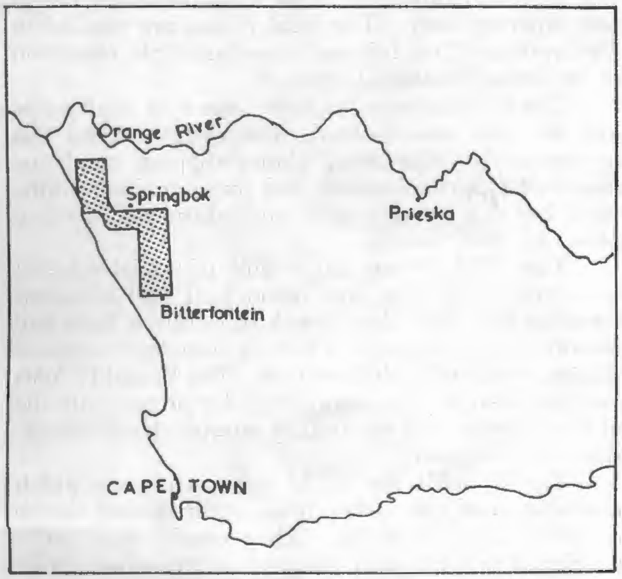


Figure 1 Location of the area mapped.

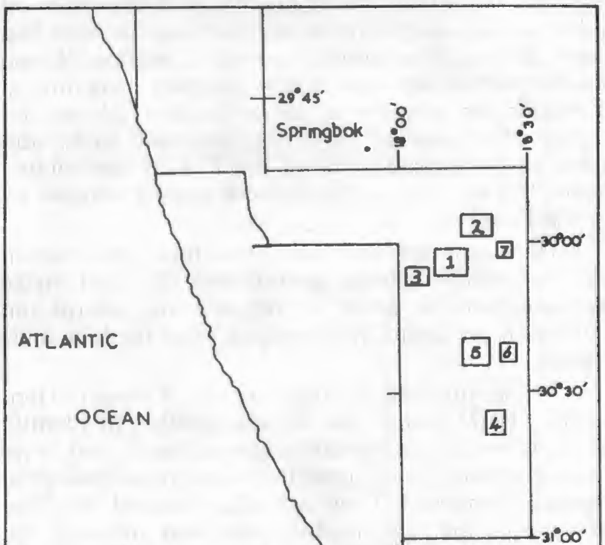


Figure 2 Location of examples discussed. Numbers correspond to Plate numbers in text.

The examples chosen show most clearly both the general style of each of the main phases of deformation, and the patterns resulting from their mutual interference. Over much of the area, therefore, the evidence is less clear than is shown by the examples, but the latter are by no means unique, and one of the results to emerge from this work was to show that, in reasonably well exposed areas, a thorough study of the photographs will usually reveal localities at which the most important structural relationships can be determined, and these then provide valuable aids to the interpretation of the remainder of the area.

The method of work was as follows:—

Suitably small areas were chosen by one of us (P.J.) on the basis of the known field geology, and were then interpreted by the other (A.R.N.). This interpretation was then checked against the field data, and it was found that usually only minor alterations were necessary.

II. PREVIOUS WORK

Although no other studies of this type have been carried out in Namaqualand, there are a few published works which deal with the same type of problem and are therefore relevant. In eastern Greece, Bodechtel and Papadeas (1968) studied an area of complex folding, faulting and metamorphism and were able to distinguish three phases of folding, the earliest trending northwest, followed by a northeasterly trending set, and finally a north-south set of folds. They measured dips photogrammetrically and plotted their results stereographically. They were also able to differentiate three phases of faulting from their relationships to each other and to the folding. Unfortunately their paper was not illustrated with any actual aerial photographs.

Stephens (1969) showed that it is possible to use modern methods of structural analysis on data obtained from aerial photographs: once true north can be established, strike of bedding or foliation can be measured with an accuracy equal to that possible in the field, although measurement of dips presents some problems due to vertical exaggeration. However, he was able to construct β and π diagrams for adjacent small domains in Malawi, and these showed sufficient inhomogeneity to suggest that the area had been affected by a second period of folding. Using similar techniques on a single complex structure in Tanzania, he was able to define the axial planes and plunge directions of three superimposed folds, and show how the axial plane of the F_1 fold was rotated about the F_2 axis, and both were slightly warped by gentle F_3 folding.

He concluded that valid structural information can be obtained from quantitative dip and strike measurements in areas of regional metamorphism, but again no actual photographs were used in illustration.

While studying a large area in Uganda, Hepworth (1967) noted that it was possible to identify areas where a particular tectonic trend and style were dominant, and these he called photogeological tectonic domains. They are characterised by "the attitude of the regional fold axes and trend of the regional strike; lithology and metamorphic grade; structural or tectonic style; tectonic sequence" (op. cit. p. 255). Three of these units were recognisable in Uganda: the first has an east-west trend consisting of strike ridges, foliation, fractures and granite dykes; the second trends north-south and has strong axial plane foliation and prominent cross-joints; the third is characterised by close-spaced northwest-trending, nearly vertical dips which are the result of intense folding and shearing of gneisses. Age relationships are given by the overprinting of the second on the first and of the third on the second, at some localities. This technique, clearly of most use in the reconnaissance mapping of old orogenic belts, depends on there being a reasonable geographic separation between the different units, and this seems to be the case in East Africa, since the method was later used again in Tanzania (Hepworth and Kennerley, 1970; Hepworth, Kennerley and Shackleton, 1967).

III. GENERAL GEOLOGY

A full description of the geology of the area will be found elsewhere (Joubert, 1971) and what follows is a summary of the features most relevant to photo-interpretation, i.e. lithology, sequence and structure.

The rocks are metasediments and metavolcanics, generally of high metamorphic grade, i.e. gneisses and schists. Original lithologies probably included quartzites, feldspathic quartzites, arkoses, limestones, pelites and semipelites. This sequence may be correlated with the Kheis "System" in which case its age would be greater than 2 600 m.y. (Joubert, 1971). The basement on which these rocks were laid down was granitic and is now also represented by gneiss. The stratigraphic column for the area is shown in Table I.

TABLE I

vi	Pyroxene granulites, pyroxene and hornblende-bearing gneisses, fine-grained biotite gneisses with minor leptites in the east; mainly fine-grained biotite gneisses with some amphibolites in the west. Represented by KhG and KhA in Figures 3-10.
v	Metaquartzites: these are most prominent in the west, thinning and disappearing eastwards except for small lenses at or near the base of the mafic rocks, and are in places accompanied by minor bands and lenses of crystalline dolomite. Not present in areas described in this paper.
iv	Aluminous schists and gneisses: these consist mainly of cordierite-sillimanite schists in the east, and muscovite schists in the west. Represented by Kh.Gr.
iii	Leptites, usually only a thin band, but it is fairly consistently present. Represented by Kh.Gn.
ii	Pink biotite gneiss, prominent in the southeast of the area, but absent in the west. Represented by Gnm.
i	Nababeep gneiss (basement). Variable, but usually a streaky augen gneiss, in which lensoid aggregates of quartz and feldspar are enclosed by biotite-rich streaks and laminae. Represented by Gn.

The deformational history of these rocks is very long and complex, including folding and shearing under a variety of metamorphic conditions. In the following account, the individual episodes of deformation are grouped together into events, following the recommendations of Sutton (1965).

First Event: Four episodes of folding have been recognised, and are designated F_1 to F_4. F_1 is represented by the widespread tectonic banding, in which can be found intrafolial folds with thickened hinges and tapering limbs. The axial planes are parallel to the layering. This folding caused multiple repetition of the same lithological types.

The F_2 folds occur on both large and small scales and are also near-isoclinal. The original trend was northwesterly, with axial planes dipping gently or moderately northeastwards and axes plunging northwest, but this trend is now much disturbed in many places by later folding.

The F_3 folds are large and of variable style; most commonly they are monoclinal and east-west trending and their short, vertical, southern limbs are usually highly sheared. There is also some tectonic sliding associated with these folds. The F_2 and F_3 folds are the main factors controlling the present attitude of the layering, and where they interfere large brachy-structures are seen.

The F_4 folds are broad open structures which mildly deform the earlier folds, again giving rise to broad domes and basins. They usually have well-developed vertical axial planar fractures which strike northwest. The plunge of these structures varies with the pre-existing dip of the foliation which they deform, and hence is steep in some places. They die out rapidly both along and across strike, and thus have a rather disharmonic appearance. Granite, followed by pegmatite, was introduced at this time, which radiometric dating places at about 1 000 m.y.

Second Event: This consisted of the development of major shear zones, which in order of decreasing age and intensity are as follows:—

First, a west-northwest trend, within which folds and lineations plunge westwards; second, northeasterly shears in which linear structures plunge northeast, and third, north-south shears in which linear structures plunge north. Marginal folds, which are initially open and gently plunging, become very tight and steeply plunging within the shear zones, where the rocks are strongly refoliated. Fractures parallel the shear zones.

Third Event: This was confined largely to the western (coastal) regions, and consisted of the development of strong north-northeast shear zones, along which the rocks were reduced to phyllonites. Folds formed parallel to these zones, and with the development of relatively minor north-northwesterly shears, conjugate folds were formed. Mafic dykes were intruded along north-northeast, north-northwest and north-south fractures, and granite intruded in the north: these rocks give radiometric ages of about 880 m.y. and about 850 m.y. respectively, giving an approximate date for this deformation. A much later and final phase consisted of a repetition of north-south folding and fracturing. The faulting was of normal type, with development of breccias and other cataclasites, and gave rise to horst and graben structures, of which the dominant structure is a major complex horst in the Kamiesberg area. Most of the faults are probably due to rejuvenation of older lines of weakness.

IV. GENERAL PHOTOGEOLOGY

The photos are prints of standard Government panchromatic photography flown in 1960 on a scale of 1:40 000, using a 114,2 mm lens in a RC5 camera. The format is 7 in x 7 in (18 cm x 18 cm).

The topography of the area as a whole is quite rugged, with a dissected escarpment in the west overlooking a raised coastal plain, the degree of dissection diminishing westwards until a high level of plateau is reached in the east. Exposures are consequently good except where bedrock is covered by alluvial and colluvial material, and the vegetative covering is sparse due to the low rainfall. Such conditions are very nearly ideal for photogeological interpretation, the main difficulty being the lack of lithological differentiation.

A. Lithology

This aspect of the photogeology is the one to which, in general, least certainty can be attached, and the difficulties are compounded for areas of metamorphic rocks due to the convergence of properties of different lithologies with increasing metamorphic grade. A study of the photos in this case reveals that the predominant rock types form a rugged terrain, with frequent "whaleback" topographic forms, coarse banding, very light tones where bare rock is exposed, and are strongly jointed. The topography and jointing suggest a hard, massive rock and the whaleback forms are characteristic of granite, but the banding suggests gneissosity, and thus the rocks can be identified with some confidence as granitic gneisses or granulites.

Many textural varieties exist which can be distinguished on the ground, but whose weathering properties are so similar that they are often indistinguishable on the photos. Only where their composition becomes more mafic does their appearance change sufficiently for them to be easily recognisable. The most distinct lithological types, e.g. quartzites and limestones, are present only in rather scattered localities and in fairly small amounts. The basic criteria for lithologic recognition in the area as a whole are as follows:—

1. *Tone.* The gradation from felsic to mafic gneisses is accompanied by an increasing darkness of tone. However, tone is rarely uniform, and the appearance is usually mottled due to alternation of exfoliation surfaces which are smooth and light-toned, with patches where the rock is strongly jointed and therefore blocky and appears darker. Metaquartzites and quartz schists are very light-toned, but some quartzites are arkosic and are then very difficult to identify. Crystalline limestones appear as small white patches in the gneisses.
2. *Surface texture.* Accompanying the change from felsic to mafic in the gneisses is a change of surface appearance: the granitoid rocks have a rough and blocky surface with some exfoliation surfaces, but the more mafic the rock, the smoother the surface appears.
3. *Resistance to weathering.* The felsic gneisses are most resistant, and they usually form the highest ground. Mafic bands have a variable but lesser resistance; the hills they form may be less high, or they may actually form valleys, depending on the relative resistance of the immediate country rocks. The white metaquartzites and quartz schists are very prominent topographically.
4. *Foliation.* In the leucocratic rocks, where tone and texture are largely similar, the degree of foliation can be used in places to differentiate one type from another. For instance, the Nababeep type gneiss is usually unfoliated, the pink gneisses foliated, and the leptites may be quite well foliated. This criterion must be applied with care, however, and is not to be relied upon in the absence of confirmatory data. The foliation is due to a lithological layering which will be shown below to have a complex tectonic origin, and is not bedding. The mafic rocks show the best banding due to variations in composition, even including intercalated leucocratic bands.

B. Structures

Folding can be traced out by means of lithological layering and by foliation in compositionally uniform rocks. The best markers are the dark mafic bands in more leucocratic gneisses. Lines of fractures are very prominent on most photos, and grade from joints up to major faults. However, the degree of topographic expression is not always related to the importance of the fracture: many prominent straight-line valleys are clearly fracture-controlled but show no evidence of any displacement, while some prominent fault zones are hardly visible. Shear zones are another distinctive element in the structure, and show up in several different ways:—

(a) banding is dragged into and aligned parallel to the shear;

(b) dark zones where mafic rocks have been dragged into the shear — often negatively weathered and forming trenches across hills;

(c) prominent ridges where thin quartz appears to have been repeatedly folded along strike;

(d) parallel-sided zones of no outcrop crossing well-exposed rocks. These may be marked by marginal ridges.

V. PHOTOGEOLOGICAL EXAMPLES

In this section seven small areas are described, and the extent to which (a) lithology and (b) structure can be determined from aerial photographs is discussed. In each case the photographs are reproduced as a Plate, and the corresponding interpretation shown as a Figure on the opposite page.

The Rooifontein structure (Plate I and Figure 3)

Most of the rocks making up this complex synform are coarsely banded leptites and pink gneisses. The presence of banding inhibits the formation of exfoliation domes, but quite large exfoliation surfaces are present. Individual bands cannot be traced very far. These rocks are separated from Nababeep gneiss by only a thin band of mafic gneiss, and in this case the Nababeep gneiss also shows some banding, so that it is not distinguishable from the leptites on the photos. Overlying the leptites are hornblende- and hypersthene-gneisses, which are rather poorly foliated and slightly darker in tone. Some bands are more easily eroded, but otherwise there is only the tone to distinguish them from the leptites.

The layering in the gneisses is a notable feature, and it is necessary to first establish the nature of this layering as far as possible. It is roughly parallel to planes where composition changes occur, which suggests bedding, but against this are several other lines of evidence. First, it has the characteristic of being widely spaced, much more widely than normal sedimentary bedding in most cases. Second, individual rock units between foliation planes thicken and thin, and none can be traced very far laterally. Third, and most important, is the presence of fold closures in this foliation (A and B, Figure 3). At B, a mafic band divides into two and outlines the fold closure.

There is thus strong evidence that the layering is not bedding, but a foliation parallel to the axial planes of early isoclinal folds. Abundant confirmatory evidence of this was found in the field. This early folding is called F_1, and thus the phase of folding which deformed this foliation is F_2. Therefore the main synformal structure must be attributed to F_2. However, when the axial trace of this structure is drawn in, its sinuous nature becomes apparent, and this is interpreted as being due to further deformation by a phase of folding which can be called F_3. From the form of the trace of the F_2 axial plane, it seems likely

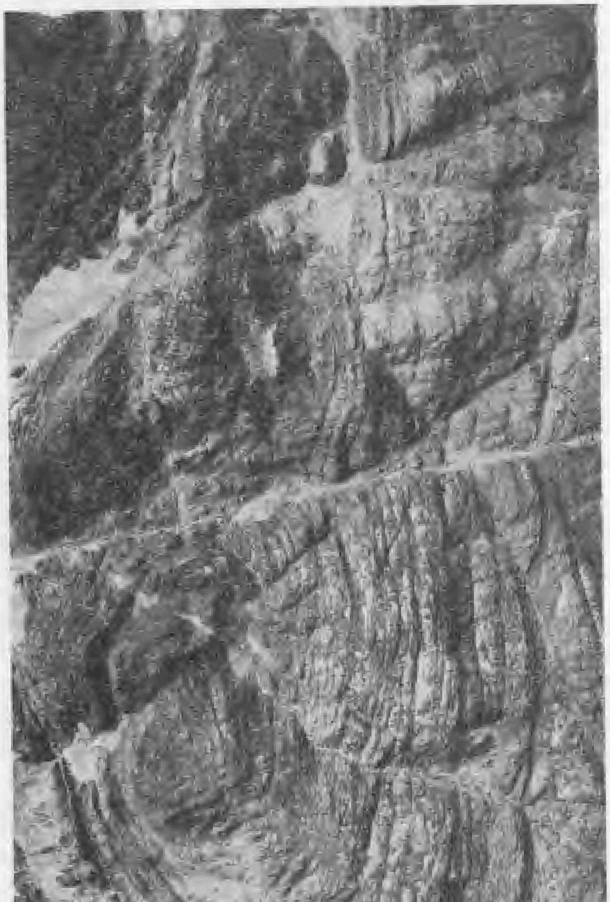


Plate I The Rooifontein structure. (S. African Government photography).

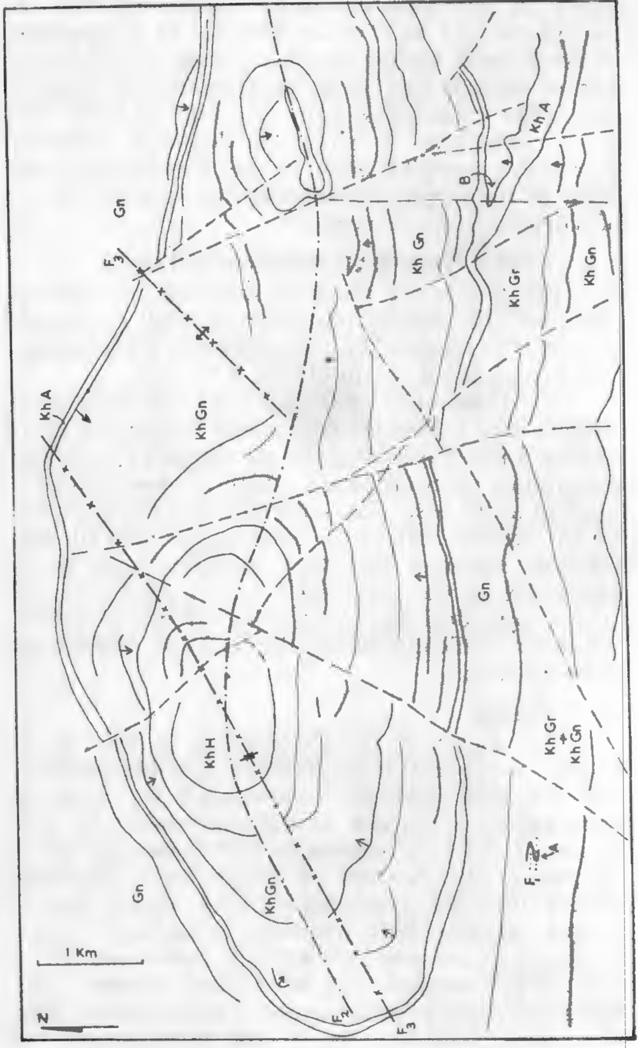


Figure 3 The Rooifontein structure.
For key to abbreviations see Table I.

that two F_3 folds are present, their axial traces trending northeast. A syncline crosses the western end of the F_2 synform, and its effect is to open out the synform into the elongated basin seen on the photos. This is flanked on the southeastern side by a more gentle anticline, which only affects the northern limb of the F_2 structure, but is responsible for swinging the F_2 axis from northwest to approximately east-west.

Allowance can now be made for the F_3 structures in reconstructing the original F_2 fold. Its trend must have been approximately east-west, and at its eastern end, where the effect of F_3 was at a minimum, dips are very steep on the north limb and more moderate on the south limb. Thus the axial plane probably had a steep northerly dip. The asymmetry of the fold is in fact still preserved in the parts of the fold affected by F_3, in that the dips on the north side are steeper.

The latest structures are faults and joints. The faults show very small displacements but are very prominent topographically, forming major valley features. Their general trend is north-south or slightly west of north. Less extensive fractures occur along northwest and northeast lines. The joints show a similar spread, and also a similar predominance in a north-south direction.

The Tweefontein structure (Plate II and Figure 4)

The core of the structure consists of pink biotite gneiss (Gnm) which in this area is generally massive or shows only very coarse banding. Exfoliation domes are not well-developed. The surface texture is rough due to blocky weathering, which in turn is due to the strong development of jointing in several directions. The tone is rather dark, but mottled with small lighter patches where smooth exfoliation surfaces are exposed. Its resistance to weathering is variable, and is possibly related to the intensity of joint development, but generally it forms some of the highest hills. Drainage lines are short and steep, and are also frequently controlled by joint directions.

Overlying the biotite gneiss are leptites and leptynites (KhGn). Due to the varying lithology, banding is often well-developed, although individual bands cannot usually be traced very far. The surface morphology is variable, in some places being quite rugged while elsewhere it is relatively smooth. The difference between these and the underlying gneisses is not great, and on the photos is based mainly on the presence of banding shown up by differential weathering.

Above the leptites is a large and complex group of mafic rocks, consisting of biotite gneiss, cordierite gneiss and hornblende-hypersthene gneiss (KhG, KhA, KhGr). These varieties cannot be identified on the photos, although banding is visible. The group as a whole is easily identifiable by the fineness of the banding, the overall darker tone, and the relatively low relief. Leucocratic bands occur, often outlining small-scale folds, and usually forming low ridges.

Foliation traces out a classic pattern of refolded folds. The latest phase is an east-west one, and the reorientation of the earlier folds gives a rather asymmetric "mushroom" or "fir-tree" pattern (Ramsay, 1967, pp. 528-529). The latest fold is antiformal, and swings the earlier fold axis through about 150° from east-southeast to west-southwest. Plunge directions in the early fold suggest that this was also antiformal, and the geometry suggests a northeast-dipping axial plane. The late fold plunges moderately eastward. Further fold axes can be traced around the nose of the late fold in the east, and the most northerly one shows a closure of foliation on its northern flank, indicating a still earlier phase of folding. A similar but less clear case occurs in the southeast.

Thus three phases of folding can be demonstrated from photo evidence alone: F_1 is isoclinal, with the axial plane lying in the foliation, i.e. present foliation is in fact an axial plane cleavage. This set of folds has been refolded by F_2: probably also tight, but with moderate to steeply inclined axial planes. The trend of these folds is now variable, due to the next phase. F_3 synformal axis runs through here and may have easterly plunge. The F_2 fold in the extreme north may owe some of its acuteness to the F_3 phase; an F_3 synformal axis runs through here and may have caused appression of the existing F_2 fold limbs.

The Rooi Doorn Kloof structure (Plate III and Figure 5)

Lithologies are difficult to distinguish here. Nababeep gneiss is present in the north, and is very massive, while to the south there are leptites, pink gneiss and biotite gneiss with mafic bands. These are interbanded by folding and all show some foliation which outlines the form of the structure, but the individual lithologies cannot be identified.

The foliation and layering can be seen curving around the hinge of a large northwest-trending fold. However, several of the bands pinch out on the fold flanks, giving a pattern characteristic of refolded folds. Thus it seems likely that the alternation of lithologies in the main fold is not a stratigraphic sequence but is due to refolding of a set of earlier, near-isoclinal folds. Fieldwork confirms this deduction: the early folds are of F_1 age, and the northwest-trending later fold, which is an overturned, near isoclinal reclined fold with a fairly steep northwest plunge, and steeply northeast dipping axial plane, belongs to F_2. Examination of the adjacent photographs shows that the F_2 axial trace also swings gently, becoming east-west further east, and this swing is due to a still later phase, F_3. The curvature is hardly perceptible in the area shown in Figure 5, however.

The Elands Kloof structure (Plate IV and Figure 6)

Three groups of rocks are represented: the first, consisting of leptites and pink gneisses (Gnm, KhGn), forms the highest ground. These rocks are poorly banded, and have a mottled appearance due to small light-toned patches of bare rock contrasting with dark patches of scrub vegetation. The surface morphology is rough and irregular. The second group comprises biotite gneiss with mafic bands (KhG), and these are as usual characterised by finely spaced foliation, less positive relief, a smoother surface and darker tone. In this example there is also a characteristic vegetation pattern consisting of small clumps of dark bushes, sub-circular to irregular in shape. Ultramafic gneiss (KhA) forms the third group and has a very dark tone and a massive, rounded, irregularly fractured outcrop form.

The structural interpretation shows a basin in the north, with a trough extending from it in a southeasterly direction, and detailed examination shows that this is the result of the mutual interference of three phases of folding. The latest phase is represented by a northwest trending synform which can be assigned to F_4 on the basis of its trend and gentle, open nature. In the north this induces a gentle swing in the axis of another open synform which originally

Plate II The Tweefontein structure (S. African Government photography).

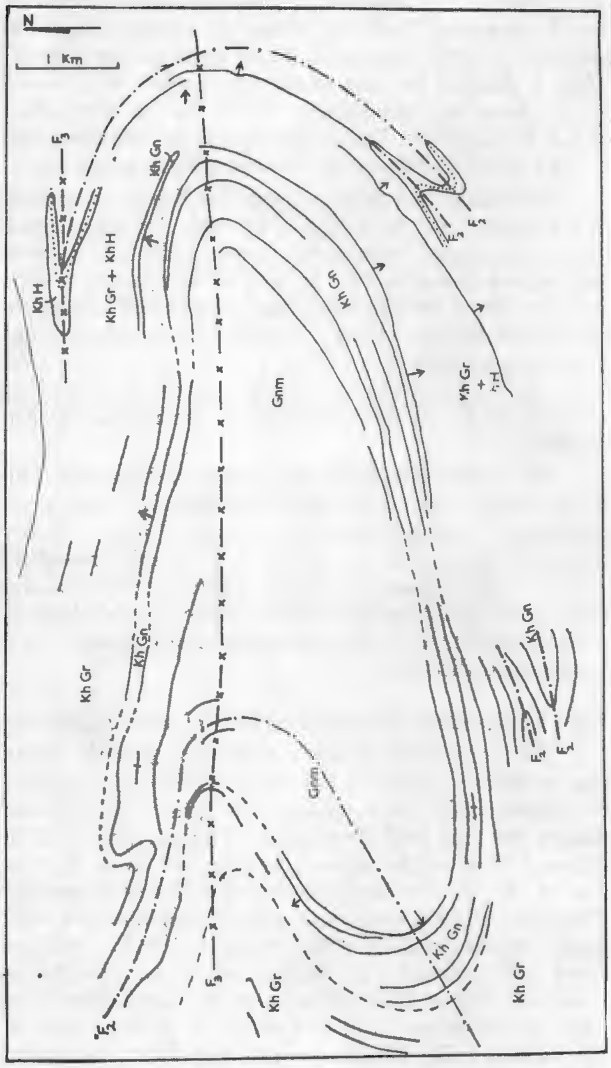


Figure 4 The Tweefontein structure.

must have had an east-west or east-northeast trend. Again, the trend and style help to identify this fold as belonging to F_3. The interference of F_3 and F_4 synforms thus produced a basin which is somewhat asymmetric, the northwestern side having dips which are steeper, even overturned in places.

Further southeast, the leptites and biotite gneisses intertongue, and the tightness of the folding and the sharp closures suggest F_2 folds. This diagnosis can be proved in the field. These folds have been more severely deflected than the F_3 fold, possibly due to their axial planes having an originally shallower dip: this seems probable from a study of their axial plane dip along the axis of the F_4 fold, where the original dip should be preserved. In this example, the differentiation of F_2 and F_3 is difficult, since they have the same trend, but there is still sufficient difference in style for a correct identification to be made. F_1 folds are not visible at all in this case. The later stages of deformation are represented by a major fracture on the western side, trending north-northeast, and a smaller fracture of similar trend in the east from which a third fault branches off to the north-northwest.

The Slagieskop structure (Plate V and Figure 7)

The core of this large antiformal structure is Nababeep-type gneiss (Gn) which is very uniform and structureless except for fractures. It shows some exfoliation domes which show up as light-toned patches compared with the more normal darker tones of the well-jointed, blocky gneiss. In this gneiss is a prominent dark-toned band (KhA) with a smooth surface expression: both features typical of mafic rocks especially when, as here, combined with negative weathering. Biotite- and cordierite-gneisses (KhGr) are quite well foliated, and form generally subdued topography, but otherwise have no unique characteristics. The shear zones (S) closely resemble these foliated gneisses, but their foliation is rather more penetrative and they can be transgressive. The porphyritic granitic gneiss (Gnp) is distinctive in that it is massive and shows prominent exfoliation domes with characteristic shape and light tone, and although this is also true locally of the overlying leptites (KhGn), the latter show some foliation and in most places a more blocky weathering.

The major antiform trends east-northeast and plunges steeply west. Its axial plane dips north, since the southern limb is slightly overturned. The orientation and style are distinctive of the F_3 episode, but in this case there is a difference in the presence of a shear zone more or less concordant with the foliation and formed during folding. A second shear zone is present in the west, and can be seen to cut across the

Plate III The Rooi Doorn Kloof structure (S. African Government photography).

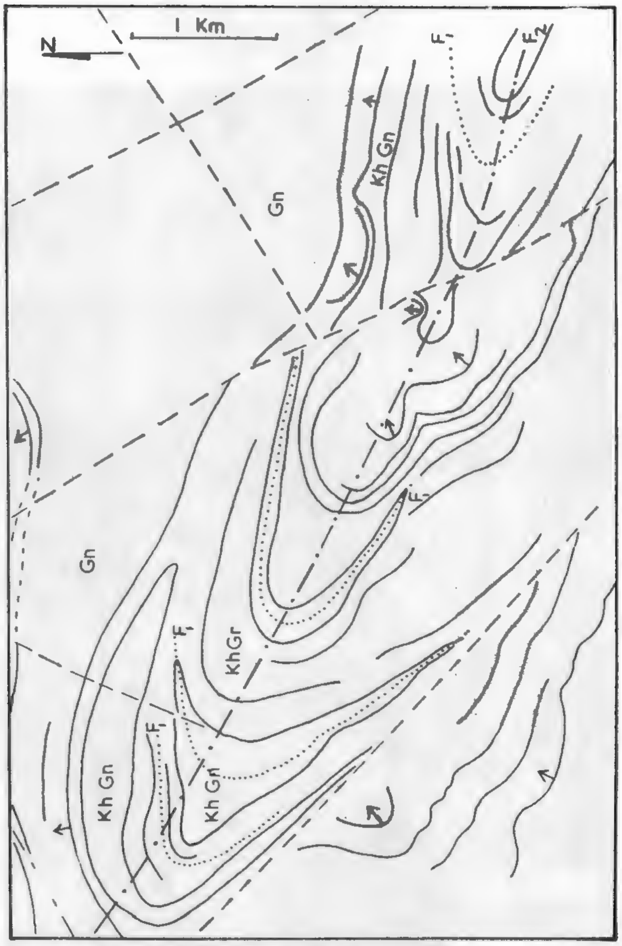


Figure 5 The Rooi Doorn Kloof structure.

Plate IV The Elands Kloof structure (S. African Government photography).

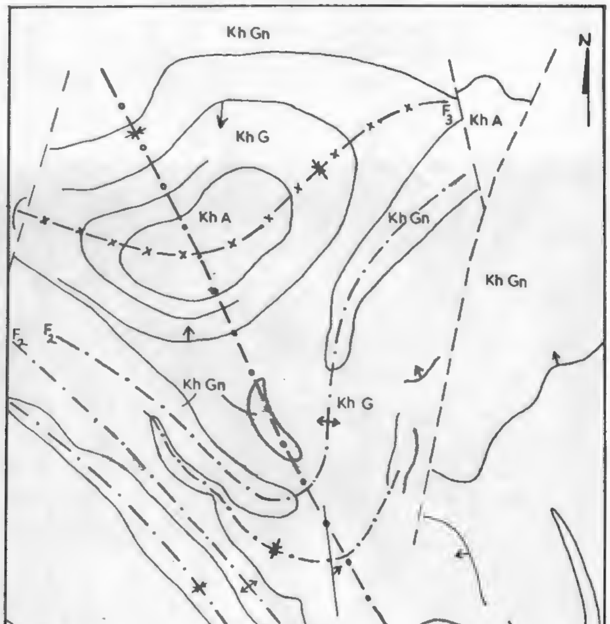


Figure 6. The Elands Kloof structure.

Plate V The Slagieskop structure (S. African Government photography).

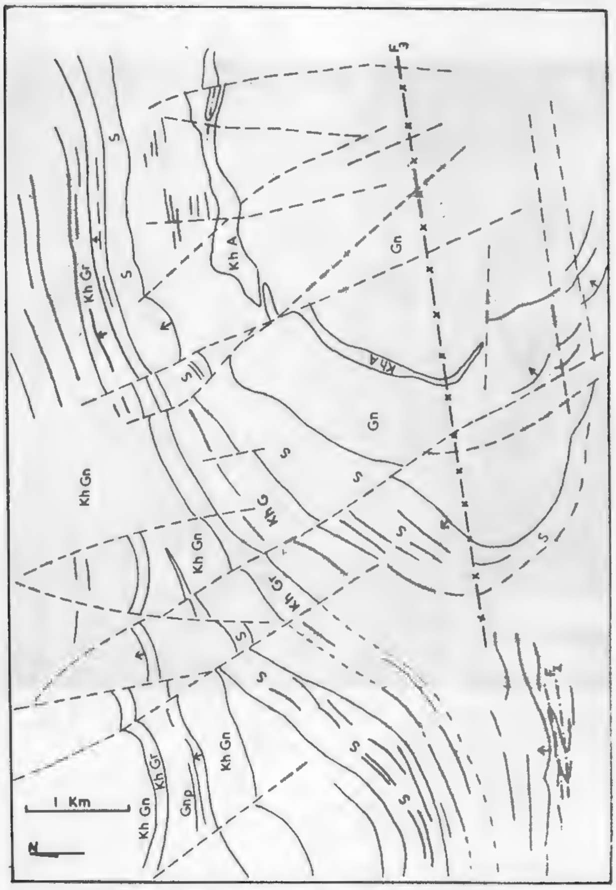


Figure 7 The Slagieskop structure.

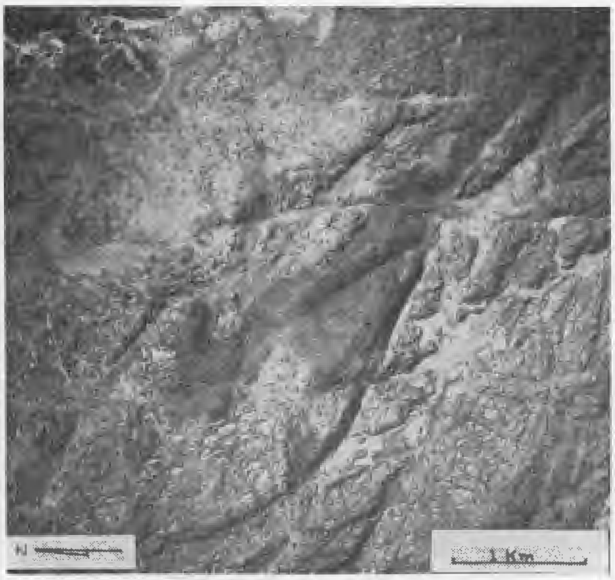


Plate VI The Banke structure (S. African Government photography).

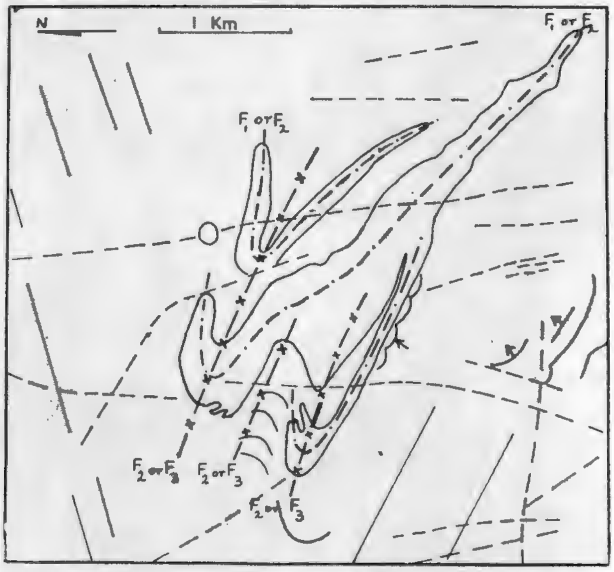


Figure 8 The Banke structure: from photo-interpretation.

foliation at a small angle before dying out. The repetition of lithological units would normally be a good indication of an earlier phase of folding, but in this area the appearance of several of the units on air photos is so similar that this is very difficult to recognise. However, small tight folds are visible in the southwest corner and their style suggests that they belong to F_2. Similarly the behaviour of the mafic band (KhA) suggests the presence of F_2 folding, particularly where it splits up at its eastern extremity. Fieldwork showed that in fact F_2 folds are present all round the closure of the main F_3 fold, but these are not visible on the photos.

Fracturing and minor faulting are well displayed in this example. Again, the main trend is northwest or north-northwest, occasionally north-south, and again age relationships are not sufficiently clear to be deduced from the photographs.

The Banke structure (*Plate VI and Figures 8 and 9*)

Only two lithological units are involved here: most of the area is underlain by biotite gneisses (KhG), which show very little foliation on the whole. The main exceptions occur near the contact of the second rock type, the mafic gneiss (KhA). The latter shows a complex outcrop form which can only be explained in terms of repeated folding, but in this case some marked differences appeared between the photo-interpretation and the structure as mapped in the field. The photo-interpretation is given in Figure 8, which shows an early set of three main antiforms, refolded fairly sharply by a west-northwest-trending set of later folds. Neither trend nor style seemed quite diagnostic for either set, and the earlier ones were therefore labelled F_1 or F_2 and the later ones F_2 or F_3.

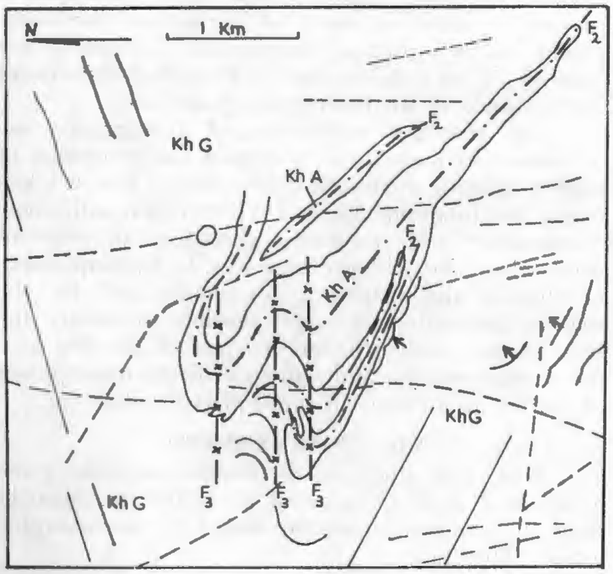


Figure 9 The Banke structure: from field mapping.

Fieldwork showed that the early folds were in fact of F_2 age, and that the interpretation of the more northerly folds was wrong (compare Figures 8 and 9). The trend of the later folds had also been wrongly interpreted, being almost exactly east-west instead of east-northeast. The reason for this lies in the nature of the F_3 deformation here: accompanying the folding is a good deal of shearing, involving small movements on quite closely spaced planes, and with small folds lying between shear planes. This means that it is in fact almost impossible to plot a single axial plane for each fold, since the fold is made up of the displacements on a large number of shears. The direction of the shears is almost due east-west, and this is the direction shown in Figure 9. In the interpretation, it had been assumed that the F_3 axial plane could be traced by joining the closures of the later folds, but in this case the assumption was not justified.

It is perhaps worth noting that this whole structure would be impossible to detect were it not for the presence of the mafic rocks, because of the lack of foliation in the biotite gneisses. Other minor points are the presence of north-south and northwest-trending fractures, and the small structure near the centre of the area which is a kimberlite pipe probably of late-Cretaceous age.

The Dik-Matje structure (*Plate VII and Figure 10*)

In this area the general strike which is approximately east-west due to F_3 deformation has been subsequently deformed by an F_4 fold with a north-north-west striking axial plane. As can be seen from Figure 10, this is a fairly gentle open structure of disharmonic style, dying out rapidly both along and across strike. The orientation and style, taken together, are diagnostic for F_4 folds. The mechanism of folding is predominantly by flexural-slip as shown by the development of shearing in the zones where the major disharmony occurs, and also by an incipient local thrust in the core of the fold, similar to those figured by De Sitter (1956, p. 190 and 198). It is evident from the photographs that the structure is antiformal, and that the plunge is moderate, north-northwesterly, due to the existing north-northwest dip of the layering following F_3 folding.

Leptites and pink gneisses (KhGn) form the core of the structure and the high ground to the south. They show occasional very coarse banding, and a fairly uniform light grey tone with a few paler exfoliation surfaces. Much of the surface has a blocky appearance due to several sets of joints. The shear zone in these rocks shows up prominently as a more deeply eroded horizon with a finer surface texture and some foliation: it would be difficult to distinguish it from a band of different composition were it not for the way that it dies out in the south-west.

The leptites are overlain by biotite-gneisses with mafic bands (KhGr). These show a transition from the west, where several mafic bands are present, to the east, where only the biotite gneiss occurs. This transition is accompanied by an increase in the degree of shearing, so that the layering becomes very fine.

The hornblende- and hypersthene gneisses (KhH) are much less resistant to erosion and form the lower ground to the north. Exposures are fewer and the tone generally darker, although light bands are visible and there is generally some foliation. The long straight shear zone (of a later stage of deformation) shows up as a band with much finer foliation and dark tone and could easily be mistaken for a mafic band.

Large fractures of both north- and north-north-west trend are present, as well as several prominent joint sets, the major ones being north-south, north-northwest, and east-west.

VI. RESULTS

This study has examined the application of aerial photographic interpretation to the unravelling of a particular area of complex structure and high-

Plate VII The Dik-Matje structure (S. African Government photography).

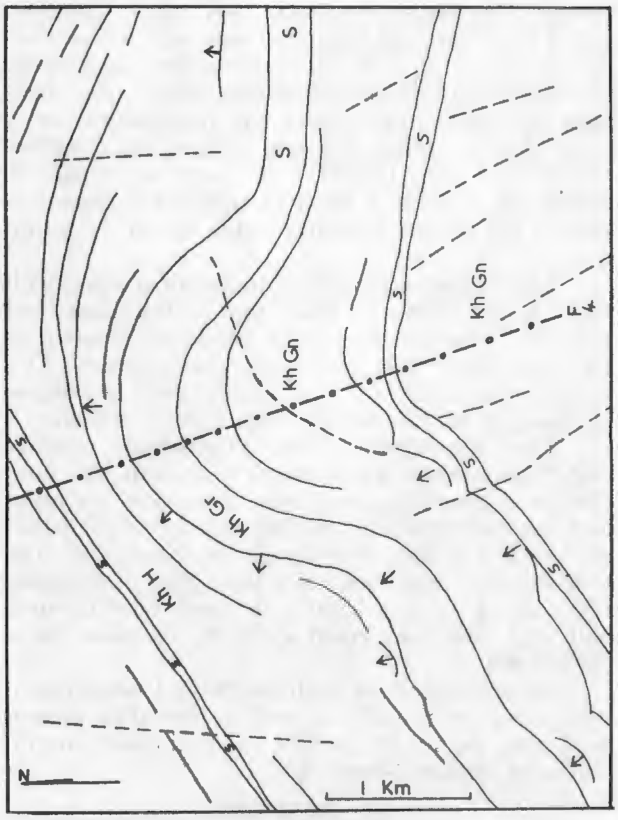


Figure 10 The Dik-Matje structure.

grade metamorphism. The results can be summarised as follows:—

1. The sequence of folding which can be determined from aerial photographs agrees with that established by fieldwork, and correct inferences can also be drawn concerning the style of each phase of folding.
2. The trend and frequency of fractures can be fully studied on photographs, but their age relationships are difficult to determine since displacements are rarely visible.
3. In some cases, e.g. the Banke structure, photographic evidence is inconclusive as to the age of the folds concerned, and is even to some extent misleading as to the trend of the later folds. However, the presence of two sets of folds is clear from the visible outcrop pattern.
4. Structures appear most clearly where outlined by contrasting lithologies: in this area usually by bands of mafic gneiss in sequences of felsic gneisses.
5. The leptites are rarely distinguishable from the pink gneisses on photographs, except in one case where the leptites are well-foliated.
6. Basic gneisses can be recognised by a combination of factors such as dark tone, subdued topography, and (usually) banding.
7. Shear zones may be confused with well-foliated gneisses unless they are cross-cutting.
8. In this area, vegetation is too sparse to be of much help in intepretation, except in isolated cases.

From these results it is clear that, as in most photogeological studies, the structural interpretation is more complete than the lithological one. This is particularly true in areas of high-grade metamorphism, where original lithological differences are blurred by recrystallization and original differences in resistance to weathering are minimised.

The resulting uniformity of topographic expression over large areas may give the impression of large magmatic intrusions unless careful note is taken of the few foliations present. These will usually show a continuity with structural directions in adjacent areas where the evidence is clearer. In Namaqualand, because of the structural complexity and for the reasons just stated, it is not possible to deduce the stratigraphic sequence, but in spite of this the geometry, distribution, and sequence of the main phases of folding are evident on aerial photographs.

VII. CONCLUSIONS

From this study, it is possible to make some generalised conclusions about photo-interpretation in areas of complex structure and high metamorphic grade. These are:—

1. Where exposures are adequate, and some differential weathering has etched out foliation, folds of more than one generation can be identified, their age relationships determined, and often their characteristic style can be established.
2. In regions of complex folding, layering cannot be assumed to represent bedding. An intensive search should always be made for evidence of early isoclinal folding.
3. In regions of high-grade metamorphism, lithological identification is possible only in general terms, e.g. mafic or granitic gneiss. In places,

much more detailed subdivision of a sequence may be possible without knowing the exact lithology of the rocks concerned, but the weathering characteristics of individual units may change or merge, making long distance correlation very difficult.

4. The total fracture pattern is most easily seen on aerial photographs, but where these are of different ages it may be impossible to establish their time relationships where displacements are small.
5. Wide shear zones, which are now known to be a characteristic of many basement terrains, are often almost concordant with foliation over much of their length, and in detail resemble a finely foliated part of the stratigraphic sequence when seen on photographs. However, their impersistence, and occasionally cross-cutting nature, are usually sufficient to identify them.
6. Even in areas which superficially look least promising, it is worthwhile making a detailed photogeological interpretation before commencing fieldwork. This is likely to yield much information on what to expect. It will indicate which are the more complex areas on which more time should be spent, and in fact will go a long way to obviate the feeling of "working in the dark", which is experienced by many geologists in the initial stages of the survey of a new area of very complex geology.

VIII. ACKNOWLEDGEMENTS

Information from official air photographs is reproduced under Government Printer's Copyright Authority No. 4431 of 27th January, 1971.

REFERENCES

Bodechtel, J. and Papadeas, G. (1968) Tectonic aerial interpretation in the Mediterranean region exemplified by the metamorphic series of eastern Greece, near Marathon. *Photogrammetria* **23**, 201-210.

De Sitter, L. (1956) *Structural Geology*. McGraw-Hill.

Hepworth, J. V. (1967) The photogeological recognition of ancient orogenic belts in Africa. *Quart. J. geol. Soc.* **123**, 253-292.

Hepworth, J. V., Kennerly, J. B. and Shackleton, R. M. (1967) Photogeological investigation of the Mozambique front in Tanzania. *Nature* **216**, 146-147.

Hepworth, J. V. and Kennerley, J. B. (1970) Photogeology and structure of the Mozambique orogenic front near Kolo, north-east Tanzania. *Quart. J. geol. Soc.* **125**, 447-479.

Joubert, P. (1971) The regional tectonism of the gneisses of Namaqualand. *Bull. No. 10, Precambrian Res. Unit,* Univ. of Cape Town.

Ramsay, J. G. (1967) *Folding and Fracturing of Rocks.* McGraw-Hill.

Stephens, E. A. (1969) Structural analysis from air photographs in areas of regionally metamorphosed rocks. *Photogrammetria* **25**, 5-26.

Sutton, J. (1965) Some recent advances in our understanding of the controls of metamorphism (p. 22-45). *In*: Pitcher, W. S. and Flinn, G. S., Editors, *"Control of Metamorphism.* Oliver and Boyd.

A. R. Newton,
Department of Geology,
University of Cape Town,
Cape Town,
Republic of South Africa.

P. Joubert,
P.O. Box 135,
Rondebosch,
Cape Town,
Republic of South Africa.

DISCUSSION

PROFESSOR RAMSAY: I think the authors have demonstrated very clearly the practical use of the technique of identifying these various fold interference patterns. I completely agree with their interpretations. One problem intrigues me. Dr. Joubert showed us that the metamorphic state of these rocks varies from west to east. I wonder, does the structural style vary with metamorphism; if so, does this pose a particular problem of correlation of folds from area to area?

DR. JOUBERT: No, as far as the relationship between the style of folding and grade of metamorphism is concerned. However in the area of lower grade of metamorphism there is a lot of shearing. It is very difficult to distinguish the earlier structures in that part of the area, because as you know, the styles of folding along these shear belts are often indistinguishable from those of the earlier folds. Something which I did not mention, is that the axial traces of earlier folds swing away from east to northeast and parallel the later structures as one approaches the coast due to large-scale, left-lateral movement there. It is difficult to distinguish between the earlier and later structures in the west. However, the isoclinal folds are still present at the coast and although the grade of metamorphism is lower, the lineations associated with the F_2 types of folds are quite distinct.

4. CONCLUSIONS

Since this work has two main aspects, one concerned with photo-interpretation and the other with the evolution of the Cape Fold Belt, it will be appropriate to formulate the conclusions under these two headings.

Photo-interpretation

1. It has been shown that photo-interpretation is a feasible method for structural reconnaissance studies of large areas in the Cape Fold Belt: reliable conclusions can be drawn regarding the style of folds, and their frequency, distribution and orientation. Faults and fractures show up well, and can be plotted in more detail than is given on most published maps.

2. The usefulness of the LANDSAT imagery depends largely on the degree of expression of the geology in terms of topography, land use, etc., so that although detail in the Fold Belt is plentiful, it is very scarce in areas of pre-Cape rocks and in the cultivated areas south of the Langeberg. What is shown on the 1:1 million map (Geol. Survey, 1970) depends mainly on the larger-scale mapping on which it was based, and consequently the amount and accuracy of detail is variable. Comparison of the two showed that they are often complementary, so that both are necessary to any study claiming completeness. The limited stereoscopy available on the LANDSAT imagery showed the advantages of the three-dimensional view, and the value of the imagery would be greatly enhanced if overlaps could be extended to give full stereoscopic cover.

3. The value of photography for projects involving remapping and updating of old maps was established by comparison of the photomaps with 1:50 000 field sheets of the Geological Survey. In spite of differences in aim, the agreement between the maps was good, and it is clear that much time could be saved in remapping projects by an intensive preliminary photogeological study.

4. New insights were obtained into both stratigraphy and structure, e.g. the distribution of the Peninsula and Nardouw Formations, through tracing the marker horizon of the Cedarberg Formation, and the recognition of another marker high up in the Nardouw Formation; the tracing of the Worcester and Tradouw faults in the Heidelberg

area, and the evidence for a major fault on the south side of the Outeniqua anticline; and the recognition of an overall systematic reduction in fold wavelength and amplitude in the sequence Table Mountain Group - Bokkeveld - Witteberg.

5. It was demonstrated that photogeology can play an important role in elucidating the sequence of deformations in areas of complex folding such as Namaqualand, and enables new interpretations to be suggested for previously mapped areas such as O'okiep.

Evolution of the Cape Fold Belt

1. Several lines of evidence are put forward which suggest gravitational gliding as the basic mechanism of deformation in the Cape Fold Belt, e.g. the lack of metamorphic and igneous activity, the presence of two fold trends and their syntaxial relationship, the evidence of movement on the basal contact of the Cape Supergroup, and the way folding is confined to the southern slope of the Cape trough.

2. Evidence is adduced for the genetic relationship between faulting and folding, suggesting an earlier age for the major faults than had previously been proposed, and a mechanism by which faulting could have played an important part in fold formation is put forward.

3. Restoration of the South American and African plates to their pre-drift configuration leads to consideration of Cape Fold Belt equivalents in South America and the Falkland Islands. A generalised palaeogeography results which reveals the Cape Fold Belt as an intracratonic feature unrelated to any subduction zone, surrounded by shield areas on which subsidence was much more limited, and where, in the case of the Falkland Islands at least, deformation may have been considerably later.

4. A speculative model is put forward in terms of which the origin of the uplift required to produce gravitational gliding lies in a mantle plume which generated a triple junction with radial and concentric fractures in the crust, but failed to develop into a spreading centre and subsequently subsided. The major faults of the Cape Fold Belt formed part of the concentric fracture pattern, and movement on them therefore reversed during the subsiding stage. The radial fractures formed lines of weakness which failed when the South Atlantic began to form, one becoming the mid-Atlantic

spreading ridge, one the Agulhas/Falkland transform fault, and the third showing only limited activity as a subsiding trough in the Upper Cretaceous.

5. Acknowledgements

I am deeply indebted to Assoc. Prof. A.O. Fuller, who took over the task of supervising this study on the death of Assoc. Prof. J. de Villiers, for much helpful advice, encouragement and constructive criticism. My ideas on the Cape Fold Belt and its place in Gondwanaland benefitted from discussions with many colleagues, of whom I would particularly like to mention Prof. R.V. Dingle and Mr. C.J. Hartnady. Dr. J.N. Theron of the Geological Survey kindly made it possible for me to compare my photogeological maps with the Geological Survey field sheets. Funds for the acquisition of colour and low-sun-angle photography came from the O'okiep Copper Company and the University of Cape Town, and the photographs were taken by Prof. D.A.Scogings and Mr. R.A. Bond, University of Natal : to all these I am most grateful.

6. REFERENCES

Abdel-Gawad, M. 1969. Geological Structures of the Red Sea area inferred from satellite pictures. In Degens, E.T. and Ross, D.A. (Eds.) "Hot Brines and Recent Heavy Metal Deposits in the Red Sea". Springer.

Adie, R.J. 1952. The position of the Falkland Islands in a reconstruction of Gondwana. Geol. Mag. 89, 401-410.

Anderson, D.T. 1964. Colour photography as an aid to geological interpretation. Proc. Seminar Air Photo. Interp. Developm. Can. 4, 2.

Beloussov, V.V. 1963. Basic Problems in Geotectonics. McGraw-Hill, pp.809.

Benedict, P.C., de N. Wiid, D., Cornelissen, A.K. and Staff. 1964. Progress Report on the Geology of the O'okiep Copper District. In "The Geology of Some Ore Deposits of Southern Africa" Vol.II. Geol. Soc. S. Afr.

Blanchet, P.H. 1957. Development of fracture analysis as an exploration method. Bull. Amer. Ass. petrol. Geol. 41, 1748.

Bodechtel, J. and Papadeus, G. 1968. Tectonic aerial interpretation in the Mediterranean region exemplified by the metamorphic series of Eastern Greece, near Marathon. Photogrammetria 23, 201.

Boyer, R.E. and McQueen, J.E. 1964. Comparison of mapped rock fractures and airphoto linear features. Photogramm. Engng. 30, 630.

Braddock, W.A. 1970. The origin of slaty cleavage: evidence from the Precambrian rocks in Idaho. Bull. geol. Soc. Amer. 81, 589-600.

Brown, C.W. 1961. Comparison of joints, faults and airphoto linears. Bull. Amer. Ass. petrol. Geol. 45, 1888.

Bullard, E.C., Everett, J.E. and Smith, A.G. 1965. The fit of the continents around the Atlantic. Roy. Soc. Lond. Philos. Trans., ser.A, 258, 41-51.

Burke, K. and Dewey, J.F. 1973. Plume-generated triple junctions: key indicators in applying Plate Tectonics to old rocks. Jour. Geol. 81, 406-433.

Chaves, J.R. and Schuster, R.L. 1968. Colour photos for highway engineering. Photogramm. Engng. 34, 375.

Clark, B.R. 1970. Mechanical formation of preferred orientation in clays. Amer. J. Sci. 269, 250-266.

Cloos, E. 1947. Oolite deformation in the South Mountain Fold, Maryland. Bull. geol. Soc. Amer. 58, 843.

Coates, D.A. 1969. Stratigraphy and sedimentation of the Sauce Grande Formation, Sierra de la Ventana, Southern Buenos Aires Province, Argentina. I.U.G.S. Symposium Gondw. Stratig. Buenos Aires, 799-819.

Colwell, R.N. (Ed.) 1960. Manual of Photographic Interpretation. Amer. Soc. Photogramm., Washington D.C.

Craddock, C. 1974. Tectonic evolution of the Pacific Margin of Gondwanaland. Proc. 3rd Inter. Gondw. Symp., Canberra.

Crowell, J.C. and Frakes, L.A. 1968. Late Paleozoic glacial facies and the origin of the South Atlantic ocean. 23rd Inter. Geol. Congr. Prague 13, 291-302.

Currie, J.B., Patnode, H.W. and Trump, R.P. 1962. Development of folds in sedimentary strata. Bull. Geol. Soc. Amer. 73, 655-674.

Dalziel, I.W.D. 1974. Evolution of the margins of the Scotia Sea. In Burke and Drake "The Geology of Continental Margins". Springer, pp.1009.

De Beer, J.H., van Zijl, J.S.V. and Bahnemann, F.K. 1974. Plate tectonic origin for the Cape Fold Belt? Nature, 252, 675-6.

De Sitter, L.U. 1956. Structural Geology. McGraw-Hill, pp.552.

De Swardt, A.M.J., Fletcher, O. and Toschek, P. 1974. Note on orogenic style in the Cape Fold Belt. Trans. geol. Soc. S. Afr. 77, 53-58.

Desjardins, L. 1950. Structural contouring for the photogeologist. Photogramm. Engng. 16, 784.

Dingle, R.V. 1973A. Mesozoic palaeogeography of the southern Cape, South Africa. Palaeogeography, Palaeoclimatology, Palaeoecology 13, 203-213.

Dingle, R.W. 1973B. Post-Palaeozoic stratigraphy of the eastern Agulhas

Bank, South African continental margin. Marine Geology 15, 1-23.

Dingle, R.V. and Scrutton, R.A. 1974. Continental breakup and the development of Post-Paleozoic Sedimentary basins around southern Africa. Bull. Geol. Soc. Amer. 85, 1467-1474.

Du Toit, A.L. 1937. Our Wandering Continents. Oliver & Boyd, pp.366.

Du Toit, A.L. 1939. Geology of South Africa. Oliver & Boyd, pp.539.

Elliott, D.H. and Watts, D.R. 1974. The nature and origin of volcaniclastic material in some Karroo and Beacon rocks. Trans. geol. Soc. S. Afr. 77, 109-112.

Ewing, J.J., Ludwig, W.J., Ewing, M. and Eittrein, S.L. 1971. Structure of the Scotia Arc and Falkland Plateau. Jour. geophys. Res. 76, 7118-7137.

Fichter, A.J. 1954. Geometry of the imaginary stereomodel. Photogramm. 10, 134-139.

Fischer, W.A. 1963. Depiction of soil-covered structures by infra-red aerial photography. U.S.G.S. Prof. paper 475-B, 67.

Fischer, W.A., Moxham, R.H., Polcyn, F. and Landis, G.H. 1964. Infra-red survey of Hawaiian volcanoes. Science 146, 733.

Fuller, A.O. 1970. The occurrence of laumontite in strata of the Karroo System, South Africa. I.U.G.S. 2nd Inter. Gondw. Symp., South Africa, 455-456.

Geologiese Opname Seismologiese Reeks 4. 1974. Govt. Printer, Pretoria, pp.48.

Geotimes. Nov. 1974. Report on Leg 36, D.S.D.P.

Gough, D.I. 1973. Possible linear plume under southernmost Africa. Nature phys. Sci. 245, 93-94.

Greenway, M.E. 1972. The Geology of the Falkland Islands. Brit. Ant. Surv. Sci. Rept. 76. N.E.R.C., London.

Greenwood, J.E.G.W. 1964. Status and development of photogeology. Mining Mag. Lond. 110, 382.

Hackman, R.J. 1967. Time, shadows, terrain and photo-interpretation. U.S.G.S. Prof. paper 575-B, 155.

Hales, A.L. and Gough, G.I. 1960. Isostatic anomalies and crustal structure in the southern Cape. Geophys. Jour. 3, 225.

Halpern, M. 1968. Ages of Antarctic and Argentine rocks bearing on continental drift. Earth Plan. Sci. Lett. 5, 159-167.

Harrington, H.J. 1956. In "Handbook of South American Geology". W.F. Jenks (Ed.). Mem. Geol. Soc. Amer. 65.

Harrington, H.J. 1962. Palaeogeographic development of South America. Bull. Amer. Ass. petrol. Geol. 46, 1773-1814.

Harrison, J.V. and Falcon, N.L. 1934. Collapse structures. Geol. Mag. 71, 529-539.

Hartnady, C.J. 1966. Structure of the pre-Cape Beds near Worcester. Unpub. Hons. Rept., Univ. of Cape Town.

Hartnady, C.J. 1969. Structural analysis of some pre-Cape Formations in the Western Province. Prec. Res. Unit Bull. 6, Univ. of Cape Town.

Hartnady, C.J., Newton, A.R. and Theron, J.N. 1974. Stratigraphy and structure of the Malmesbury Group in the southwestern Cape. In "Contributions to the Precambrian Geology of Southern Africa". A. Kroner (Ed.). Prec. Res. Unit Bull. 15, 193-213.

Hemphill, W.R. 1958. Small-scale photographs in photogeologic interpretation. Photogr. Engng. 24, 562.

Hemphill, W.R. and Danilchick, W. 1968. Geologic interpretation of a Gemini photo. Photogr. Engng. 34, 150.

Henderson, G. 1960. Air photo lineaments in Mpande area, Western Province, Tanganyika, Africa. Bull. Amer. Ass. petrol. Geol. 44, 53.

Hepworth, J.V. 1967. The photogeological recognition of ancient orogenic belts in Africa. Quart. J. geol. Soc. Lond. 123, 253.

Hepworth, J.V. and Kennerley, J.B. 1970. Photogeology and structure of the Mozambique orogenic front near Kolo, north-east Tanzania. Quart. J. geol. Soc. Lond. 125, 447.

Hoschek, G. 1969. The stability of staurolite and chloritoid and their significance in metamorphism of pelitic rocks. Contr. Min. & Pet. 22, 208-233.

Howard, A.D. and Mercado, J. 1970. Low-sun-angle vertical photography versus thermal infra-red scanning imagery. Bull. geol. Soc. Amer. 81, 521.

Hubbert, M.K. and Rubey, W.W. 1959. Role of fluid pressure in mechanics of overthrust faulting. Bull. geol. Soc. Amer. 70, 115-166.

Huntingdon, J.F. 1969. Methods and applications of fracture trace analysis in the quantification of structural geology. Geol. Mag. 106, 430.

Jackson, V.N. 1967. Digital structural analysis. Photogr. Engng. 33, 290-296.

Jones, H. 1970. Prospecting by infra-red techniques. Mining Mag. 122, 39.

Joubert, P. 1971. The regional tectonism of the gneisses of Namaqualand. Prec. Res. Unit Bull. 10, Univ. of Cape Town.

Kirk, J.N. 1970. A regional study of radar lineament patterns in the Ouachita mountains, McAlester Basin - Arkansas Valley, and Ozark regions of Oklahoma and Arkansas. CRES Tech. Rep. 177-4, University of Kansas.

Larsen, R.L. and Ladd, J.W. 1973. Evidence for the opening of the South Atlantic in the early Cretaceous. Nature, 246, 209-212.

Lattman, L.H. 1958. Technique of mapping fracture traces and lineaments on aerial photographs. Photogr. Engng. 24, 568.

Lattman, L.H. and Nickelsen, R.P. 1958. Photogeologic fracture-trace mapping in Appalachian Plateau. Bull. Amer. Ass. petrol. Geol. 42, 2238.

Lawson, A.C. 1927. Folded Mountains and Isostasy. Bull. geol. Soc. Amer. 38, 253.

le Roux, D.M. 1974. Struktur-ondersoek van die Kaapse plooigordel in die omgewing van Barrydale. Unpub. M.Sc. thesis, Univ. of Stellenbosch.

Lowman, P.D. 1969. Geologic orbital photography: experience from the Gemini program. Photogrammetria 24, 77.

MacDonald, H.C. 1969. Geologic evaluation of radar imagery from Darien Province, Panama. Modern Geology 1, 1-63.

Martin, H. 1961. The hypothesis of continental drift in the light of recent advances of geological knowledge in Brazil and in South West Africa. Annex. to Trans. geol. Soc. S. Afr. vol. 64.

Martini, J.E.J. 1974. The presence of ash beds and volcanic fragments in the greywackes of the Karroo System in the southern Cape Province (South Africa). Trans. geol. Soc. S. Afr. 77, 113-116.

Matsumo, K., Hase, H. and Nishimura, K. 1969. On infra-red imagery and its applications to mapping of geological distributions. Photogrammetria 25, 61.

Mekel, J.F.M. 1974. A short history of photogeology. ITC publication No.30, ITC, Enschede.

Mekel, J.F.M., Savage, J.F. and Zorn, H.C. 1970. Slope measurements and estimates from aerial photographs. ITC publication Ser.B No.26, ITC, Delft.

Miller, V.C. 1968. Current trends in photogeology and in the use of other remote sensing methods in geological interpretation. Earth Sci. Rev. 4, 135.

Minard. 1960. Colour aerial photographs facilitate geological mapping on the Atlantic coastal plain of New Jersey. Photogr. Engng. 26, 112.

Newton, A.R. 1966. Some photogeological principles and their application in the Cape Province. S.Afr. Jour. Photogramm. 2, 272.

Newton, A.R. 1973A. Pseudostereoscopy with radar imagery. Photogr. Engng. 39, 1055-1058.

Newton, A.R. 1973B. A Gravity-Folding Model for the Cape Fold Belt. Trans. geol. Soc. S. Afr. 76, 145-152.

Newton, A.R. 1974A. A comparison of black-and-white, colour, and infra-red photographs for geological interpretation at Witvlei, South West Africa. Rem. Sens. Envir. 3, 29-34.

Newton, A.R. 1974B. Nature of South Africa's Cape Fold Belt. Nature 258, 499-500.

Newton, A.R. and Joubert, P. 1973. Photogeology in a granitic gneiss terrain: Namaqualand, South Africa. Spec. Pub. Geol. Soc. S. Afr. 3, 277-287.

Norman, J.W. 1968. Photogeology of linear features in areas covered with superficial deposits. Instn. Min. & Metall. Trans. Sec. B, 77, B60.

Paarma, H. and Talvitie, J. 1968. High altitude false colour photo-interpretation in prospecting. In Smith (Ed.) "Manual of Color Aerial Photography", Amer. Soc. Photogramm., pp.550.

Permyakov, Ye.N. 1949. Tectonic jointing of the Russian platform. MOIP Publications 12,(16).

Pincus, H.J. and Dobrin, M.D. 1966. Geological applications of optical data processing. J. geophys. Res. 71, 4861.

Potgieter, T.C. 1950. The structure and petrology of the George granite plutons and the invaded pre-Cape sedimentary rocks. Ann. Univ. Stell. 26, 323-412.

Ramsay, J.G. 1967. Folding and Fracturing of Rocks. McGraw-Hill, pp.568.

Ramsay, J.G. and Graham, R.H. 1970. Strain variation in shear belts. Canad. Jour. Earth Sci. 7, 786.

Renner, J.G.A. 1968. The structural significance of lineaments in the eastern Monsech area, Province of Lerida, Spain. ITC Publication Ser.B. No.45, ITC, Delft.

Rhodes, R.C. 1974. A Gravity Model for the Cape Fold Belt: Discussion. Trans. geol. Soc. S. Afr. 77, 207-8.

Rust, I.C. 1967. On the sedimentation of the Table Mountain Group in the western Cape Province. Unpub. D.Sc. thesis, Univ. of Stellenbosch.

Rust, I.C. 1973. The evolution of the Paleozoic Cape Basin, southern margin of Africa. In Nairn and Stehli (Eds.) "The Ocean Basins and Margins, Vol. I". Plenum, N.York.

Ryan, P.J. 1969. Stratigraphy of the Ecca Series and lowermost Beaufort Beds (Permian) in the Great Karroo basin of South Africa. In Amos

(Ed.) Gondwana Stratigraphy. I.U.G.S. Gondw. Symp., Buenos Aires, 944-965.

Sabins, F.F. 1967. Infra-red imagery and geological aspects. Photogr. Engng. 33, 143.

Scholtz, D.L. 1946. On the younger pre-Cambrian granite plutons of the Cape Province. Proc. geol. Soc. S. Afr. 49, 35-82.

Schwarz, E.H.L. 1905. Geological survey of the Divisions of Tulbagh, Ceres and Worcester. Ann. Rept. Geol. Comm., 261-290.

Scrutton, R.A. and du Plessis, A. 1973. Possible marginal fracture ridge south of South Africa. Nature 242, 180-182.

Shearer, E.M. 1957. Stereo-structural contouring. Bull. Amer. Ass. petrol. Geol. 41, 1694.

Slemmons, D.B. 1969. New methods of studying seismicity and surface faulting. EOS (Trans. Amer. geophys. Union) 50, 397-8.

Smith, A.G. and Hallam, A. 1970. The fit of the southern continents. Nature 225, 139-144.

Sohnge, P.G. 1934. The Worcester Fault. Trans. geol. Soc. S.Afr. 37, 253-277.

Stephens, E.A. 1969. Structural analysis from air photographs in areas of regionally metamorphosed rocks. Photogrammetria 25, 5.

Stocken, C.G. 1954. The pre-Cape rocks of the central Cango. Unpub. Ph.D. thesis, Univ. of Cape Town.

Strangway, D.W. and Holmer, R.C. 1966. The search for ore deposits using thermal radiation. Geophysics 31, 225.

Stratton, T. 1970. Tectonic framework of sedimentation during the Dwyka Period in South Africa. I.U.G.S. 2nd Gondw. Symp., S.Afr., 483-490.

Theron, J.N. 1969. The Baviaanskloof range - a South African nappe. Trans. geol. Soc. S.Afr. 72, 29-30.

Theron, J.N. 1970. A stratigraphic study of the Bokkeveld Group (Series). I.U.G.S. 2nd Gondw. Symp., S.Afr., 197-204.

Toogood, D.J. (in press). The Structural Geology of the Malmesbury between De Wet and Vink, Cape Province. Annals of the Geol. Surv. S.Afr.

Van der Bent, E.T.L. 1969. Dip estimation for photogeology. Photogr. Engng. 35, 1225.

Van der Meer Mohr, H.E.C. 1969. Geological interpretation of hyper-altitude photographs from Gemini spacecraft. Photogrammetria 24, 167.

Vicksne, A., Liston, T.C. and Sapp, C.D. 1969. SLR reconnaissance of Panama. Geophysics 34, 54.

Viljoen, R.P., Viljoen, M.J., Grootenboer, J. and Longshaw, T.G. 1975. ERTS-1 imagery: an appraisal of applications in geology and mineral exploration. Minerals Sci. Engng. 7, 132-168.

Wallace, R.E. and Moxham, R.M. 1967. Use of infra-red imagery in the study of the San Andreas fault system, California. U.S.G.S. Prof. paper 575-D, 147.

Williams, P.F., Collins, A.R. and Wiltshire, R.G. 1969. Cleavage and pene-contemporaneous deformation structures in sedimentary rocks. Jour. Geol. 77, 415.

Wise, D.U. 1967. Radar geology and pseudogeology on an Appalachian Piedmont cross section. Photogr. Engng. 33, 752.

Wittkind, I.G., Hemphill, W.R., Pillmore, C.L. and Morris, R.H. 1960. Isopach mapping by photogeological methods as an aid in the location of swales and channels in the Monument Valley area, Arizona. U.S.G.S. Bull. 1043-D, 57.

Wobber, F.J. 1967. Fracture traces in Illinois. Photogr. Engng. 33, 499.

Zambrano, J.J. and Urien, C.M. 1974. Pre-Cretaceous Basins in the Argentine continental shelf. In Burke and Drake (Eds.) "The Geology of Continental Margins". Springer, 463-470.

Toogood, D.J. (in press). The Structural Geology of the Malmesbury between De Wet and Vink, Cape Province. Annals of the Geol. Surv. S.Afr.

Van der Bent, E.T.L. 1969. Dip estimation for photogeology. Photogr. Engng. 35, 1225.

Van der Meer Mohr, H.E.C. 1969. Geological interpretation of hyper-altitude photographs from Gemini spacecraft. Photogrammetria 24, 167.

Vicksne, A., Liston, T.C. and Sapp, C.D. 1969. SLR reconnaissance of Panama. Geophysics 34, 54.

Viljoen, R.P., Viljoen, M.J., Grootenboer, J. and Longshaw, T.G. 1975. ERTS-1 imagery: an appraisal of applications in geology and mineral exploration. Minerals Sci. Engng. 7, 132-168.

Wallace, R.E. and Moxham, R.M. 1967. Use of infra-red imagery in the study of the San Andreas fault system, California. U.S.G.S. Prof. paper 575-D, 147.

Williams, P.F., Collins, A.R. and Wiltshire, R.G. 1969. Cleavage and pene-contemporaneous deformation structures in sedimentary rocks. Jour. Geol. 77, 415.

Wise, D.U. 1967. Radar geology and pseudogeology on an Appalachian Piedmont cross section. Photogr. Engng. 33, 752.

Wittkind, I.G., Hemphill, W.R., Pillmore, C.L. and Morris, R.H. 1960. Isopach mapping by photogeological methods as an aid in the location of swales and channels in the Monument Valley area, Arizona. U.S.G.S. Bull. 1043-D, 57.

Wobber, F.J. 1967. Fracture traces in Illinois. Photogr. Engng. 33, 499.

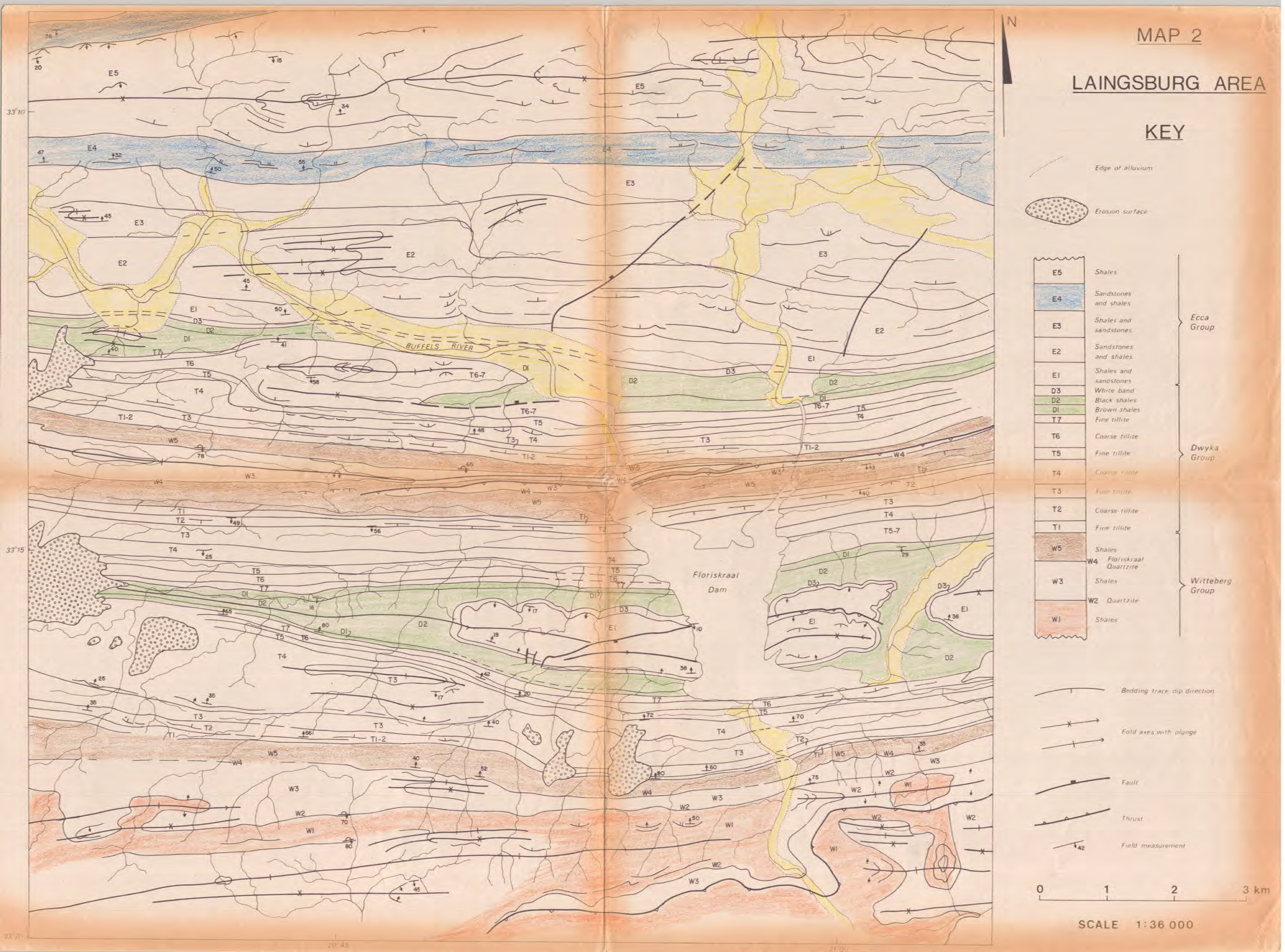
Zambrano, J.J. and Urien, C.M. 1974. Pre-Cretaceous Basins in the Argentine continental shelf. In Burke and Drake (Eds.) "The Geology of Continental Margins". Springer, 463-470.

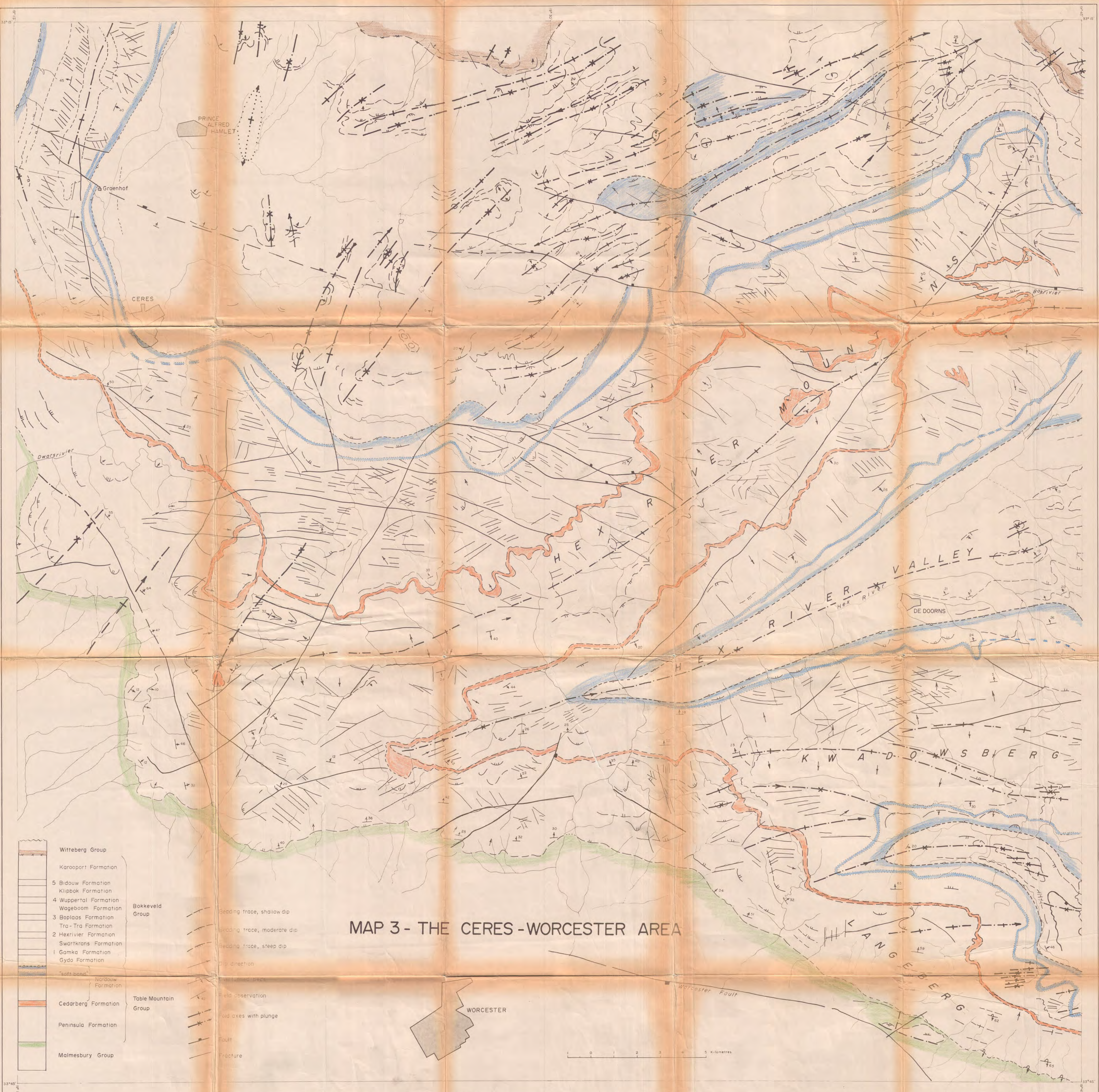
MAP 1

HEIDELBERG AREA

MAP 2

LAINGSBURG AREA





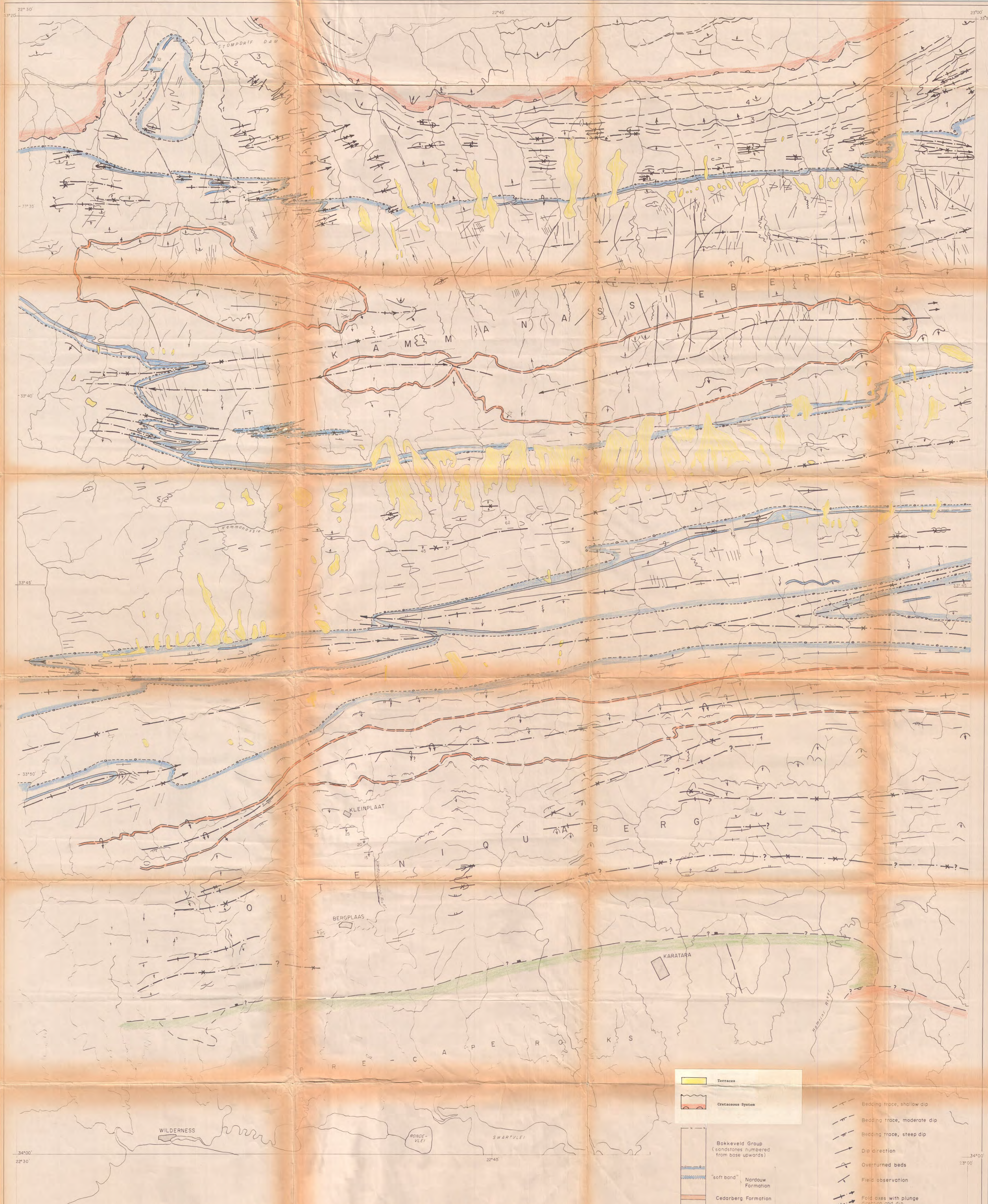
MAP 3 - THE CERES - WORCESTER AREA

MAP 4 (A)

20°00'
VERKEERDEVLEI
MATROOSBERG SIDING
WABOOMBERGE
KOO BERGE
LANGEBERGE
33°45'
20°00'

MAP 4(B)

TOUWS RIVER-WABOOMSBERG AREA

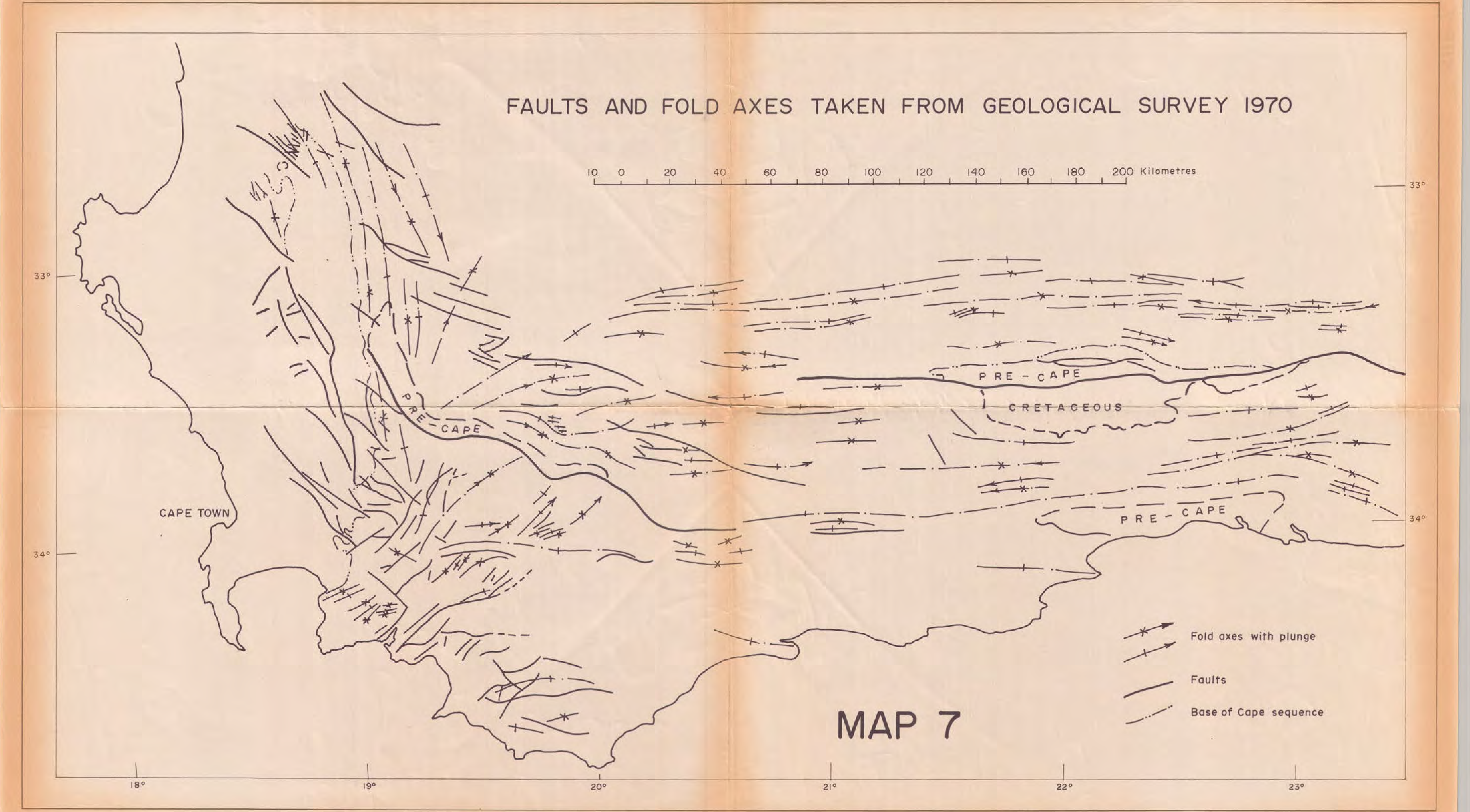


MAP 5 THE KAMMANASSIE - OUTENIQUABERG AREA

MAP 6

FOLDS AND FAULTS INTERPRETED FROM LANDSAT IMAGERY

FAULTS AND FOLD AXES TAKEN FROM GEOLOGICAL SURVEY 1970



MAP 7

MAP 8

THE O'OKIEP AREA

SCALE 1:100 000

Simplified from Benedict et al (1964)

●	*Noritoid*
RG	*Rietberg granite*
GrGn	*Grey granulite*
RSQ	*Ratelpoort schist and quartzite*
AuG	*Augen gneiss and red granulite*
CON	*Concordia gneiss*
Wo	*Wolfram schist*
TrS	*Transition zone*
Nab	*Nababeep gneiss*
Hb	*Hornblende gneiss*
SGS	*Springbok granulite and schist*
SQ	*Springbok quartzite*
BrGn	*Brandberg gneiss*
MOD	*Modderfontein granite*