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Se også:
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Comments to Prof. B A Sturts report (F Nixon)
(Begge i BV 1212)

FOR FALCONBRIDGE NIKKELVERK A/S

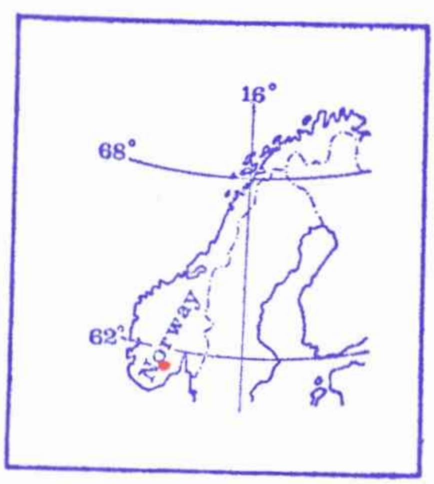
A/S SULFIDMALM

PROJECT 905 -7

STRUCTURAL OBSERVATIONS ON THE
KJETTEVANN PROSPECT, IVELAND.

BRIAN A. STURT

1972



1 INTRODUCTION

The study of the structural styles of deformation and of the strains which affect the rocks of the Kjettevann area, Iveland made by the writer 10. - 11./6./72, is based purely on field work on these days and to information provided by the conpany's geologist in the area (F.Nixon), to the various geological reports and the proveded bore-hole logs from Kjettevann. This particular report will not attempt to provide any regional synthesis of the Iveland area but will primarily be limited to a discussion of certain details of the small-scale tectonics, intrusive relationships between the various members of the complex and the possible implications of the structural style to the disposition of the ore-bearing peridotite leading to predictions which may be possibly drawn from this analysis.

One of the most apparent and immediate differences to the previous knowledge of the tectonics of this small area, already in possession of the company, is the importance of flattening-extensional deformation in analysing the pattern of strains undergone by the rocks of this complex. This is perhaps something which might not be expected from the regional compilation of the data which the company has accrued to date, but can be readily appreciated from a detailed examination of a number of critical outcrops and by the application of the strain ellipsoid theory in terms of the pure-shear condition and in certain cases under conditions of simple shear. It will be shown in the subsequent account that in, at least the small area under discussion, that the rock sequence has suffered considerable shortening in a direction normal to the layering with a consequent extension in the essentially two-dimensional system of that layering. In this connection the competence differnces between rocks of different composition, texture etc. becomes perhaps of critical importance in the shape patterns which are assumed as the result of the strains undergone by the rocks. To put the matter simply the incompetent or less competent members of the complex will be capable of flowage by extension, whereas the competent or more competent lithologies will tend to yield by process of boudinage producing lensoid outcrop patterns. It will be shown that this is the strain pattern that appears to apply to the rocks of the Kjettevann prospect, and that this may have significance in terms of the possible made of continuation of the mineralized zone.

It can also be shown as the result of the present study that the area has suffered both polyphasal structural development and polyphasal sequence of igneous emplacements during the protracted deformational process. However, the writer must stress that he has not examined other parts of the Iveland Complex and must hold the basis of this particular report to the small area in question although it would seem likely that many of the comments may have relevance to other parts of the complex.

II STRUCTURAL ANALYSIS OF THE KJETTEVANN COMPLEX

As stated in the introduction this cannot be taken to represent a regional account of the tectonic patterns but more as an analysis of the strain patterns of rocks in the local Kjettevann area, and the possible implications of this analysis. In the first instance comments will be made about the strain patterns of the two main rock types shown on the company's compilation map from the Western side of Kjettevann, viz. gneisses with "migmatitic structure" and "amphibolites".

(i) Gneisses with "migmatitic structures"

(a) General Features

Observations were made on these rocks particularly in the area 230W - 270W and 330N - 450N. The main rock type here is of a feldspar-rich gneiss with more amphibolitic horizons. The gneiss contains many thin schlieren of basic material lying parallel to the gneissic layering and giving the appearance of a discontinuously banded gneiss. The precise origin of these basic schlieren is impossible to ascertain, though they may well represent former basic sheets in the gneisses which have now been thoroughly flattened and extended. It is quite obvious that these gneisses with their contained basic schlieren have undergone high-grade plutonic metamorphism with anatectic mobilization of the felsic components, as innumerable rootless felsic veins can be observed to stem from the feldspathic gneisses and to intrude the basic schlieren. Other more marked feldspathic veins with fairly sharp margins cut-through both the gneisses and the basic schlieren, though are themselves cut by later basic dykes and subsequent pegmatitic veins, dykes and sheets. Indeed in these rocks it is possible to trace the following sequence of intrusive events: -

1. Host-rock of gneisses with "migmatitic structure" - containing basic schlieren.
2. Anatectic mobilization of felsic components to produce
   - (a) Diffuse veins, and probably
   - (b) Feldspathic veins with fairly sharp margins.
3. Basic dykes of at least two generations.
4. Pegmatite veins (deformed) cutting basic dykes of 3.
5. Pegmatite dykes and sheets of regional Iveland pegmatite swarm.

(b) Deformational Features

One of the most obvious features of these rocks is the effects of flattening/extensional strain under a dominantly pure shear regime. This is particularly seen by a study of the various generations of felsic veins in these rocks. From Appendix I of this report the basic essentials ofthe strain-ellipsoid theory to flattening-extensional deformation are outlined. From this it will be appreciated that veins lying within the compressional field of the strain ellipsoid, defined by the planes of no-finite longitudinal strain, will be shortened by folding, and those lying within the extensional field will be extended by boudinage. As the strain regime is progressively flattened so certain of the folded veins will enter the extensional field and be subject to boudinage (Fig 7D). In the migmatitic gneisses under consideration it may be observed that early cross-cutting veins are extensively shortened (Fig. 1) and as they or portions of their limbs enter into the field of extensional strain so they become extended by boudinage (Fig. 1). In comparison thin veins parallel or sub-parallel to the main foliation and indeed the basic schlieren previously mentioned become strongly extended both by thinning and seperation, i.e. by a boudinage mechanism. It is extremely difficult to quantify the extent of shortening/extension which occurs in this straining owing to the effects of extension of shortened material as it enters the extensional field of the strain ellipse.

It can be shown however that such veins are cut by basic dykes (see 3. of sequence above) which themselves have been subject to subsequent boudinage. These dykes are themselves cut by pegmatite veins 4. and 5. of the small-scale intrusion sequence. In the case of the earlier of these vein sets (i.e. 4.) it can be shown that these have also been considerably shortened normal to the main foliation (Fig. 2), and semi-quantitative estimates indicate a shortening of the sequence in the order of 40-50%. However, as seen from Fig. 2 this is of a smaller order of magnitude where the acid vein cuts the basic dyke than where it is cutting the migmatitic host rocks - a reflection of the relative competence of the two hosts. This pattern of shortening/extension occurs in the plastic field of deformation and it can also be demonstrated that in these steeply inclined rocks that deformation of similar type continues in the semi-brittle to brittle field subsequently. This is shown by (i) a number of mylonitic shears at a low angle to the foliation i.e. 25° of both left-lateral and right-lateral type and (ii) a conjugate fault set as indicated in Fig. 3 .

(ii) Foliated Amphibolites

These are well shown in a series of exposures at the southern end of Kjettevann and the deformation style is virtually identical with the migmatic gneisses described under 1. These are gneissose basic rocks containing schlieren of more mafic material (probably dyke material) highly flattened and streaked out parallel to the foliation of the host. Also containing more entire basic band (concordant-sub-concordant) presumably representing basic sheets. These latter show variable pinch-and -swell (i.e. boudinage) and most of them are found to taper out if traced far enough along the layering. Cross-cutting felsic veins are strongly shortened and as the vein orientations rotate beyond the planes of no-finite longitudinal strain they become extended, indeed Fig. 1 is from these rocks.

Significantly as these rocks approaches the mineralized peridotite zone so isolated small boudins of peridotite with disseminated sulfide mineralization are encountered. (Fig 5) If, as would appear likely that the peridotite boudins represent detached portions of the main ore-bearing ultramafic, this would indicate the probable tectonic style adopted by the deformed peridotite. The boudinage of the peridotite took place in the plastic strain-regime, and the small boudins referred to are variably transected by the brittle strain features described for the gneisses with migmatitic structure.

At the southern end of Kjettevann just to the E of the outlet stream an excellent section of the deformed amphibolite complex is to be observed. Here it is obvious that extensional strains have been profound as is seen from the strong flattening and streaking of the rocks. Indeed the whole appearance of the rocks is of a gabbro gneiss (amphibolitic gneiss) with schlieren and irregular tapering bands of more melanocratic material, the schlieren are very flattened lens-like plates and the bands shown strong flattening and extension by boudinage. It is difficult to be categoric to say how much of the more melanocratic phase represents intrusive dyke material owing to the effects of the extensional/flattening strains, however, it is possible to see stages in the process, and at least two sets of dyke-like rocks can be distinguished, subsequent to the strongest deformation though these were still subjected to boudinage and displacement on brittle shears. The whole sequence shows strong pinch-and-swell features, and there has obviously been pronounced small-scale sliding.

III INTRUSIVE RELATIONS OF THE MINERALIZED ULTRAMAFIC ROCKS

The western contact of ultramafic with the gneissic amphibolite complex is well exposed at the southern tip of Kjettevann and the ultramafic is clearly intrusive into these gneissic rocks. Near its border the ultramafic contains many xenoliths of the country rock, and in many cases these bear strong foliation, and obviously represented rocks strongly deformed prior to the ultramafic emplacement. There are also many xenoliths which exhibit little or no evidence of deformation, and taking the appearance of the population of xenoliths as a whole relative to the character of the strain-state of the marginal amphibolite gneisses it would certainly seem that the ultramafic was intruded before the deformation of the country rocks had reached their present degree. Other features corroborate this picture: -

(i) There are zones of locally developed foliation within the ultramafic.

(ii) The ultramafic is cut by feldspar-rich veins which often have strong foliation developed parallel to their margins - the presence of such foliation in these veins and its lack in the ultrabasic, is principally a reflection of the differences in shear strengths of the two rocks i.e. shear strength Ultramafic > shear strength felsic vein.

(iii) Along both east and west contact of ultramafic small boudins (up to 2m long) have been observed in the gneissic amphibolite host.(Fig 5)

(iv) The ultramafic is cut by both the mylonitic shears and small faults mentioned under(2 i b).

(v) The ultramafic is intruded by a later gabbroic material which would appear to be the rock of the gabbro zone shown on the company's compilation map. The age-relations in these exposures are unambiguous (see below). However, it is possible to see that this gabbro has zones of very strong foliation development, and indeed that basic dykes cutting the gabbro are often boudined and sometimes themselves foliated (Fig 4)

As indicated above the peridotite is intruded by a later gabbro which appears to be the body mapped E. of Kjettevann. These relations can be studied on the shore of Kjettevann (120-180N/20W-O), where the gabbro is observed to net-vein the ultramafic. It can further be seen that the gabbro bears xenoliths of the ultramafic (particularly well observed in a number of large blocks.) Further to the North of the present known ultramafic at Kjettevann H.Furnes mapped on 10./6./72 a lens-shaped ultramafic body with sulfide dissemination surrounded by later gabbro. This gabbro veins the ultramafic and small xenoliths of it are found in the surrounding gabbro.

In light of the foregoing discussion regarding the probable structural history of the mineralized ultramafic, and from the geophysical indications of shape of the mineralized body at S. Kjettevann it would appear that the ultramafic probably is represented by a series of boudinage lenses formed during the extensional deformation of a once continuous sheet. The clear intrusive relations of the "later gabbro" and the lens-shape of the ultramafic body mapped by Furnes indicate that the boudinage occurred before the gabbro intrusion. If this is the case the trend of the ultramafic zone is probably independent of the gabbros. Based on this analysis and the company's mapping results a prediction of the probable continuation of the zone of ultramafic with the disseminated mineralization can be made, and this is shown in Fig. 6 . It would be difficult to extend the prediction beyond that indicated by Fig. 6 as the structures cannot be anticipated beyond this.

One feature would appear to perhaps have some importance is that the N-S trending folds south of Klepp where dips change from steep to sub-horizontal are in fact folding the flattening strain ellipsoid described from Kjettevann. This indicated that if the boudinaged ultramafic is itself folded by such structures that both the outcrop patterns and the geophysical anomalies will be somewhat complex, as a result of rotation of the lensoid bodies the peridotite are taken to represent.

APPENDIX I

Interpretation of the Strain Ellipsoid with possible reference to the shape and disposition of ore bodies.

It will be seen from Fig. 6A that two very important planes in the 3 dimensional strain ellipsoid are those known as The Planes of No-Finite Normal Strain (or the planes of no-finite longitudinal strain). In the two dimensional diagram of the XY plane of the strain ellipsoid the lines ℓℓ and ℓ'ℓ' represent the radius of an initial circle in the unstrained sphere. These planes essentially delimit a shortening strain field from an extensional strain field.

One much vaunted art of the structural geologist is using the shape changes of objects of known initial shape during finite deformation. It must however be pointed out that the determination of homogeneous strains in rocks is not as easy as it sounds, in high-grade metamorphic rocks objects of original spherical shape e.g. oolites, spherulites, pebbles, reduction spots in slates are absent, as indeed are non-spherical bodies such as fossils, current-bedding, worm-tubes etc. It might thus be thought that this analysis could not be applied to high-grade rocks such as those of the Iveland area, this of course is true if one is concerned with quantitative calculations of the finite strains involved. However, considerable information can be obtained concerning the qualitative aspects of these finite strains by a consideration of the properties of the strain ellipsoid and by the study of the deformation of veins which cross-out and/or parallel the layering. Let us simply pose the problem.

1 If the vein is orientated normal to the layering and the thickness across the layering is shortened the vein will shorten by folding. If the thickness of the vein remains constant the original length (ℓ^{o}) can be measured and the percentage shortening can be calculated with reference to the new thickness normal to layering: -

$$\% \text{ shortening} = \frac{\ell^{o} - \ell^{n}}{\ell^{o}} \times 100$$

2 If the vein lies within the layering and shortening takes place normal to the layering the vein will extend by boudinage as it lies in the YZ plane of the ellipsoid i.e. right in the field of extensional strain.

3 In inbetween orientations relative to the layering the vein will either shorten by folding, extend by boudinage or both according to its position in relation to the strain ellipsoid see Fig 7 B for the pure shear condition and Fig 7 C for the simple shear condition.

From the accompanying diagram Fig. 8 the case for progressive incremental pure shear strain is illustrated, showing the form of the two-dimensional ellipsoid in relation to progressive increase in the degree of flattening and extension.

It is realized that these theoretical observations in themselves have little import in the search for mineral deposits but the concepts embodied here have considerable import in thinking of the geometries of ore bodies under prospect. Let us take the example of minerallized peridotite layer where the wall rocks are a thick sequence of foliated amphibolites and consider this system under a process of flattening/extensional deformation. The peridotite will represent the competent horizon (av. shear strength rel. high) the foliated amphibolite the incompetent unit (av. shear strength relatively low), the ~~relevant~~ result will be that the amphibolite will extend by plastic flow whereas the competent peridotite will yield by boudinage. As a result of the boudinage the peridotite layer will now assume a series of shapes dependant upon the precise nature of the strains involved. Two different models for such a body are shown in Fig. 8 and 9a . In Fig. 8 the triaxial strain condition is such that the axes of the ellipsoid have the length relation $x < y < z$ and the boudins will have the form of flattened cylinders or elongated rectangular blocks - the exact shape depending on the competence contrasts. In the case of pure flattening where strain in all directions within the plane of layering is equivalent (i.e. $x < y = z$), the boudinage will have a chocolate tablet form in general terms though the seperations may be considerable. The conditions in nature may in fact lie between the two extremes (Fig 9)

For our purposes, however, a knowledge of the approximate shape model for the body can help us in a number of ways: -

1. To aid in the geophysical prospecting work and its interpretation.

2. Possible reduction in costs of a drilling programme.

3. Help in the process of total tonnage estimation.

These are all fairly obvious features and would be true for any shape model proposed by any method - as long as it was reasonable.

The other point which is of value is that by paying some attention to the internal strain features of the wall-rock i.e. in relation to the strain-ellipsoid, we can often derive important information regarding the deformation and style of deformation of the orebody which is not obvious either from a study of the body itself or from the more general results of the regional tectonic synthesis: -

(1) By observing the strains incurred by veins in the wall rock we can make a qualitative assessment of flattening-extensional strains which have occurred in the more limited area.

(2) By the observation of boudinage structures in the rocks of the local area we may be

able to explain the significance of lens-shaped outcrop patterns of the ore body, or even elongated elliptical geophysical anomaly patterns (see Fig. 9b)

(3) By recording the three-dimensional shapes of boudins, prediction models can be set up for the three-dimensional form of the ore bodies.

(4) By realizing that boudins represent the break-up of a once continuous finite layer it may be possible to predict extensions to the known mineralized zone.

All this being said the writer is aware that this applies to particular tectonic conditions, but these are not in the least rare in high grade metamorphic terranes, and the condition of flattening extensional deformation in such terranes has all to often been overlooked.

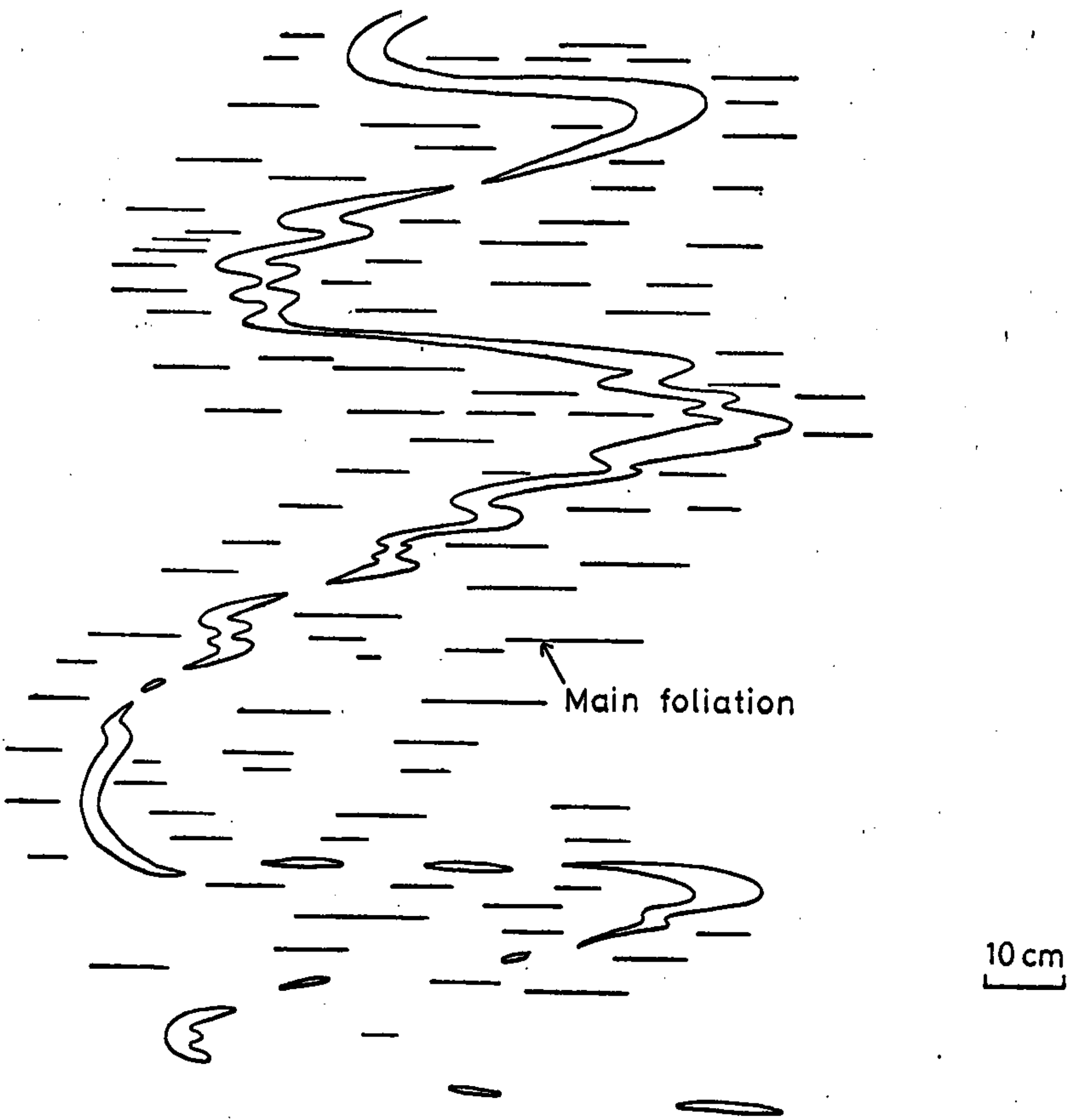


Fig.1 Shortened and extended vein

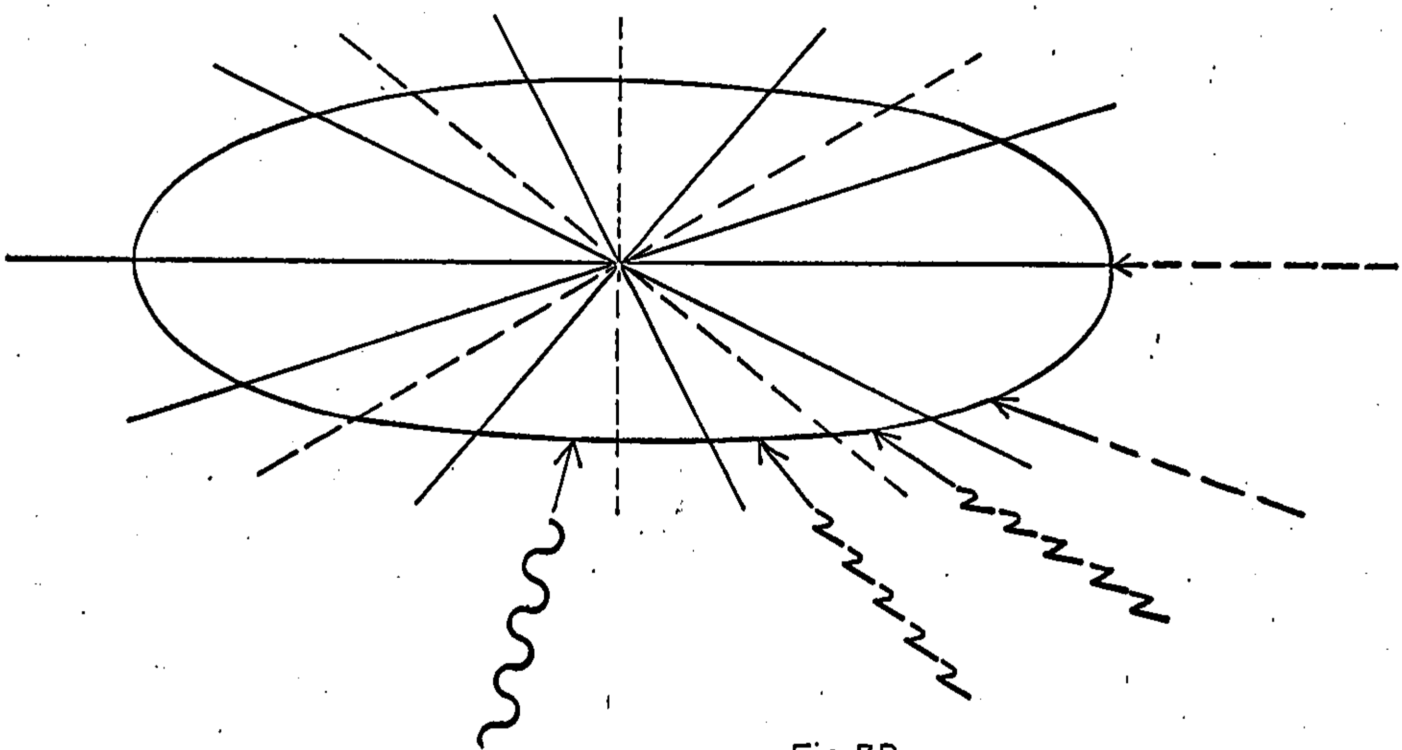


Fig.7D

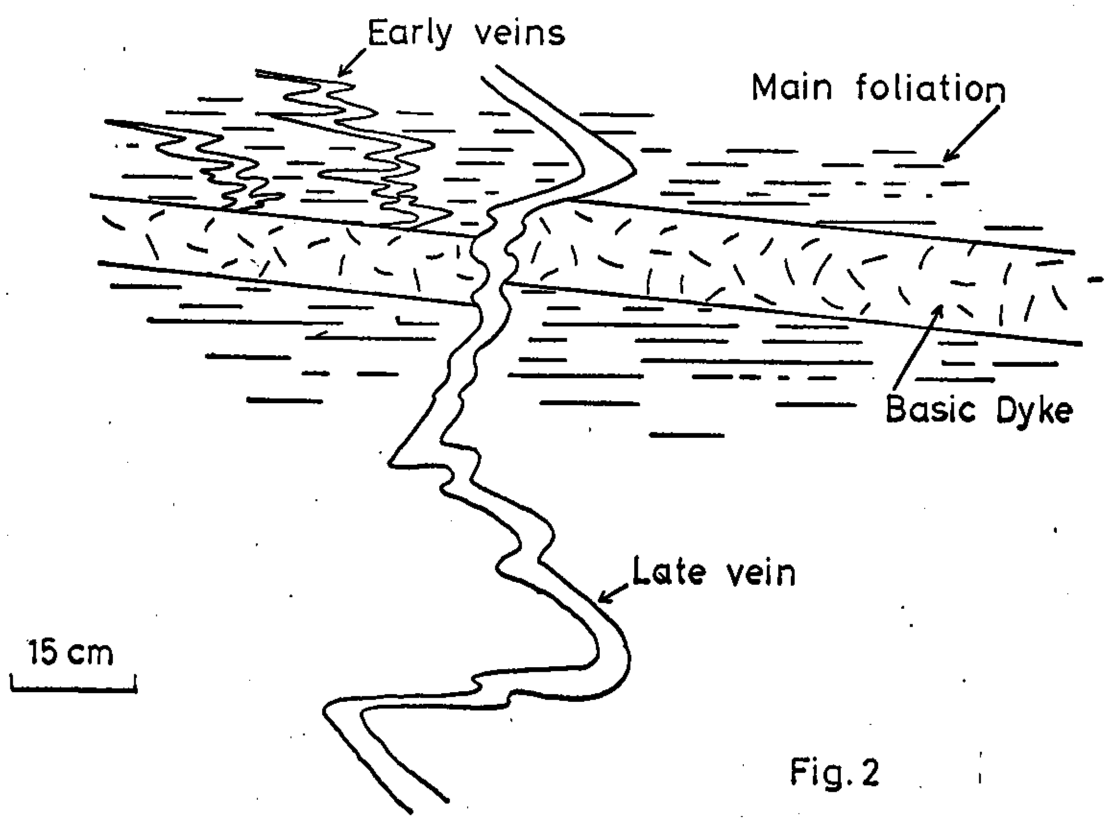


Fig. 2

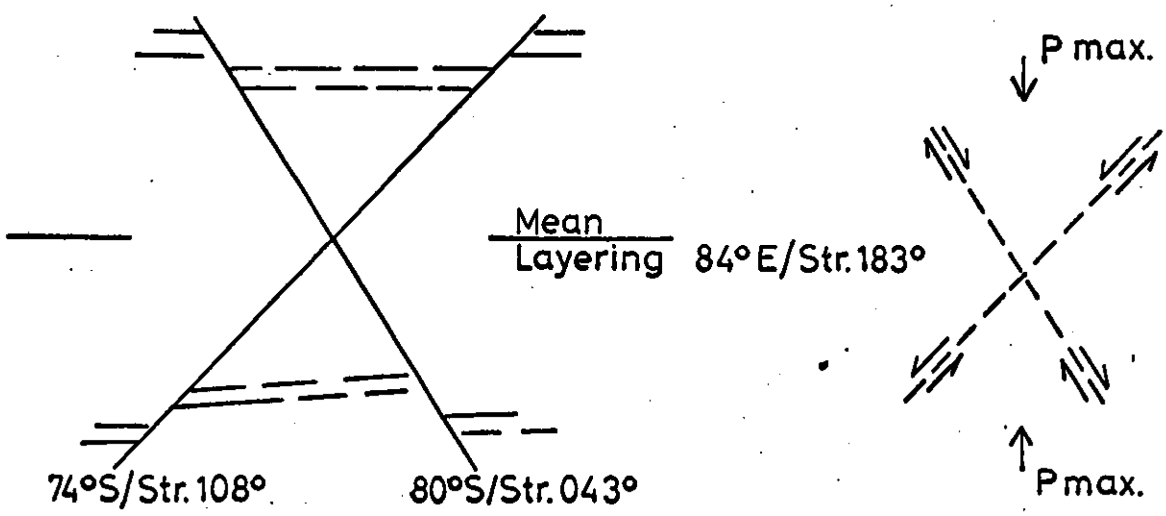


Fig. 3

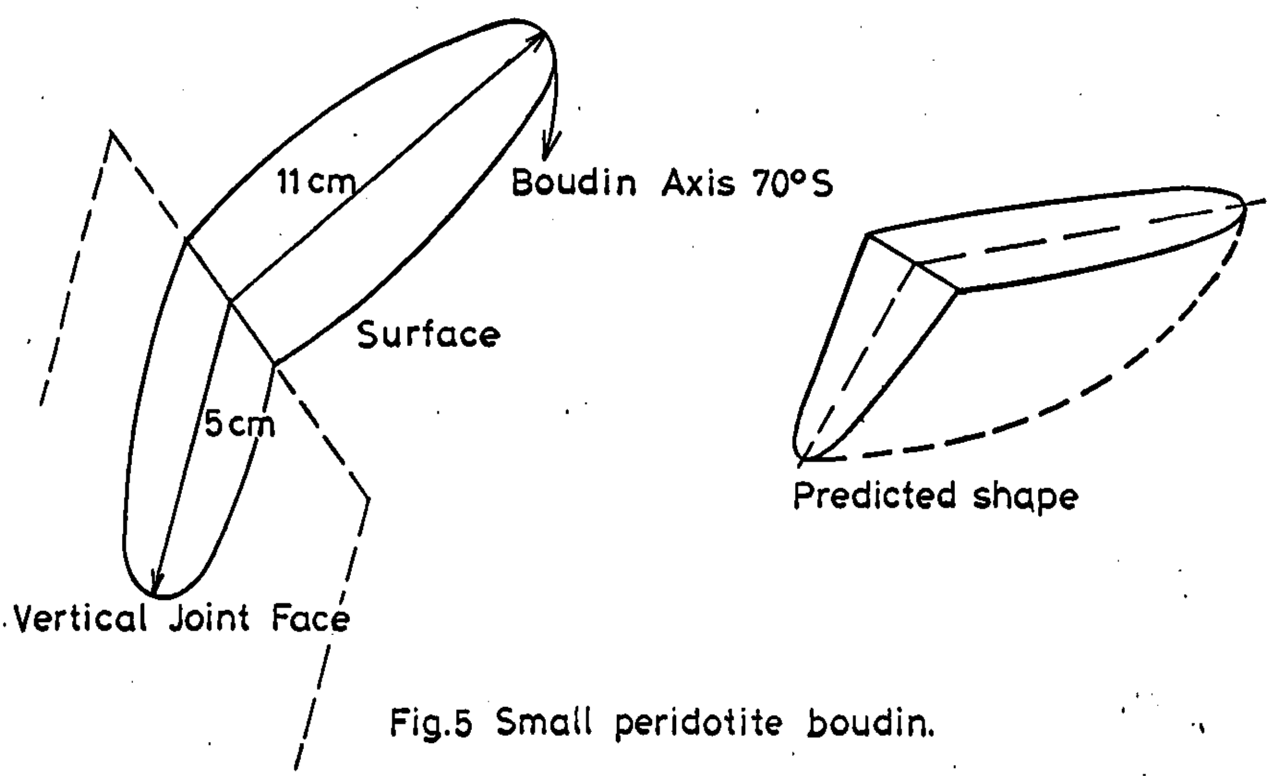


Fig.5 Small peridotite boudin.

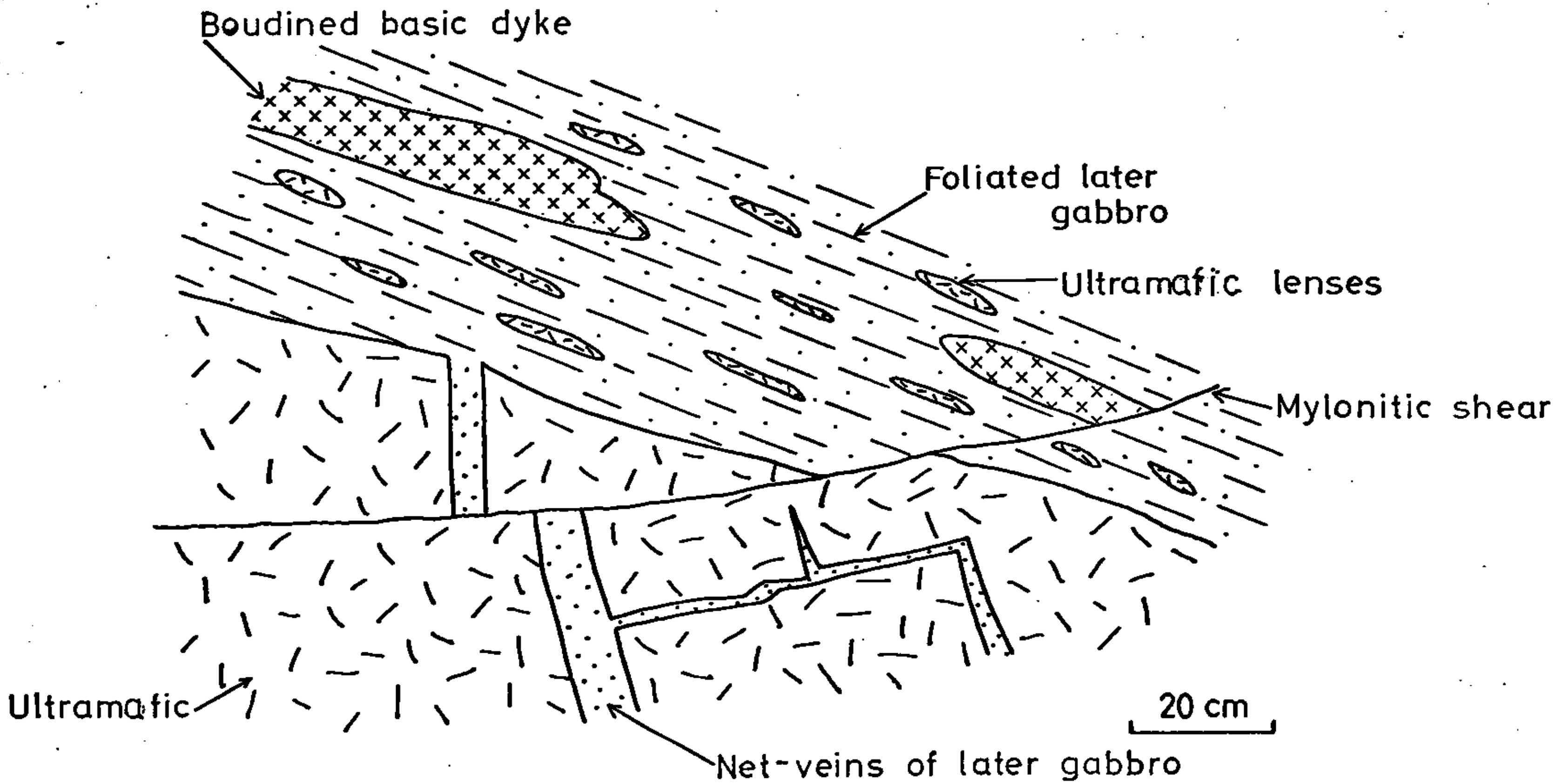


Fig. 4 Intrusive relations of later gabbro

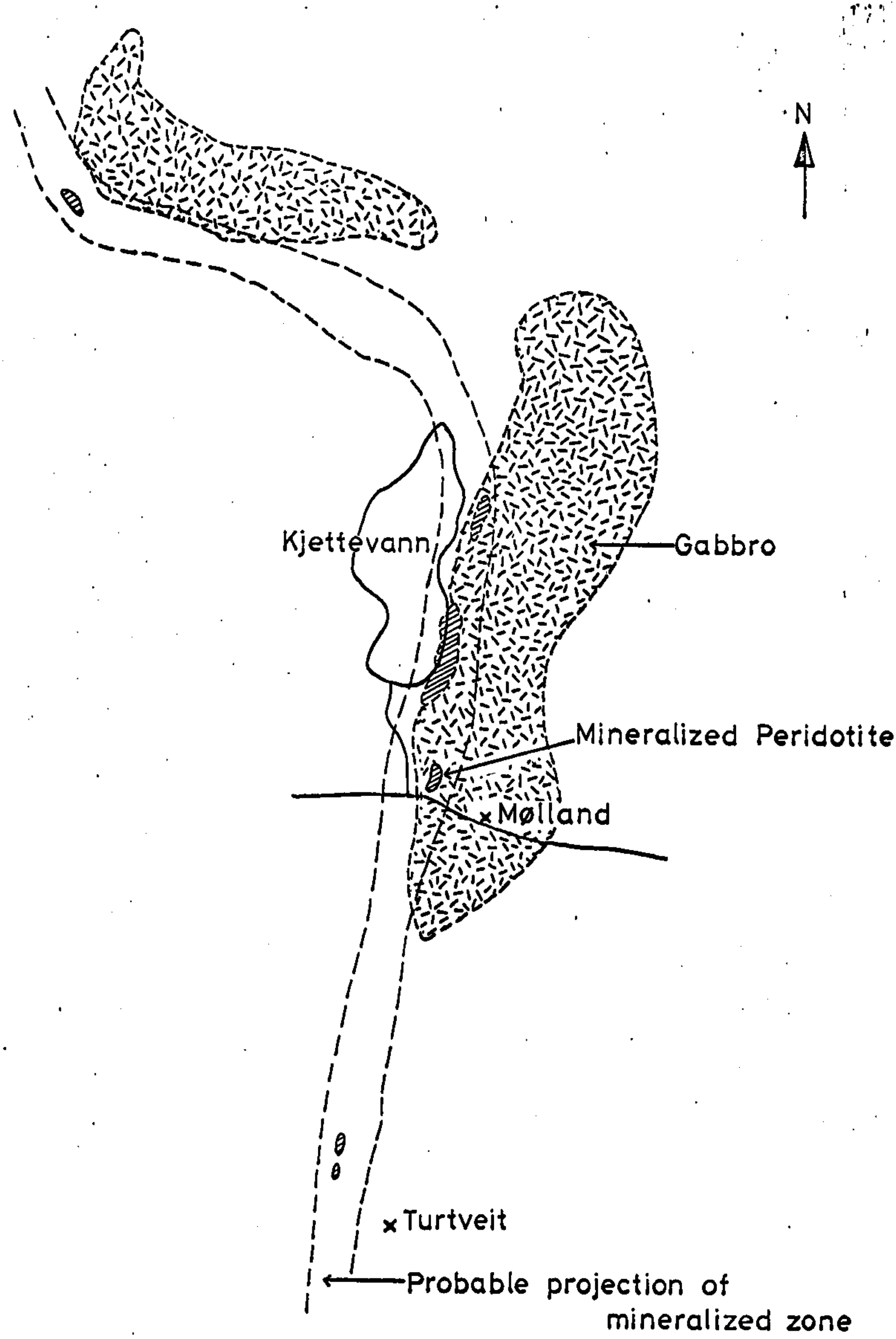
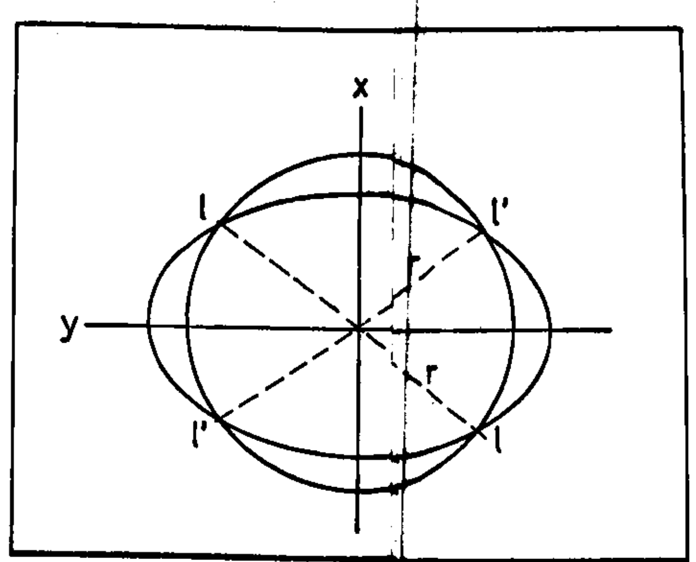
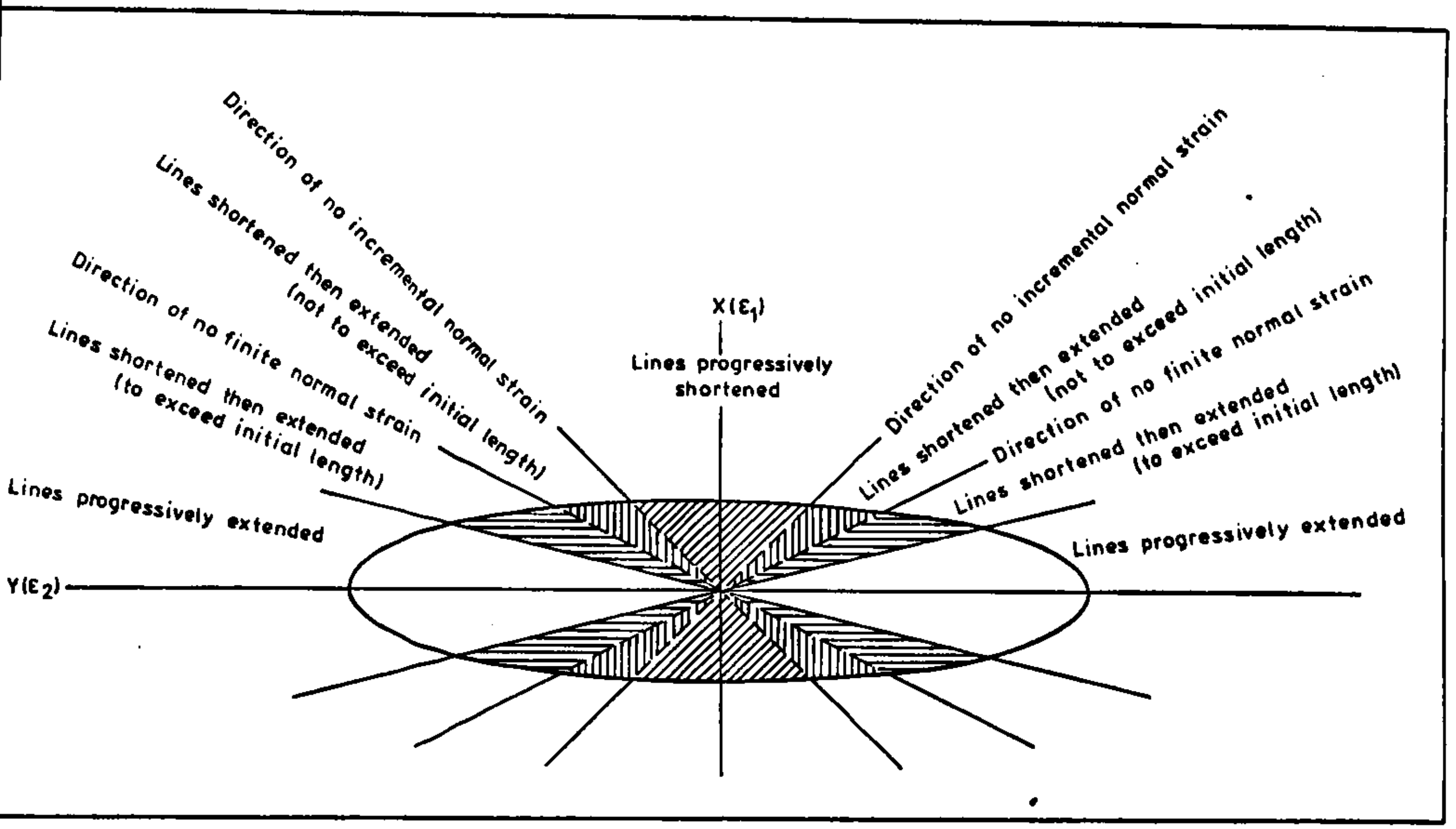


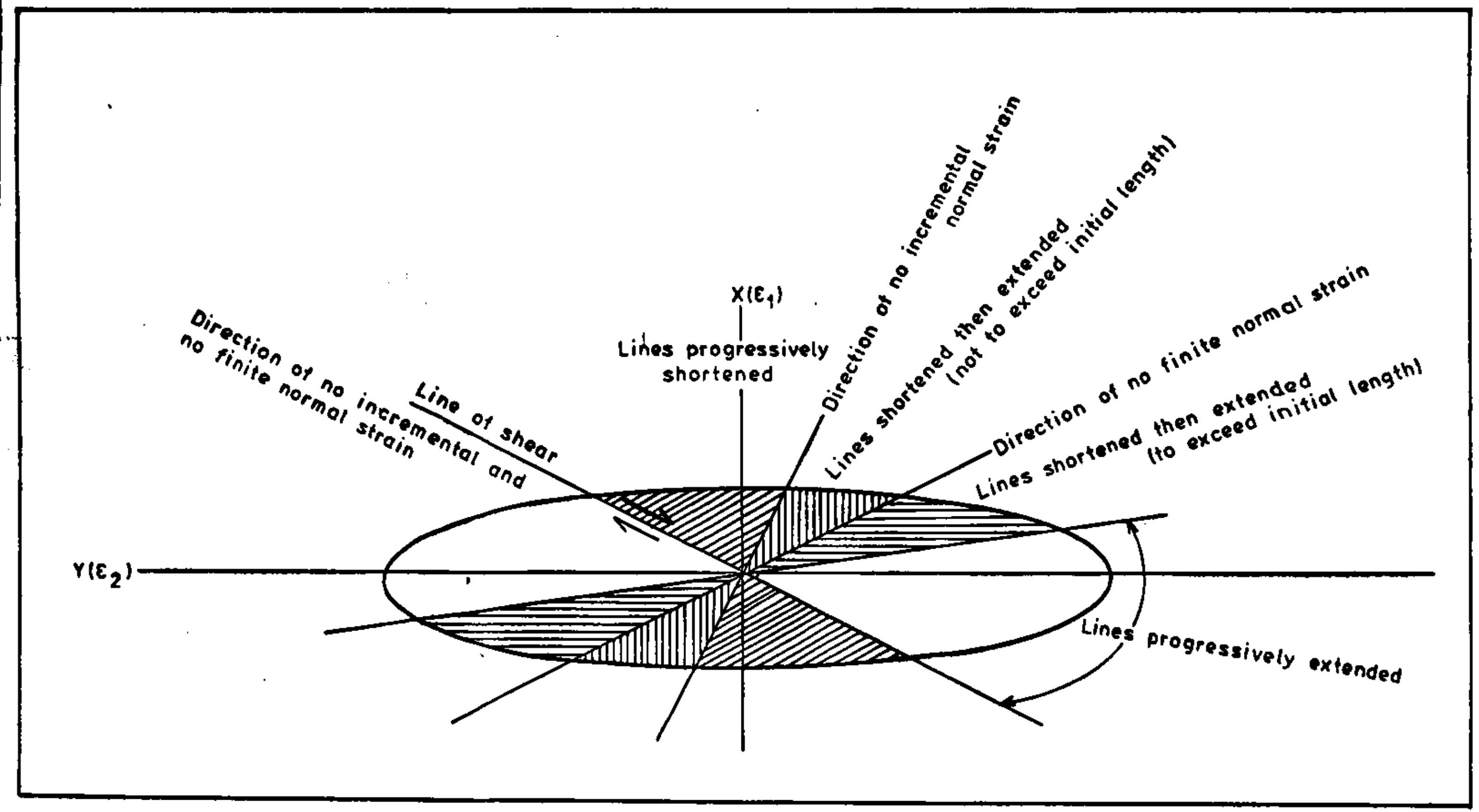
Fig.6 Rough Sketch-Map of the Kjettevann region.



A. xy plane of strain ellipsoid



B. Pure-shear condition



C. Simple shear condition

Fig. 7

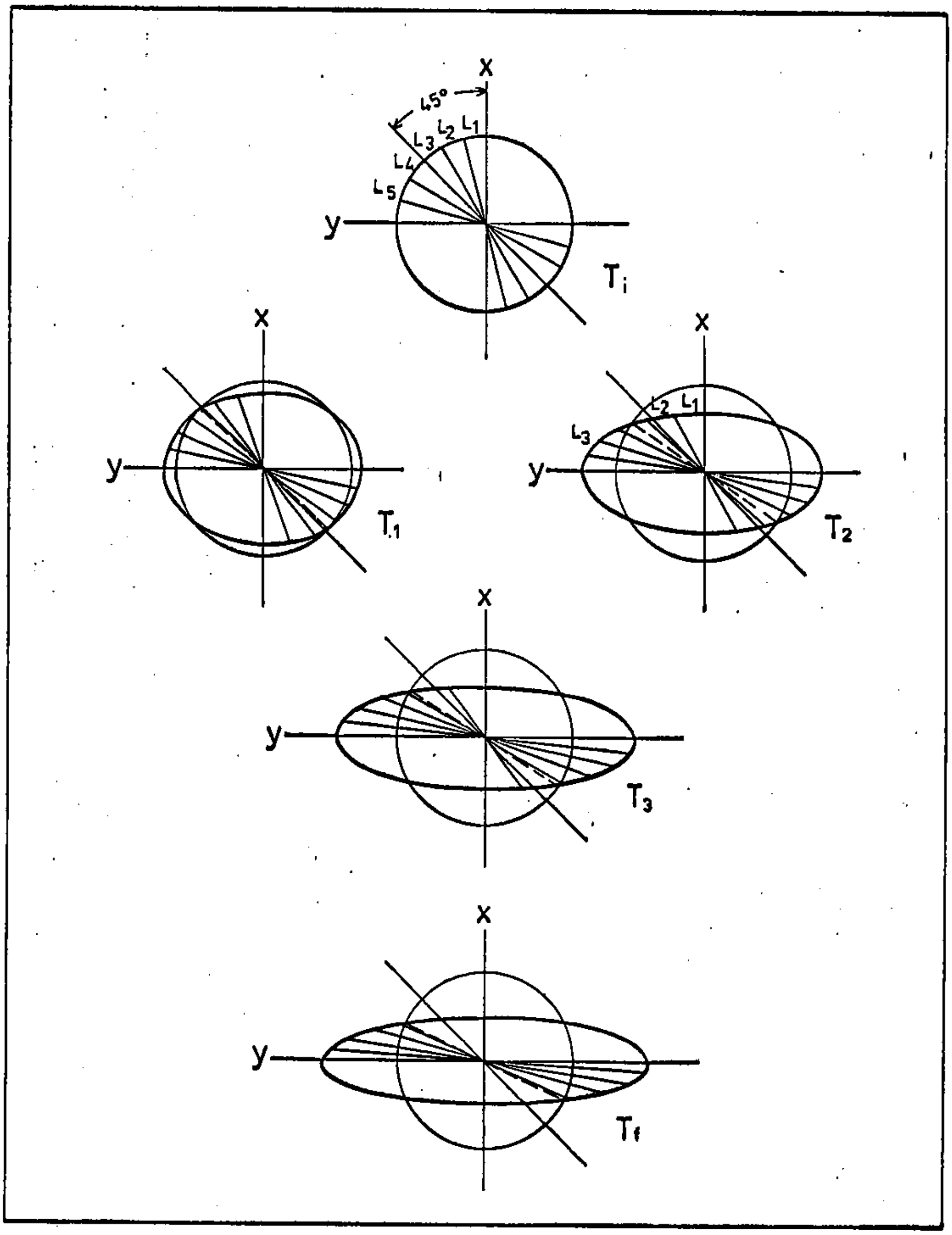


Fig. 8 Progressive incremental pure shear strain

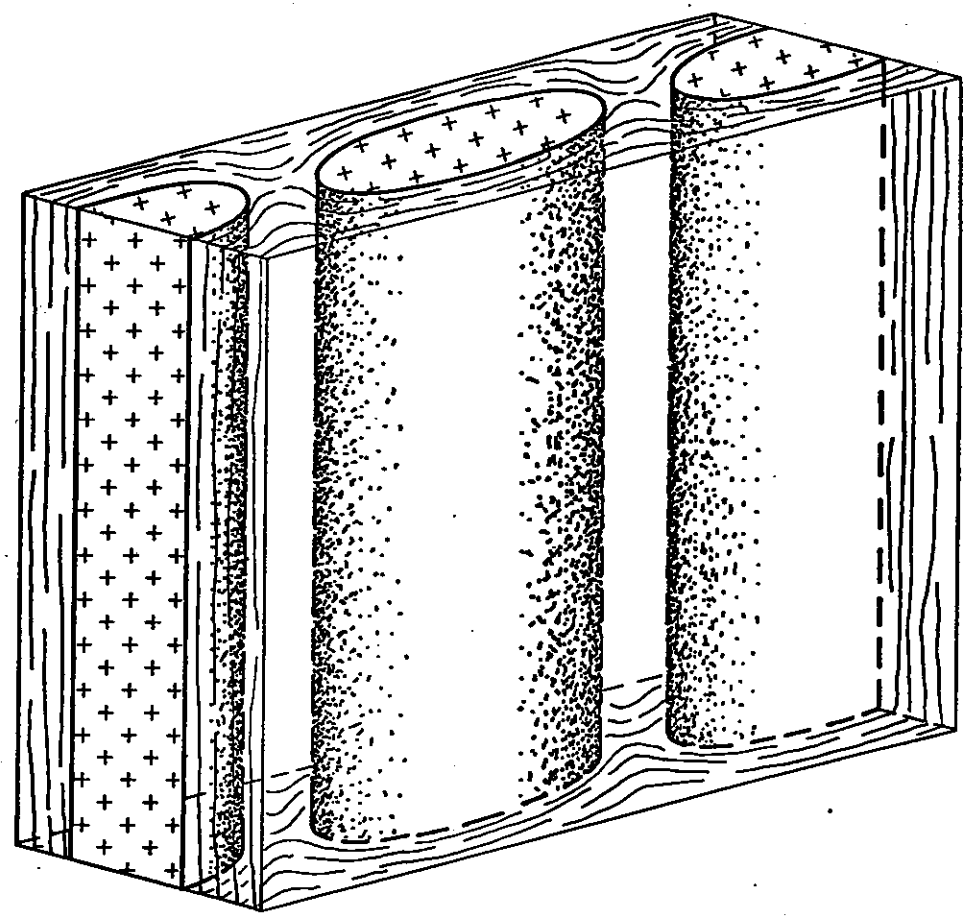


Fig. 9 Three-dimensional model of cylindroidal boudinage.

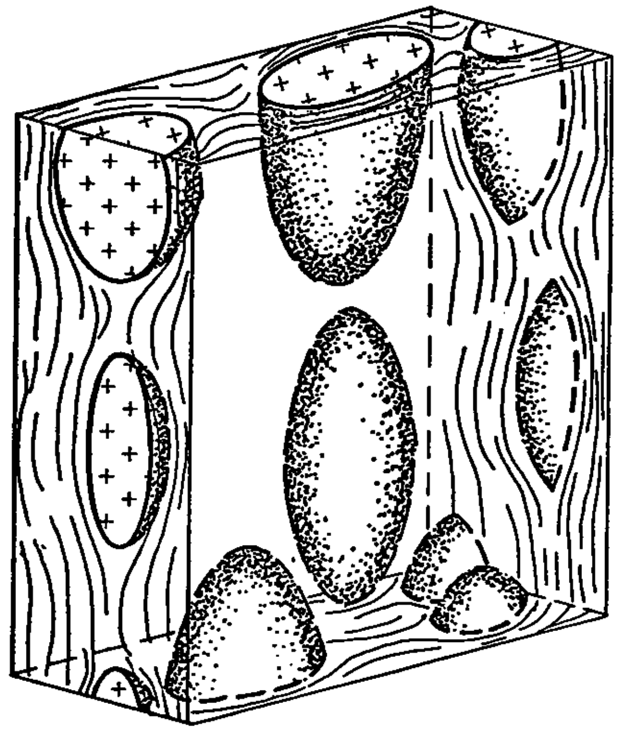


Fig.9a Three dimensional shapes of lensoidal boudins

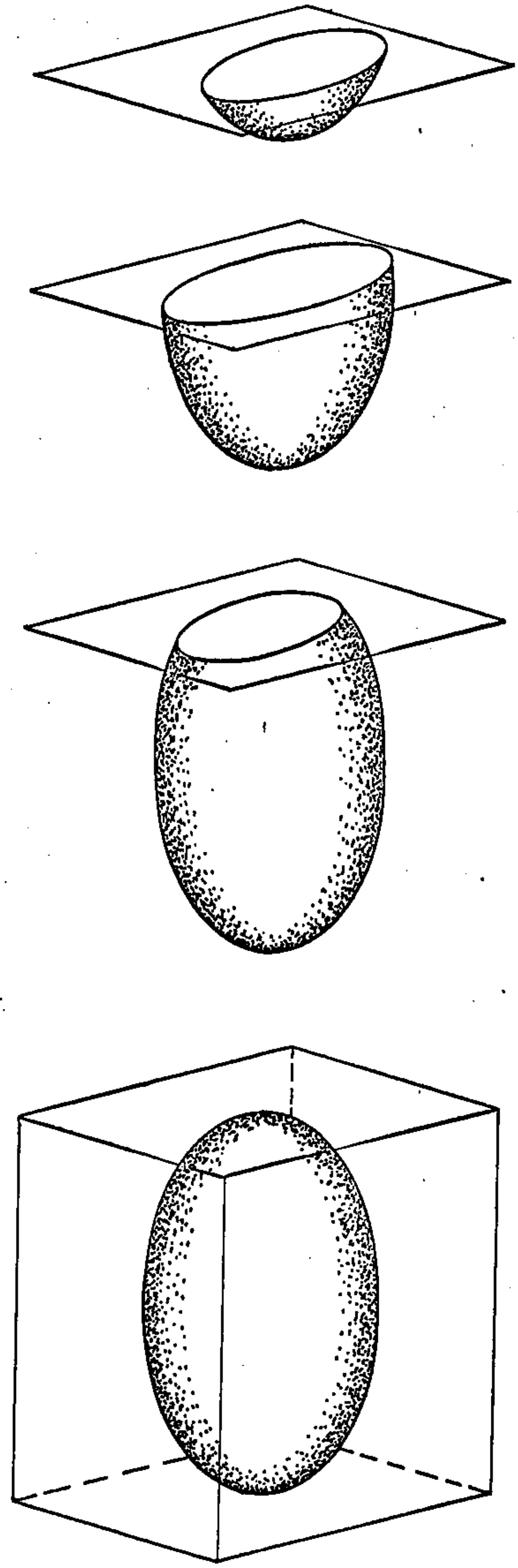


Fig. 9b Progressive sections through a lensoid boudin to show relation between surface outcrop and sub-surface structure