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A REPORT ON SOME ASPECTS OF THE GEOLOGY OF THE LØKKEN AREA

by

E. H. Rutter

September 1968

INTRODUCTION

This is an interim report on the geological mapping of the Løkken Area. It is intended to supplement what has been said in earlier reports by myself and my colleagues and the general description of the geology of this area submitted as a paper to NGU in December 1967.

Most of the fieldwork this summer has concentrated on more detailed observation of the stratigraphy and structure of the schistose rocks forming the northern flank of the Løkken Synform and the complementary folds to the north.

THE PRESENTATION OF GEOLOGICAL DATA

The conventional presentation of geological information is in the form of a geological map, which attempts to synthesise field observations and the authors interpretation of those observations. It is usually accompanied by a written explanation of relevant details where necessary.

A map synthesis of the area covered by four of the new 1 : 10,000 topographic maps is presented with this report. These sheets bear nearly all of the structural data collected in those areas. In addition,all of the structural data is presented in the form of data sheets with numbered references to the field exposures where the measurements were made. The field exposures are located by numbers on the 1 :15,000 air photo overlays which were used for mapping purposes. Lithologies, too are indicated on the overlays. Mr. Chaplow has arranged his data in a similar fashion, and this too is included with this report.

It is hoped that this method of presentation will prove most convenient for any further analysis which may be desired, and will facilitate the eventual compilation of a complete geological analysis of this region, when the basic metavolcanics in particular, have been more thoroughly studied.

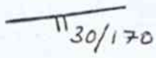
Finally, the geological structure of the area, as far as is known at present, is interpreted with the help of a cross section.

NUMBERING OF THE OVERLAYS AND DATA SHEETS

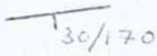
The exposures where orientation readings were made are listed sequentially in the data sheets. Where there are gaps in the numerical sequence, these refer to exposures where rock type observations only were made and where no readings were taken. These exposures are sometimes numbered on the air photo overlays, however.

Note : The terms used to describe fold geometry in this report are, unless otherwise stated, those suggested by Fleuty (Proc. Geol. Assoc., 1964).

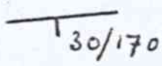
<u>Explanation of symbols used on the Geological Maps</u>.



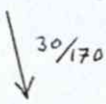
Orientation of f_1 Schistosity Surfaces .



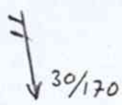
Orientation of Surfaces of Primary Layering.



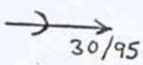
Orientation of f_2 Schistosity Surfaces.
(Crenulation Cleavage)



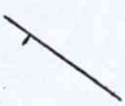
Plunge of Principal f_1 Elongation, i.e. Direction of longest axis of deformed objects such as pillows, vesicles, pebbles and spherulites, without reference to any possible original shape anisotropy.



Plunge of f_2 lineation, usually a crenulation lineation on the surface of f_1 schistosity, or axial direction of f_2 minor folds.



F_1 Fold axial direction, given by axial direction of f_1 minor folds or by bedding/cleavage intersection.



Fault - observed

Fault - inferred

Low angle fault (thrust) - observed

" " " " " inferred

Lithological Boundary - Observed

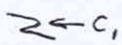
" " " " inferred

Horizontal Component of Younging Direction :


- Right way up) (Primary (Features

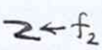

- Inverted) only

Bedding Cleavage Intersection -

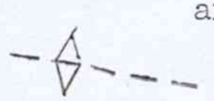

Indicated by the"equivalent minor fold", but bearing the letter "c" instead of "f", with a subscript indicating the phase of deformation.The arrow indicated the direction which gives the recorded sense of asymmetry.

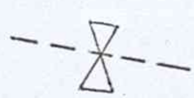
Minor Fold Asymmetry -

Indicated by a minor fold symbol with the letter "f", bearing a subscript which


indicates the phase of deformation, and an arrow, indicating the direction which gives the recorded sense of asymmetry.

Fold Axial Traces - Intersection of fold axial surface with land surface.


Antiform


Synform

PETROGRAPHY AND STRATIGRAPHY

Most of the rocks occurring in the area have been described fairly adequately by many authors in the past. The main petrographic observation made this summer is the fact that petrographic distinctions can be made fairly easily in rocks lying to the north of Løkken which have been largely disregarded until recently, and grouped together as mica schists of the Gula Group.

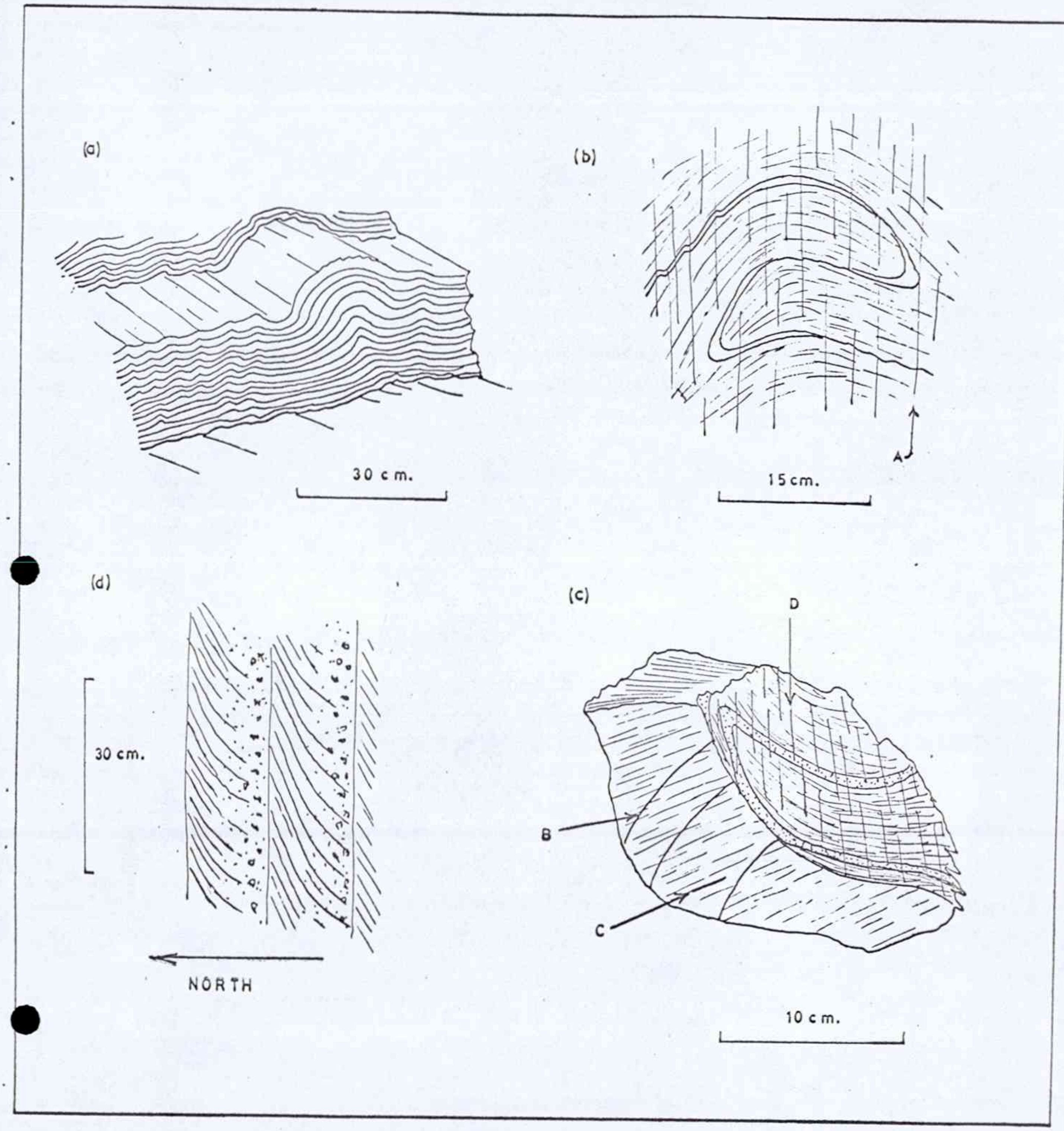
It has been very easy to map a band of flaggy, quartz rich, biotite flecked, laminated mica schist which extends for several km. on both sides of the Svorkmo Antiform. This band thins out westwards, the southern outcrop disappearing further to the east than the northern one. Hence the facial limit of this lithology trends very slightly obliquely to the f_2 fold axial direction. This limit may represent a true facial limit, or it may represent the hinge of an f_1 synclinal nappe, a possibility surmised in the section on f_1 structures.

The flaggy quartz schist occurs in an undifferentiable sequence of predominantly black or grey quartz-muscovite schists. Bedding is frequently seen, and the schists appear to be lithologically similar to the chlorite schists, but with a much less basic composition.

In the north and west of the area mapped the schists are much more acidic, and are of garnet grade. Frequently, lenses of quartz-feldspar segregation are seen intercalated within the schists, which are structurally the lowest, and probably also stratigraphically the oldest rocks in the area. However, the metamorphic grade boundaries probably cut quite obliquely across the f_1 structures, and are folded by the f_2 structures, so it would be wrong to make any inferences of age from metamorphic grade.

GEOCHEMISTRY

The investigation of chemical variations within lava pillows and between lava flows is not yet complete. Thin sections have been made of all the 40 or so rocks which are being analysed, and a precursory examination of these has suggested that a number of volcanic horizons exist within the area which are truly intermediate in composition (keratophyres). These rocks have a sub-spherulitic texture, and in hand specimen have an appearance which is impossible to distinguish from thoroughly basic lavas!



a) Second fold in Mica schist North of Dragset.

b) Refolded first fold in chlorite schist N. of Svorkmo Antiform.

d) Bedding/cleavage and refracted cleavage relations in chlorite schist north from Løkken.

c) Refolded first fold in mica schist north of Løkken. Note folded first lineation B folded around second lineation C.

STRUCTURAL GEOLOGY

An outline of the geological structure of the area was given in the paper submitted to NGU in 1967. This interpretation of the general structural geometry and history of the area has been further corroborated by what we have found in the past few weeks.

THE SECOND FOLDS

The f_2 antiform complementary to the Løkken synform, perhaps most conveniently called the Svorkmo Antiform, since its hinge trace passes through the village of Svorkmo, has been mapped from Dragset Mine to the Svorksjøen area by John Matthews and myself. The fold profile is usually tight to isoclinal, with the axial surface either vertical or overturned toward the north. The fact that the Løkken and Svorkmo fold axial surfaces are slightly inclined in opposite directions suggests that rapid thickness variations take place within the sedimentary sequence. The form of these variations is suggested in the accompanying profile section. Less rapid thickness and facies changes take place along the f_2 axial direction, though there appears to be a general thinning and fold tightening westward. Lack of exposure in the area north from Dragset Mine has made it impossible in a short time to delineate the f_2 major fold form with certainty, but it appears that the axial traces of the Svorkmo Antiform and the complementary synform to the north approach each other and may possibly ~~annhialate~~ annihilate each other.

In the section north from Rørvandet it is has not been possible to find either the Svorkmo Antiform or the Løkken Synform. In all exposures the f_1 schistosity is nearly vertical and there is often a strong f_2 crenulation cleavage at a small angle to the f_1 schistosity. It is probable that the Løkken Synform still exists in this area but that it is isoclinal. The Svorkmo Antiform may or may not exist.

One of the purposes in extending the mapping west to Rørvandet was to determine the form of the quartz keratophyres in that area. These rocks simply occur in the form of a number of vertical lenses within the f_1 schistosity. Theyare largely cut offby a fault in the east. The rocks are extremely massive, quartz rich and fine grained. They weather into prominent ridges separated by boggy valleys containing chlorite schists which appear to be basic igneous rocks. The acid rocks may not have been thinned greatly in the deformation of the area, since they are even now very thick compared with their lateral extent.

North from the Svorkmo Antiform, the complementary synform can be detected. This structure is markedly overturned toward the north, particularly in the west. The northern flank of the synform is very extensive, and on the air photos north of Dragset the asymmetric swing in the strike of the f_1 schistosity around the hinge of the synform is very clearly seen. It is probable that somewhere on this flank the core of the f_1 synclinal nappe outcrops, so that further north still one begins to pass down the stratigraphic sequence into progressively older rocks.

The principle of asymmetry of minor folds indicating the form of major folds does not appear to hold well in the case of the Svorkmo Antiform. Incongruous minor folds have b een found on the flanks of the major f_2 folds, often coupled with intense crenulation cleavage, at a number of localities. It may be possible to fit these in with a continuous strain distribution (i.e. continuous f_2 cleavage pattern) when the effects of relative development of cleavage and bedding in the formation of f_2 folds is considered. This will be more fully discussed in John Matthews' report, with particular reference to the remarkable development of this phenomenon in the Svorka River section.

THE FIRST FOLDS

No new work has been done on the outcrop of Hovin Group rocks immediately to the south of Løkken. However, some discussion is required regarding some points which arose during last year's mapping. At the eastern end of the outcrop the rocks appear to be folded into an f_1 antiformal syncline, as indicated on the profile section, plunging gently to the west. At the western end of the outcrop in the mapped area however, north from Storås, the bedding/cleavage and sedimentary structures suggest a more complicated section, perhaps the development of an f_1 antiformal synclinorium. Such a structure might help to explain the presence of a wedge of pillow lavas in the conglomerate 1 km. south from Damli Lake.

The profile section shows a number of f_1 minor fold structures within the basic metavolcanics. These have been inferred from dip measurements on the vaskiss and from the well displayed angular divergence between schistosity and primary layering within the pillow lavas around the Bjørnlivann section. Studies of dip measurements on vaskiss and inferred from old boreholes afford the most promising hope of determining the f_1 structures within the Støren Group Metavolcanics outcrop.

The belt of Chlorite schists, originally greywacke sandstones, shales and breccia conglomerates derived from basic volcanic rocks, which are easily traced for many km. in the north of the area, have been found to display the bedding/cleavage and younging relationships shown on the profile section to a remarkable extent. This is the prime justification for the nappe structure indicated on the section. Unfortunately,the axial surface trace of this nappe appears to be entirely above erosion level. The axial direction of the f_1 and f_2 folds is approximately horizontal, despite plunge culminations and depressions, so parts of the nappe structure above the erosion level at Løkken do not appear to be brought lower down either to the east or to the west.

The bedding cleavage relations observed in the chlorite schist are consistent as far north as th southern outcrop of the flaggy quartz schist, and north from the northern outcrop of the flaggy quartz schist. Inconsistent bedding/cleavage relations are observed within the core of the Svorkmo Antiform. This suggests that the synclinal nappe core outcrops in the core of the Svorkmo Antiform. The nappe core is indicated on the profile section, though the axial surface trace cannot be delineated wit h the confidence implied! The suggestion is made as a working hypothesis.

FAULTING AND JOINTING

A fault zone of considerable importance has been observed running north-south through Ringavatnet. This fault runs for about 5 km. in the mapped area, and appears to end just west of Dragset Mine, amid a group of splay faults.

This fault is undoubtedly the southern continuation of the fault which divides the Gangås Group of Peacey (1964) from older rocks to the west. The fault makes a marked topographic feature between Ringavatnet and Gangåsvann. Its importance lies in the fact that it separates the CambroSilurian rocks of the Trondheim Region in the east from the Basal Gneiss and Sparagmite in the west, hence a large downthrow to the east may be inferred. This is consistent with the way in which boundaries are displaced in this area. Peacey has suggested that a movement of at least 6 km. has taken place in the central part of this fault zone.

No new measurements of joint surfaces have been made this summer, since it is considered that the analysis of joints presented on a previous occasion is an adequate description of the joint pattern in the area.

STRAIN MEASUREMENTS

The shape anisotropy of a number of lava pillows was measured by Mr. Matthews and myself at three localities where undeformed pillow lavas outcrop in the south of the area, and at a number of localities in the north of the area where pillow lavas are exposed in various states of strain. Pillows approximating to triaxial ellipsoids were chosen, and the maximum, intermediate and minimum dimensions, X, Y, and Z respectively, were measured. The quantities, $a=X/Y$ and $b=Y/Z$ were computed, and 'a' was plotted against 'b' (Flinn Diagram).

The Flinn Diagram shows that the undeformed pillows plot in the field of "flattened", oblate ellipsoids, whereas the apparently deformed ellipsoids plot in the field of "constricted", prolate ellipsoids. This is predictable, on account of the ease with which a "principal elongation" direction can be measured in the deformed pillow lavas. This data indicates either that the pillow lavas have aquired a strong stretching component of total strain during the f_1 deformation, or that in the south of the area pillow lavas aquired no shape anisotropy other than that due to flattening by superincumbent load during eruption which reflected the local ~~geomorphology~~ physiography. The rock facies variations indicate predominantly east-west topographic features which could easily be incorporated into the pillow lavas ~~ans~~ as a shape anisotropy. It is also possible that the observed features reflect a combination of both effects. A fuller discussion of the general features of pillow lava deformation and their possible use as strain indicators is required, and this will be undertaken by Mr. Matthews.

Deformed conglomerate fragments are also promising for use as strain indicators, but their use will probably reqire tedious preparation of material. The use of Flinn diagrams, and the general problems of using deformed conglomerate fragments as strain indicators are fully discussed by J.G.Ramsay (pp.185, Folding and fracturing of Rocks, Pub. McGraw-Hill, 1967)

DEFORMED LINEATIONS

Because of the close parallelism of the f_1 and f_2 axial directions, it is difficult to derive useful information from a study of lineation deformation in this area. However, information is coming to light which suggests that more attention should be paid to such features. It has been found that in the hinge zones of the f_2 folds, the f_1 lineations cross at quite high angles to the f_2 axial direction. This suggests that a strong flattening strain component may overprint the f_2 buckling, especially in the case of f_2 folds in the more schistose rocks.

There are two main approaches to the analysis of deformed lineations :

a) The Technique of Construction of Lineation Isogonic Maps.

This technique was recently discovered by Dr. D. Elliott, a copy of whose paper is included with this report. The basic premise is that lineation isogonic surfaces are parallel to the dip isogonic surfaces of EARLY folds. This technique may ultimately prove useful for the detection of early folds, but only when a large number of readings have been collected, more so than we have collected to date.

b) The Technique of Stereographically Plotting Lineation Vector Loci.

This technique can be used to determine the mechanics of later folds, and is fully described by Ramsay (1967, pp. 461 and onwards). It is the application of this technique which has suggested a flattening component in the hinge of the f_2 Svorkmo Antiform. The results will be discussed by Mr. Matthews.

THE ANALYSIS OF FOLD GEOMETRY FROM ORIENTATION DATA

I believe that in the future it will become necessary to analyse geological orientation data in a more systematic way. In particular, objective statistical methods must be brought to bear, and this is probably of particular importance in the mining industry. Such methods will probably require the application of electronic computing techniques in view of the large amount of data involved. A prerequisite to this is the systematic storage of data on coding sheets as it is acquired, to facilitate retrieval for subsequent processing.

During the past year some consideration has been given to the problem of statistical analysis of orientation data. A test of the possibilities of this type of analysis was made on the data collected by Mr. Chaplow last summer in the area west of Dragset Mine. The data was analysed using the Imperial College IBM 7094-1401 computer system. The method employed was described in a thesis submitted by Dr.T.V.Loudon to the United States Office of Naval Research in 1964. The theory of the method is outlined in an extract from this thesis submitted with this report. The programming involves the fairly straightforward translation of the mathematics into FORTRAN IV. The computer output (except for most of the lists of direction cosines transformed to refer to the principal axes) is enclosed for reference purposes with this report.

The following discussion presupposes that the reader be familiar with the analysis of Loudon.

The ways in which statistical orientation data analysis can aid in objective fold description are as follows :-

1) To give a visual plot of poles to the folded surfaces. The existing Loudon program in fact plots the data on an equal angle projection after counting points on the equatorial plane, a method which leaves the projection unsuitable for ~~counting~~ contouring. Also, the counting interval is rather small. A subroutine which plots the data on an equal area projection after counting on the surface of the sphere with a 1 percent area counting cone has now been written, and this is available for future work. This method of counting poles entirely obviates the inaccuracies of the conventional counting technique which were pointed out by Strand in Norsk Geol. Tidsskr.,1945.

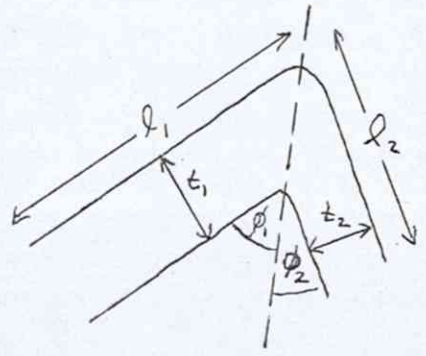
2) Determination of the Fold Axial Surfaces.
The fold axial surface can be defined by two of the principal axes of the distribution of the fold surface poles, provided that the raw data are transformed according to the relative areas and amounts of exposure on each fold limb. Loudon's analysis does NOT take account of field conditions and it assumes that the raw data are obtained uniformly distributed over each

fold limb. This is generally not the case, since although the 3 axis of the distribution is usually a good measur e of the fold axis, the 2 and 3 or 1 and 3 axes will bear no relation to the axial surface unless the data i s uniformly distributed over the fold limb areas, or unless it is transformed to be so. Fortuitously, the Dragset data fulfills the desired conditions, and the analytically determined principal axes agree well with the intuitively inferred principal axes.

As Loudon has suggested, the variance of the distribution about the three principal axes is a good measure of the tightness of folding about each axis.

3) Determination of Fold Asymmetry.

Loudon`s treatment of fold asymmetry does not take account of the fact that asymmetry must be expressed by at least two independent parameters



a) $p = l_1 / l_2$

This describes the asymmetry of a single folded surface.

b) $q = \sin \varnothing_1 / \sin \varnothing_2 = t_1 / t_2$

This describes the asymmetry arising from differences in layer thicknesses.

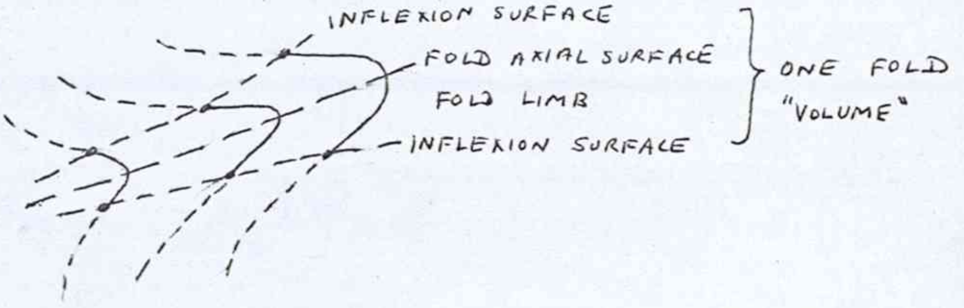
The position of the axial surface is defined by the hinge lines of adjacent folded surfaces, and hence the analysis into principal axes should involve this latter symmetry parameter.

A fold only possesses orthorhombic symmetry if both of the following conditions are simultaneously satisfied :-

$$\frac{l_1}{l_2} = 1 \text{ , and } \quad \frac{\sin \phi_1}{\sin \phi_2} = \frac{t_1}{t_2} = 1$$

4) Determination of Curvature.

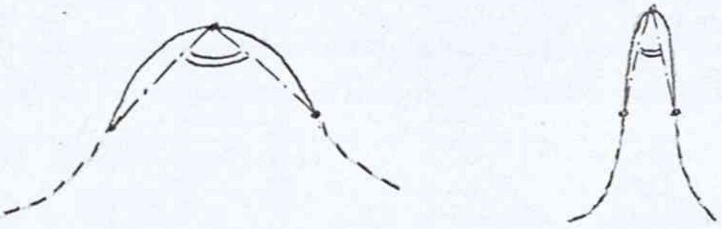
A fold can be defined as the family of curved surfaces between adjacent limb inflexion surfaces.



The curvature of each fold limb may be different, and hence each limb should be analysed separately. The variance about the vector mean of all the data collected between each inflexion surface trace and hinge trace on the mapwill give a measure of the curvature of each limb.

5) Determination of Interlimb Angle.

For orientation analysis this is most conveniently defined as the angle between lines joining inflexion points to each hinge point on each folded layer.



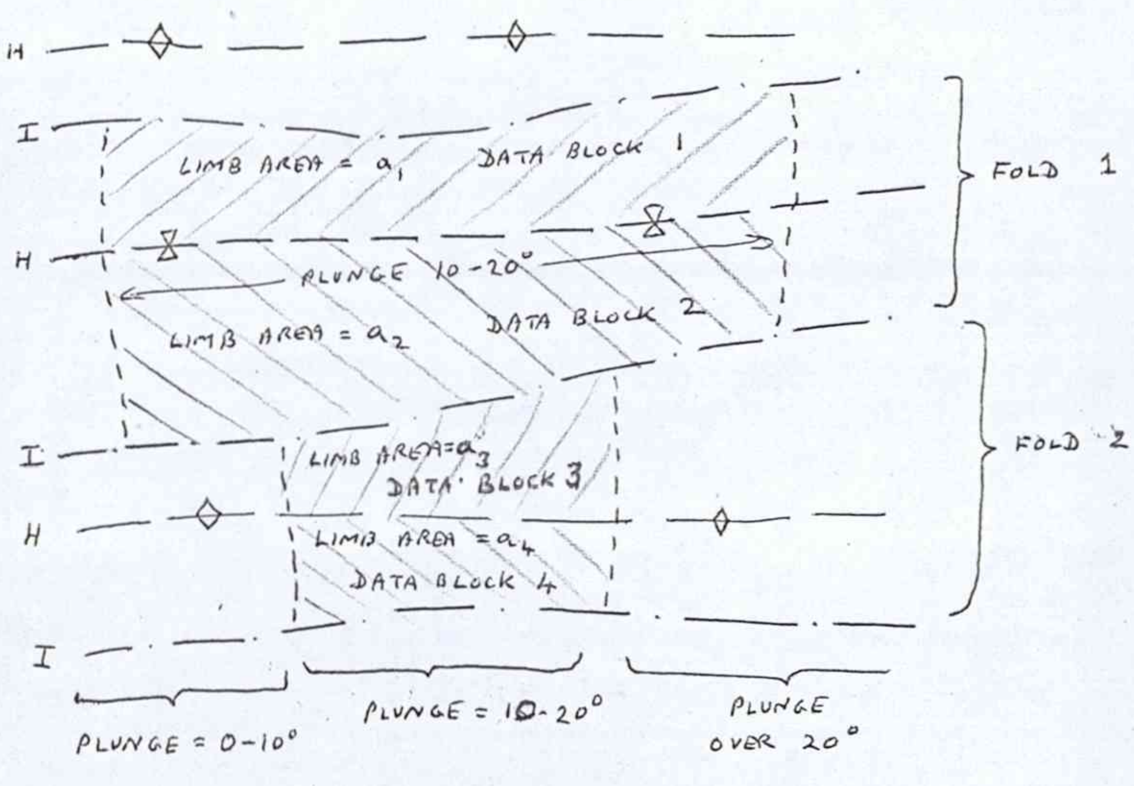
This measure is given by the angle between the vector means of each fold limb, and is in my opinion a better description of interlimb angle than the conventionally adopted definition of the angle between the tangents to the limbs at each inflexion point.

6) Analysis of Cylindricity.

This is treated as a problem in the analysis of bivariance by D. Cruden, a copy of whose paper is included with this report. The treatment is probably unnecessarily tedious, and for practical purposes it may be more convenient to adopt the traditional method of "analysis in subareas", wherein folds can be considered nearly cylindrical over a selected axial length. The orientation of the great circle which best fits the data can then be determined by the least squares method. The variance about the 3 axis is, as suggested by Loudon, probably the most convenient measure of the cylindricity of folds.

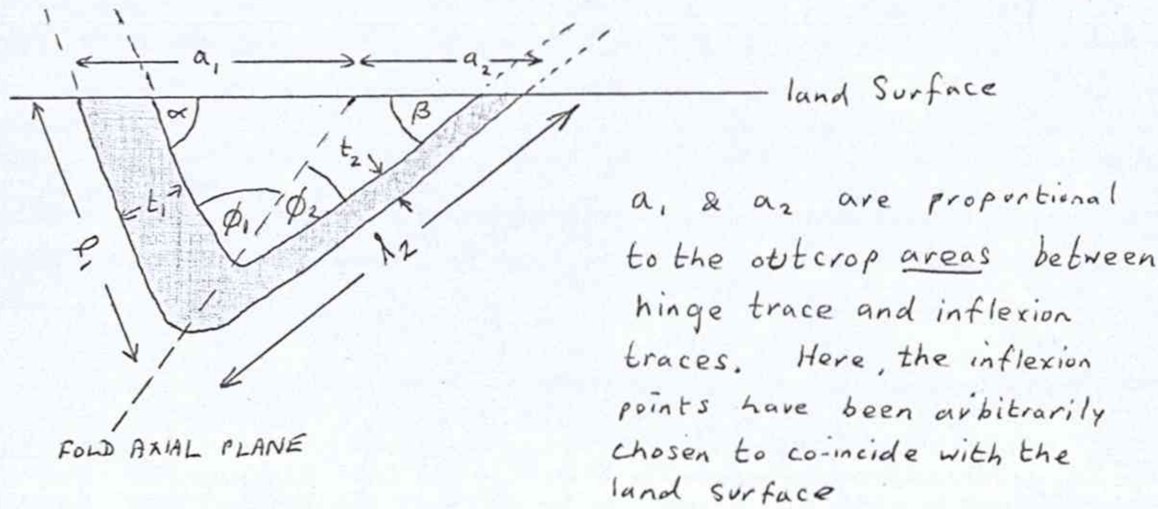
A prerequisite to the statistical analysis of orientation data is the organisation of the data into blocks distributed according to 1) fold limbs, and 2) approximately cylindrically folded areas along the fold axial direction. This is most conveniently done by drawing hinge traces and inflexion traces on the map, and by using lineation plunges, to pick out areas of approximately equal plunge, within, say, ten degrees:-

HYPOTHETICAL EXAMPLE :-



H = HINGE TRACE ; I = INFLEXION TRACE

Now, taking a profile section across an hypothetical folded layer :-



In order that the 1 and 3 axes define the fold axial plane :

Number of readings on limb 1, = r_1 , is proportional to $l_1 \cdot \sin \emptyset_1$

A similar relation exists for limb 2.

Hence the ratio of readings on each limb :

$$\frac{r_1}{r_2} = \frac{l_1 \cdot \sin \emptyset_1}{l_2 \cdot \sin \emptyset_2} = \frac{l_1 \cdot t_1}{l_2 \cdot t_2} = p \cdot q$$

Now ,

$$\frac{a_1}{a_2} = \frac{\sin \emptyset_1}{\sin \emptyset_2} \quad \text{and} \quad \frac{l_1}{l_2} = \frac{\cos \alpha}{\cos \beta}$$

by inspection.

$$\text{Hence,} \quad p \cdot q = \frac{a_1 \cdot \cos \alpha}{a_2 \cdot \cos \beta} \qquad (1)$$

Thus fold asymmetry can be expressed by two dimensionless parameters which are easily computed. It is important to note that the ratio of layer thicknesses is equal to the ratio of limb outcrop areas, a corollary of the fact that the orientation of folded layers is entirely a function of the thickness of those layers. The wide outcrop of the southern limb of the Løkken Synform, due to the thickening of the Støren Group metavolcanics southward, is a case in point.

The quantities $\cos\alpha$ and $\cos\beta$ can be determined directly from the vector mean of all the assembled data for each limb, and the ratio a_1 / a_2 is directly determined from the measured map areas between each limb and inflexion trace. The manipulations of the data to satisfy relation (1) are then most conveniently carried out in the computer as part of the program.

The results of this type of analysis are a number of vector quantities describing the orientation of the fold in space and a number of dimensionless parameters describing physical attributes of the fold such as asymmetry, tightness, curvature of limbs, cylindricity, etc. These parameters might usefully be displayed graphically to show the way in which they vary over the whole region. Such a treatment might usefully pick out systematic variations in fold geometry which are reflections of lithology and thickness, i.e. facial variations, which might otherwise not be apparent.

I shall be prepared to undertake such a computer analysis of this type, of orientation data from the Løkken Area, should it be desired at any time in the future. The data should be organised into limb "blocks", as illustrated earlier, and listed in columns headed, "azimuth" and "amount of dip" (i.e. data must be in the form of dip and dip direction, NOT dip and strike). A map should be made showing the way the area has been split up into subareas defined by inflexion and hinge traces in one direction and zones of approximately constant plunge in the other.

CORRELATION WITH NEIGHBOURING AREAS

Time has not permitted an attempt to make a definite correlation of structures with the areas to the east. One thing has become apparent, however, and that is that the fold phase which Carter described as f_1 is the equivalent of what we have called f_2. Hence the swing in the strike ot the rocks around Hølonda must be attributed to some event later than our f_2.